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Fifteenth International Technical Conference on the Enhanced Safety of Vehicles

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MELBOURNE, AUSTRALIA
13 -16 MAY 1996

eNHANCED SAFETY OF VEHICLES

Federal Office of Road Safety
Australia

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

The Fifteenth International Technical Conference on Enhanced Safety of Vehicles

Proceedings Volume 2

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

The Fifteenth International Technical Conference on Enhanced Safety of Vehicles

Sponsored by:
U.S. Department
of Transportation

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Traffic Safety
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Hosted By:
Federal Office of
Road Safety
Australia

Held At:
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13-16 May 1996

Foreword

This report of the proceedings of the Fifteenth International Technical Conference on the Enhanced Safety of Vehicles was prepared by the National Highway Traffic Safety Administration, United States Department of Transportation.

We wish to thank the authors and all those responsible for the material submitted, which aided materially in the preparation of this report.

For clarity and because of some translation difficulties, a certain amount of editing was necessary. Apologies are, therefore, offered where the transcription is not exact. Papers in each of the technical sessions are numbered sequentially. Due to the withdrawal and/or transfer of papers from one session to another, breaks in the number sequence may occur.

Introduction

The International Experimental Safety of Vehicles (ESV) Program originated under NATO's Committee on the Challenges of Modern Society (CCMS) and was implemented through bilateral agreements between the United States Government and the governments of France, the Federal Republic of Germany, Italy, the United Kingdom, Japan, and Sweden. The participating nations agreed to develop experimental safety vehicles to advance the state-of-the-art in safety engineering and to meet periodically to exchange technical information on their progress. Over time the focus of the Conference has shifted from concentration on the development of experimental safety vehicles to broader issues of motor vehicle safety. In addition the number of our international partners has expanded. The governments of Canada, Australia, the Netherlands, Hungary and Poland are also active participants. In 1991, the name of the Conference was changed to "International Technical Conference on the Enhanced Safety of Vehicles" (ESV) to reflect these broader issues.

To date, fourteen international conferences have been held, each hosted by one of the participating governments. These conferences have drawn participants from government, the worldwide automotive industry, and the motor vehicle research community. The 15th ESV Conference, held in Melbourne, Australia, was attended by the largest number of countries since its inception. Participating countries included Belgium, Canada, Denmark, France, Germany, India, Indonesia, Ireland, Japan, Korea, Malaysia, New Zealand, Poland, Russia, Singapore, Spain, Sweden, the Netherlands, the Philippines, the United Kingdom, the United States, and Australia. International cooperation in motor vehicle safety research continues at the highest level.

The proceedings of each Conference have been published by the United States Government and distributed worldwide. These reports, which detail the safety research efforts underway worldwide, have been recognized as the definitive work on motor vehicle safety research.

We are certain that this outstanding example of international cooperation seeking reductions in motor vehicle deaths and injuries will continue its past success.

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EVALUATION OF AFTERMARKET DEVICES TO REPOSITION SHOULDER BELTS

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Paper Number 96-S7-O-01

ABSTRACT

This paper will present the results from a series of HYGE sled tests that were conducted by the National Highway Traffic Safety Administration (NHTSA) to evaluate aftermarket devices designed to reposition the shoulder belt to improve fit/comfort. Three types of devices were tested using the 3- and 6-year-old and 5[th] percentile female dummies. Baseline (no device) tests were also conducted. Additionally, tests comparing the use of a belt positioning booster seat with and without one of the devices were also conducted.

INTRODUCTION

A series of 35 HYGE sled tests using the Federal Motor Vehicle Safety Standard (FMVSS) No. 213, "Child Restraint Systems", crash pulse and velocity in the standard frontal orientation and at a 15° offset, clockwise and counter clockwise (simulating an oblique impact) were conducted to evaluate the devices. Figure 1 shows an example sled acceleration time history. The 213 test fixture's seat back was rigidly fixed to minimize any motion which could affect the performance of the belt fit devices. Because these type of aftermarket belt fit devices currently are not required to comply with FMVSS No. 213, or any other FMVSS, the tests documented in this report are for research purposes only and should not be considered as compliance tests.

Three types of belt fit devices were chosen for use with the Part 572 3-year-old and 6-year-old dummies and the Hybrid III 5[th] percentile female dummy: (1) the Child-Safer™, a plastic strip which attaches to the lap belt and has three different openings through which the shoulder belt can be routed, (2) the SafeFit™, a pouch design through which the lap/shoulder belt is routed, and (3) the Seatbelt Adjuster™, a plastic clip which attaches to the lap belt and the shoulder belt is positioned under a flange to reroute the belt. These three are representative of the types of devices which are currently being marketed. Sketches of the belt fit devices are contained in Figures 2 through 4. The devices are intended to react under dynamic conditions as follows:

Child-Safer™: The bottom end of the device remains attached to the lap belt. The shoulder belt disengages from the 2 slots it is routed through at the upper end of the device when a certain amount of occupant loading on the belt occurs, allowing the belt to repositioning itself on the occupant.

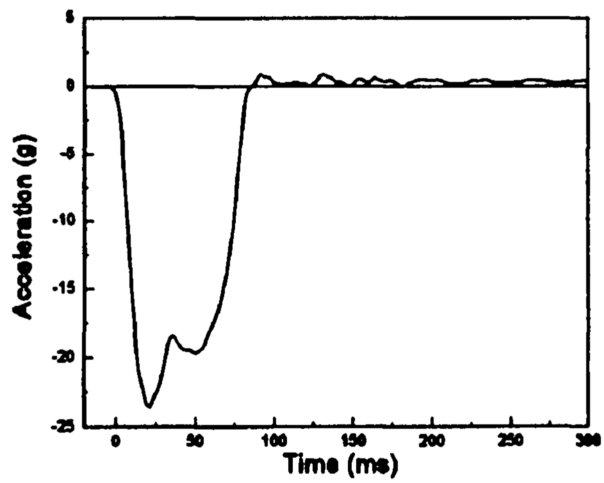


Figure 1. Sled Acceleration Curve for Test Number V296BL06ST

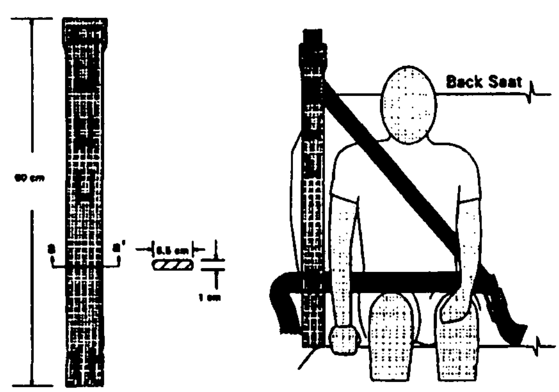


Figure 2. Sketch of Child-Safer ™ Device

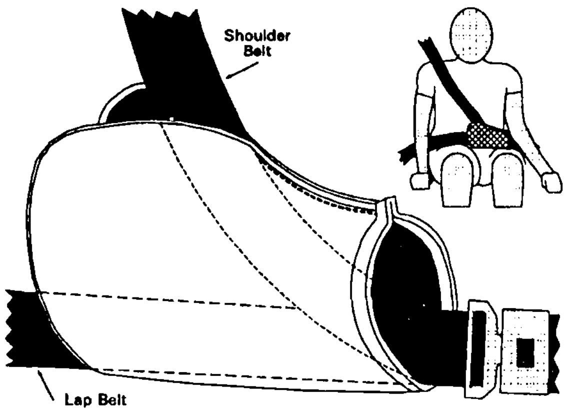


Figure 3. Sketch of SafeFit ™ Device

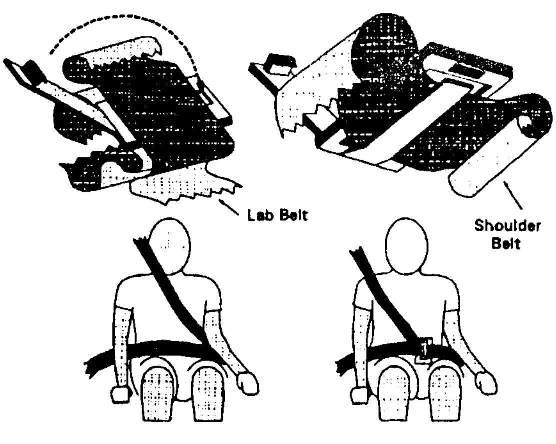


Figure 4. Sketch of Seatbelt Adjuster ™ Device

SafeFit™: The device remains attached to the belt restraint and maintains its structural integrity. The shoulder belt tends to remain where initially positioned on the occupant.

Seatbelt Adjuster™: The base of the device remains attached to the lap belt. The flange that reroutes the shoulder belt breaks away from the device, allowing the shoulder belt to reposition itself on the occupant.

The Child-Safer™ was also tested using the 3-year-old dummy seated in a Century CR-3 booster seat. It states in the device's literature that it can be used in conjunction with a booster seat to improve shoulder belt fit. Baseline (no belt fit device) tests were also conducted with the 3-year-old, 6-year-old, and 5th percentile female dummies for comparative purposes. All tests used 3-point safety belts with the anchorage locations defined in the Final Rule on FMVSS No. 213 dated September 3, 1993.*(1) The complete test matrix is contained in Table 1

The manufacturer of the Child-Safer™ device suggests that it fits occupants between the heights of 96.5 cm and 152.4 cm. The SafeFit™ device is recommended for children with a mass between 22.7 kg and 31.8 kg. The manufacturer of the Seatbelt Adjuster™ does not give any specification for who can use their product, but their literature suggests that it "works great with children" and their packaging shows an adult female using the product. The 3-year-old dummy has a mass of 15.1 kg and stands 97.5 cm high; it is in the height range for the Child-Safer™ device. The 6-year-old dummy has a mass of 21.5 kg and stands 120.1 cm; therefore it meets the height requirement for the Child-Safer™ and is 1.2 kg below the mass requirement for the SafeFit™. The 5th percentile female dummy has a mass of 46.3 kg and is 149.9 cm high; it meets the height requirement for the Child-Safer™ device. The 5th percentile female dummy is outside the weight requirement for the SafeFit™ device, but the package suggests that "anyone who is unable to wear shoulder belts properly can benefit from SafeFit™, including moms and grandmas." The Seatbelt Adjuster™ device has no requirement.

The 3-year-old and 6-year-old dummies were instrumented with triaxial accelerometer arrays in the head and thorax, with the 6-year-old also having femur load cells. Instrumentation for the 5th percentile female dummy included triaxial accelerometer arrays in the head, thorax, and pelvis, femur load cells, chest displacement potentiometer, load cells in the neck, thorax and lumbar spine, and sensors on the ilium to detect occupant submarining. In each test, there was a load cell on the lap portion of the safety belt near the lap belt outboard anchor, and a load cell on the shoulder belt portion of the safety belt near the D-ring.

SLED TEST RESULTS

The Head Injury Criterion (HIC), resultant 3 ms chest acceleration, head excursion and knee excursion were calculated for each test, and used as a means for comparison only. Based on the results observed in the clockwise oblique tests, the 3-year-old dummy was not tested in the counterclockwise oblique configuration ("15° out of belt"). It is believed that the counterclockwise configuration results would not show significant differences than were observed in the frontal and clockwise configurations. The second reason for only conducting the clockwise orientation with the 3-year-old dummy was because only one of the belt fit devices (Child-Safer™) even mentions usage by children as small as 3-years-old.

*Numbers in parentheses indicate references at end of text.

Table 1.
Test Matrix for Evaluation of Belt Fit Devices
(Lap/Shoulder Belt Used In All Tests)

Restraint Device	Dummy Size	Test Condition	Test Number
Child-Safer™	3-year-old	Standard 213	V296CS03ST
		15° into belt	V296CS03OB
		Standard 213 Century CR-3	V296CS03CB
	6-year-old	Standard 213	V296CSR6ST
		15° into belt	V296CS06OB
		15° out of belt	V296CS06CC
	5th Percentile Female	Standard 213	V296CS5FST
		15° into belt	V296CS5FOB
		15° out of belt	V296CS5FCC
SafeFit™	3-year-old	Standard 213	V296SF03ST
		15° into belt	V296SF03OB
	6-year-old	Standard 213	V296SF06ST
		15° into belt	V296SF06OB
		15° out of belt	V296SF06CC
	5th Percentile Female	Standard 213	V296SF5FST
		15° into belt	V296SF5FOB
		15° out of belt	V296SF5FCC
Seatbelt Adjuster™	3-year-old	Standard 213	V296SA03ST
		15° into belt	V296SA03OB
	6-year-old	Standard 213	V296SA06ST
		15° into belt	V296SA06OB
		15° out of belt	V296SA06CC
	5th Percentile Female	Standard 213	V296SA5FST
		15° into belt	V296SA5FOB
		15° out of belt	V296SA5FCC
Baseline (no device)	3-year-old	Standard 213	V296BL03ST
		15° into belt	V296BL03OB
	6-year-old	Standard 213	V296BL06ST
		15° into belt	V296BL06OB
		15° out of belt	V296BL06CC
	5th Percentile Female	Standard 213	V296BL5FST
		15° into belt	V296BL5FOB
		15° out of belt	V296BL5FCC

Injury Criteria and Excursion Limit Comparisons

Injury criteria and head and knee excursions derived for the tests using the 3- and 6-year-old, and the 5th percentile female dummies are contained in Table 2. HIC values less than 1000 and 3 ms resultant chest acceleration clip values less than 60 g were observed for all four dummies when tested in the baseline (no device) configuration, regardless of impact orientation. The HIC value for the 3-year-old dummy in the baseline/clockwise orientation was marginal at 995. Under FMVSS No. 213, head and knees excursion limits are 813 mm and 914 mm, respectively, forward of point Z on the standard seat fixture. The 3-year-old and 6-year-old dummies did not exceed either of these limits during any of the tests series. Head and knee excursions were not evaluated for the 5th percentile female dummy.

The following observations were made for the tests conducted with the Child-Safer™ device:

- *3-year-old dummy*
  - HIC values exceeded 1000 in both frontal and clockwise orientations
  - chest clip values were less than 60 g's in both impact orientations
  - use of the Child-Safer™ device resulted in the largest amounts of head excursion, as compared to baseline and other devices
- *6-year-old dummy*
  - HIC values were below 1000 for all three tests (clockwise orientation was marginal at 947)
  - only the counterclockwise orientation resulted in the chest clip being less than 60 g's (50.1); values for frontal and clockwise orientations were 65.2 g and 67.1 g, respectively.
  - use of the Child-Safer™ device resulted in the largest amounts of head excursion as compared to baseline and other devices
- *5th percentile female dummy*
  - HIC values exceeded 1000 in all three impact orientations
  - chest clip values were less than 60 g's in all impact orientations

The following observations were made for the tests conducted with the SafeFit™ device:

- *3-year-old dummy*
  - HIC values exceeded 1000 in both frontal and clockwise orientations
  - chest clip values were divided based on impact orientation - less than 60 g's for the frontal test; greater than 60 g's (62.1) for the clockwise test
- *6-year-old dummy*
  - HIC values were less than 1000 for all three impact orientations
  - chest clip values were less than 60 g's in all impact orientations
  - use of the SafeFit™ device resulted in the second highest amounts of head excursions in 4 of the 5 tests conducted with the 3- and 6-year-old dummies, as compared to baseline and other devices
- *5th percentile female dummy*
  - HIC value was less than 1000 in the counterclockwise orientation; HIC values exceeded 1000 at the other two impact orientations
  - chest clip values were less than 60 g's in all impact orientations

The following observations were made for the tests conducted with the Seatbelt Adjuster™ device:

- *3-year-old dummy*
  - HIC value was 999 for the frontal impact; the HIC value exceeded 1000 for the clockwise orientation
  - chest clip values were less than 60 g's for both impact orientations
- *6-year-old dummy*
  - HIC values were less than 1000 for all three impact orientations
  - chest clip values were less than 60 g's for all impact orientations
  - use of the Seatbelt Adjuster™ device resulted in the least amounts of head excursionsions in 4 of the 5 tests conducted with the 3- and 6-year-old dummies, as compared to the other two devices
- *5th percentile female dummy*
  - HIC values were less than 1000 at all three impact orientations
  - chest clip values were less than 60 g's for all impact orientations

Of all of the dummy/device configurations, the least amounts of head excursion for the 3- and 6-year-old dummies were observed when tested without a belt fit device, with the exception of the 6-year-old in the standard frontal configuration. There were no distinct trends observed for the amounts of knee excursion for the two child dummies - no one specific belt fit device and/or test buck orientation produced the largest or smallest amount of excursion.

Lap/Shoulder Belt Forces

In addition to computing the FMVSS No. 213 injury and excursion criteria, other measurements and analyses were used to compare the different belt fit devices. Table 3 contains the peak lap and shoulder belt forces for the complete matrix of tests.

Lap/shoulder belt forces depended on dummy size; the larger the dummy, the higher the safety belt forces. The shoulder belt forces for the 5th female dummy ranged from

Table 2.
Summary of Injury Criteria and Excursion Values for Sled Tests

	fit device*	HIC	Chest Clip (g)	Head Excursion (mm)	Knee Excursion (mm)
3-year-old Standard	BL	874	48.7	477	553
	CS	**1309**	55.1	560	615
	SF	**1095**	56.5	496	618
	SA	999	48.1	551	583
3-year-old 15° Offset Clockwise	BL	995	48.5	411	535
	CS	**1565**	52.3	564	665
	SF	**1435**	**62.1**	486	639
	SA	**1238**	45.4	452	580
6-year-old Standard	BL	657	50.4	481	628
	CS	769	**65.2**	567	674
	SF	427	49.1	566	649
	SA	634	50.8	473	604
6-year-old 15° Offset Clockwise	BL	595	54.3	435	602
	CS	947	**67.1**	540	661
	SF	621	57.7	461	580
	SA	794	55.1	493	640
6-year-old 15° Offset Counterclockwise	BL	409	48.5	516	607
	CS	509	50.1	628	605
	SF	386	42.8	577	589
	SA	374	45.7	554	559
5th Female Standard	BL	713	54.2	NA	NA
	CS	**1356**	56.9		
	SF	**1178**	43.7		
	SA	862	48.8		
5th Female 15° Offset Clockwise	BL	772	56.5	NA	NA
	CS	**1253**	57.5		
	SF	**1069**	36.2		
	SA	852	57.3		
5th Female 15° Offset Counterclockwise	BL	771	48.4	NA	NA
	CS	**1188**	53.9		
	SF	672	42.3		
	SA	893	51.4		

Numbers in bold exceed FMVSS No. 213 criteria.
*BL - baseline, no device CS - Child-Safer™ SF - SafeFit™ SA - Seatbelt Adjuster™

clockwise - occupant rides into shoulder portion of safety belt
counterclockwise - occupant rides out of shoulder portion of safety belt

Table 3.
Summary of Lap and Shoulder Belt Forces

	fit device*	Shoulder Belt Peak Force (N)	Lap Belt Peak Force (N)
6-Year-Old Standard	BL	4683	2618
	CS	5466	3385
	SF	4683	2432
	SA	4387	2509
6-Year-Old 15° Offset Clockwise	BL	4756	2202
	CS	3353**	2759
	SF	4545	2685
	SA	5052	2440
6-Year-Old 15° Offset Counterclockwise	BL	4794	3563
	CS	4493	3966
	SF	4089	3689
	SA	3694	3589
3-Year-Old Standard	BL	3746	1854
	CS	3767	1954
	SF	3548	1947
	SA	3438	1830
3-Year-Old 15° Offset Clockwise	BL	3391	1660
	CS	3865	1919
	SF	3697	1932
	SA	3540	1341
5th Female Standard	BL	7736	6932
	CS	8092	6440
	SF	7514	5432
	SA	7303	6103
5th Female 15° Offset Clockwise	BL	7261	7035
	CS	7852	7270
	SF	7052	5276
	SA	7931	9187
5th Female 15° Offset Counterclockwise	BL	7266	5732
	CS	7501	5984
	SF	7043	4311
	SA	6757	5201

*BL - baseline, no device CS - Child-Safer™ SF - SafeFit™ SA - Seatbelt Adjuster™

** Load cell misplaced on shoulder belt

clockwise - occupant rides into shoulder portion of safety belt
counterclockwise - occupant rides out of shoulder portion of safety belt

6757 N to 8092 N, while the lap belt forces ranged from 4311 N to 9187 N.

Peak shoulder belt forces ranged from 3694 N to 5466 N and lap belt forces ranged from 2202 N to 3966 N for tests with the 6-year-old dummy. For tests with the 3-year-old dummy, shoulder belt forces ranged from 3391 N to 3865 N and lap belt forces ranged from 1341 N to 1954 N. No apparent trends of the baseline configuration or use of any particular belt fit device having a discernible effect on shoulder or lap belt loads were observed.

The test with the 6-year-old, clockwise 15° offset into the belt (V296CS06OB), using the Child-Safer™ had an unusually low shoulder belt force of 3353 N. The eleven other tests using the 6-year-old had shoulder belt forces of 3694 N or higher. Review of the high speed films showed that the shoulder belt load cell was misplaced for the test with the 6-year-old in the clockwise 15° offset with the Child-Safer™. Instead of placing the load cell between the D-ring and shoulder of the dummy, it was positioned next to the retractor. This likely influenced the results.

Neck Loads for 5th Percentile Female Dummy

The only dummy instrumented with a neck load cell and tested with and without the belt fit devices was the 5th percentile female dummy. The load cell was installed at the dummy's upper neck and measured loading in the x- and z-axes, and the moment about the y-axis. Table 4 contains a summary of the neck loads and moments for the 5th percentile female dummy. Load and moment values summarized in the table were analyzed for comparative purposes only - no attempt was made to determine potential injury levels based on the values.

Use of a belt fit device generally resulted in increased load and moment values, compared to the baseline tests, when the female dummy was tested in both the standard frontal and 15° clockwise offset ("into belt") configurations. The presence of the belt fit devices appeared to have minimal effect on load and moment responses when the dummy was tested in the 15° counterclockwise offset ("out of belt") configuration. This is primarily due to the fact that the direction of the impact forces exerted on the dummy caused a reduction in the dummy's interaction with the shoulder belt, which in turn tended to reduce the apparent effect(s) that a belt fit device might have on the dummy responses when compared to the results from the other two impact orientations.

It is of interest to note that use of the Child-Safer™ device resulted in increased neck load and moment values for all impact orientations. The sole exception to this trend was the neck x-axis load when tested in the 15° counterclockwise orientation (virtually identical to the baseline result). The amounts of increased neck loading ranged from 12% to 51.5%, while the neck extension responses ("-" values) increased between 40% and 83% when using this device as compared to the baseline configuration. Use of the SafeFit™ device resulted in mixed responses - in some configurations it either lowered the neck load results, or was virtually identical, while in other configurations the neck loads increased between 3% and 41.5%, when compared to baseline tests. For the neck extension responses, the SafeFit™ produced either a slight reduction, no influence or increased results by 45.5%, depending on impact orientation. Similar effects were observed when the Seatbelt Adjuster™ was used - some neck loads were reduced slightly as compared to baseline tests, while neck loads increased between 12.5% and 32.5% in other test configurations. There was an 14.3% decline in neck extension response for the 15° counterclockwise ("out of belt") test, while the moment response increased between 15% and 21% for the other two impact orientations.

Dummy Kinematics

The 5th female dummy submarined during its 12 tests. The combination of seat cushion stiffness and dummy size was the primary factor influencing the 5th female dummy to submarine. Table 5 contains a summary of the iliac loads and moments for the 5th percentile female. The final position of the lap belt on the small female was also between the rib cage and the abdomen, resulting in the chest displacement potentiometer to "pop" from its carrier in 3 of the 12 tests (baseline and Seatbelt Adjuster™ in the standard frontal orientation and the baseline in the counterclockwise oblique orientation). It is noted that all of the chest potentiometer readings were below the Hybrid III injury criterion of 76.2 mm which is currently used in FMVSS No. 208, "Occupant Crash Protection". Table 6 contains a summary of the peak chest displacements for the 5th female dummy tests.

Submarining was not a problem with the 3-year-old or 6-year-old dummies. However, during the test with the 3-year-old dummy in the standard frontal condition using the Seatbelt Adjuster™, the shoulder belt slipped off the shoulder. In this test, the device did not break loose, as in the other tests. This caused the belt to remain further away from the neck than if there had been no belt fit device, and allowed the dummy to slip around the shoulder belt.

Belt Fit Device Used With Belt Positioning Booster Seat

The manufacturer of the Child-Safer™ device states in their literature that the device may be used in conjunction with a booster seat to help position the shoulder belt. It was of interest to see what effect, if any, the belt fit device had on the dummy responses compared to using a belt positioning booster seat alone. The Century CR-3 booster

Table 4.

Neck Loads and Moments for 5th Percentile Female Dummy

	fit device*	Neck x-axis Load (N)	Neck z-axis Load (N)#	Neck y-axis Moment (Nm)@
Standard	BL	1556	2463	-34.7 / +35.9
	CS	1745	3697	-63.5 / +32.6
	SF	1608	2995	-50.5 / +29.7
	SA	1460	2771	-42 / +21.9
15° Offset Clockwise	BL	1416	2987	-39 / +41.3
	CS	2143	3830	-54.8 / +18.3
	SF	2002	2724	-38.1 / +17.7
	SA	1877	3523	-45 / +29.5
15° Offset Counterclockwise	BL	1143	2780	-35 / +30.3
	CS	1145	4124	-56.9 / +37.4
	SF	1158	2661	-32 / +33
	SA	1101	3146	-30 / +27.5

*BL - baseline, no device CS - Child-Safer™ SF - SafeFit™ SA - Seatbelt Adjuster™

Neck z-axis load is tension
@ Negative value is extension; positive value is flexion

clockwise - occupant rides into shoulder portion of safety belt
counterclockwise - occupant rides out of shoulder portion of safety belt

Table 5.

Abdominal Loads and Moments for 5th Percentile Female Dummy

	fit device*	Right Iliac x-axis Load (N)	Right Iliac y-axis Moment (Nm)@	Left Iliac x-axis Load (N)	Left Iliac y-axis Moment (Nm)@
Standard	BL	3724	-24.1	4958	+27.9
	CS	3577	-24.6	4603	+74.3
	SF	3418	+73.3	962	+14.4
	SA	5133	+84.2	2697	+42.2
15° Offset Clockwise	BL	3715	-20.4	5169	+54.3
	CS	3974	-19.4	5388	+64.5
	SF	2864	+50.5	2393	+39.2
	SA	4290	+20.9	5008	+61.7
15° Offset Counterclockwise	BL	4917	+33.8	3369	+56.9
	CS	5037	+50.5	2895	+51.4
	SF	4026	+49.3	2631	+48.6
	SA	5071	+67.3	1346	+22.7

*BL - Baseline, no device CS - Child-Safer™ SF - SafeFit™ SA - Seatbelt Adjuster™

@ Negative moment is forward motion of anterior superioe iliac spine; positive moment is rearward motion

clockwise - occupant rides into shoulder portion of safety belt
counterclockwise - occupant rides out of shoulder portion of safety belt

Table 6.

Peak Chest Displacement for 5th and 50th Percentile Dummies

	fit* device	Peak Chest Displacement (mm)
5th Female Standard	BL	NA**
	CS	52.0
	SF	59.0
	SA	NA**
5th Female 15° Offset Clockwise	BL	34.2
	CS	52.0
	SF	52.7
	SA	41.1
5th Female 15° Offset Counterclockwise	BL	NA**
	CS	57.4
	SF	60.3
	SA	61.2

*BL - baseline, no device CS - Child-Safer™ SF - SafeFit™ SA - Seatbelt Adjuster™

** Potentiometer "popped" from carrier during test.

clockwise - occupant rides into shoulder portion of safety belt
counterclockwise - occupant rides out of shoulder portion of safety belt

seat was used with the 3-year-old dummy, using the identical set-up that was used for the test with the CR-3 seat during the research conducted to evaluate the effectiveness of belt positioning booster seats[2], with the exception of the addition of the Child-Safer™. The test is also directly comparable to the tests conducted during this evaluation of belt fit devices, with the exception of the addition of the booster seat.

Table 7 contains a summary of the HIC values, 3 ms resultant chest accelerations and head and knee excursion values for the belt positioning booster tests with and without the Child-Safer™ device. The HIC and 3 ms chest acceleration values for the test with the belt fit device exceeded the criterion of 1000 and 60 g's, respectively. The amounts of head excursion for the two tests were within 71 mm of one another and well below the FMVSS No. 213 criterion of 813 mm. Knee excursion for the test with the belt fit device was not numerically determined due to the inability to accurately locate the knee pivot during digitization of the film. It appears, from film coverage, that the amount would be similar to the test without the belt fit device and that both tests would be well below the criterion value of 914 mm.

Not only did two of the injury criteria show detrimental effects when using the Child-Safer™ device in combination with the Century CR-3 booster seat, the dummies kinematically performed differently in the two tests. Figures 5 and 6 are timed sequences, from the side view and from the front view, respectively, of the two tests showing the dummy kinematics. The test without the belt fit device is on the left while the test with the belt fit device is on the right. Each frame is a 20 ms increment, with the first frame being t=0 ms and the last frame sequence being t=140 ms. The most noticeable difference between the two tests was that the 3-year-old dummy was still experiencing forward and rotational motion, when tested with the Child-Safer™, at the corresponding time that the dummy tested without the belt fit device was in its rebound motion. This appears to be primarily due to the extra webbing (approximately 51 mm) that is required to weave through the belt fit device, which allowed for more forward and rotational motion of the dummy than in the "baseline" condition. With the belt fit device attached, there was sufficient extra webbing that the dummy's head almost contacted its lower extremities. This type of dummy motion was observed when belt positioning booster seats were tested with lap only belts to evaluate what would occur if the boosters were not properly used with a lap/shoulder belt restraint[3].

Table 7.
Comparison of 3 Year Old Dummy Responses
for Belt Positioning Booster Seat With and Without Belt Fit Device

	HIC	Chest Clip (g)	Head Excursion (mm)	Knee Excursion (mm)
Century CR-3 without Child-Safer™	906	48.8	511	643
Century CR-3 with Child-Safer™	**1575**	**61.6**	582	NA

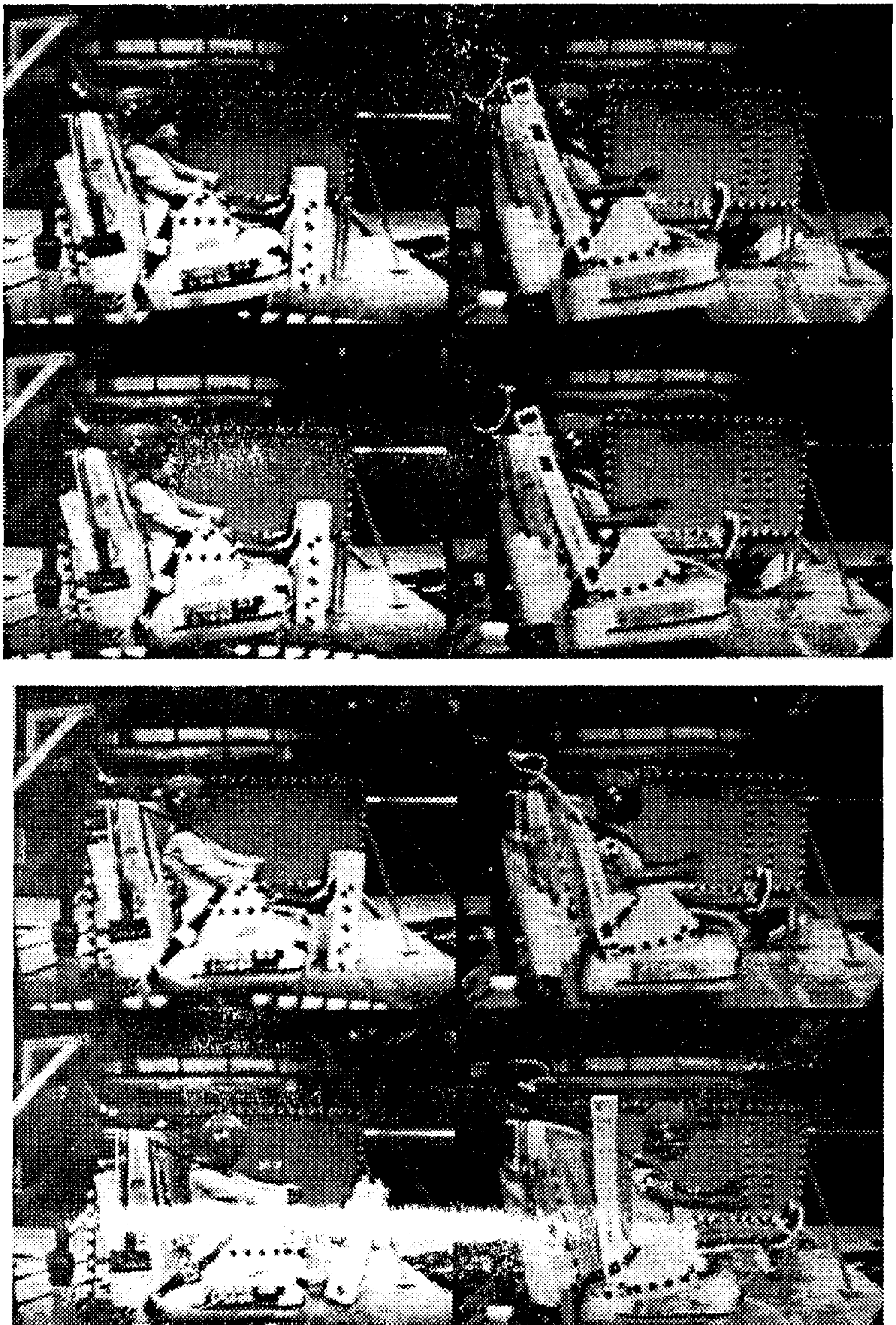
Numbers in bold exceed FMVSS No. 213 criteria which are: HIC shall not exceed 1000, 3 ms chest resultant acceleration shall not exceed 60 g's, head excursion shall not exceed 813 mm, and knee excursion shall not exceed 914 mm.

Belt Fit Device Performance

In addition to using the dummies' response data to evaluate the performance of the three types of belt fit devices, the high speed films were analyzed to compare the dummies' kinematics. For this analysis, the baseline test and tests with each of the devices were compared at 40 ms intervals, from t=0 to t=120 ms, for each dummy size/test buck orientation. The timed sequence for the 3-year-old in the standard frontal test condition is shown in Figure 7. At each time interval, the baseline and the Child-Safer™ photos are on the top row, left and right side, respectively, while the SafeFit™ and Seatbelt Adjuster™ are on the bottom row, left and right side, respectively. A brief summary of each comparison will be given here in the body of the report, with the remaining kinematic comparison sequences for the 3-year-old, 6-year-old and 5th percentile female dummies contained the Appendix.

Using Figure 7 to compare the 3-year-old in the standard frontal orientation, one observes that the dummy

Booster Only **Booster With Child-Safer™**



t=0 ms

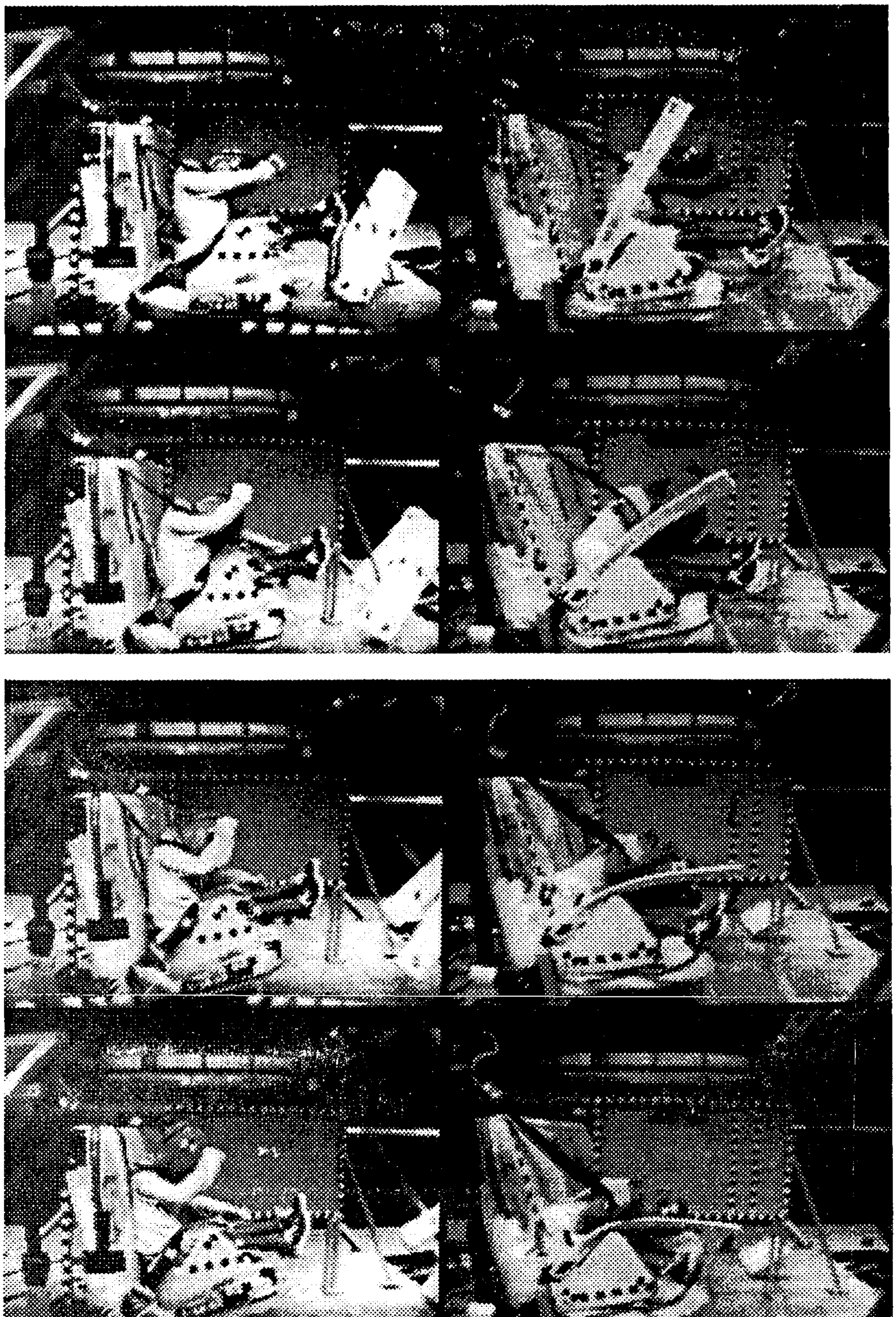
t=20 ms

t=40 ms

t=60 ms

Figure 5. Effect of using belt fit device with belt positioning booster seat - side view

Booster Only | Booster With Child-Safer™



t=80 ms

t=100 ms

t=120 ms

t=140 ms

Figure 5 (Continued). Effect of belt fit device with belt positioning booster seat - side view

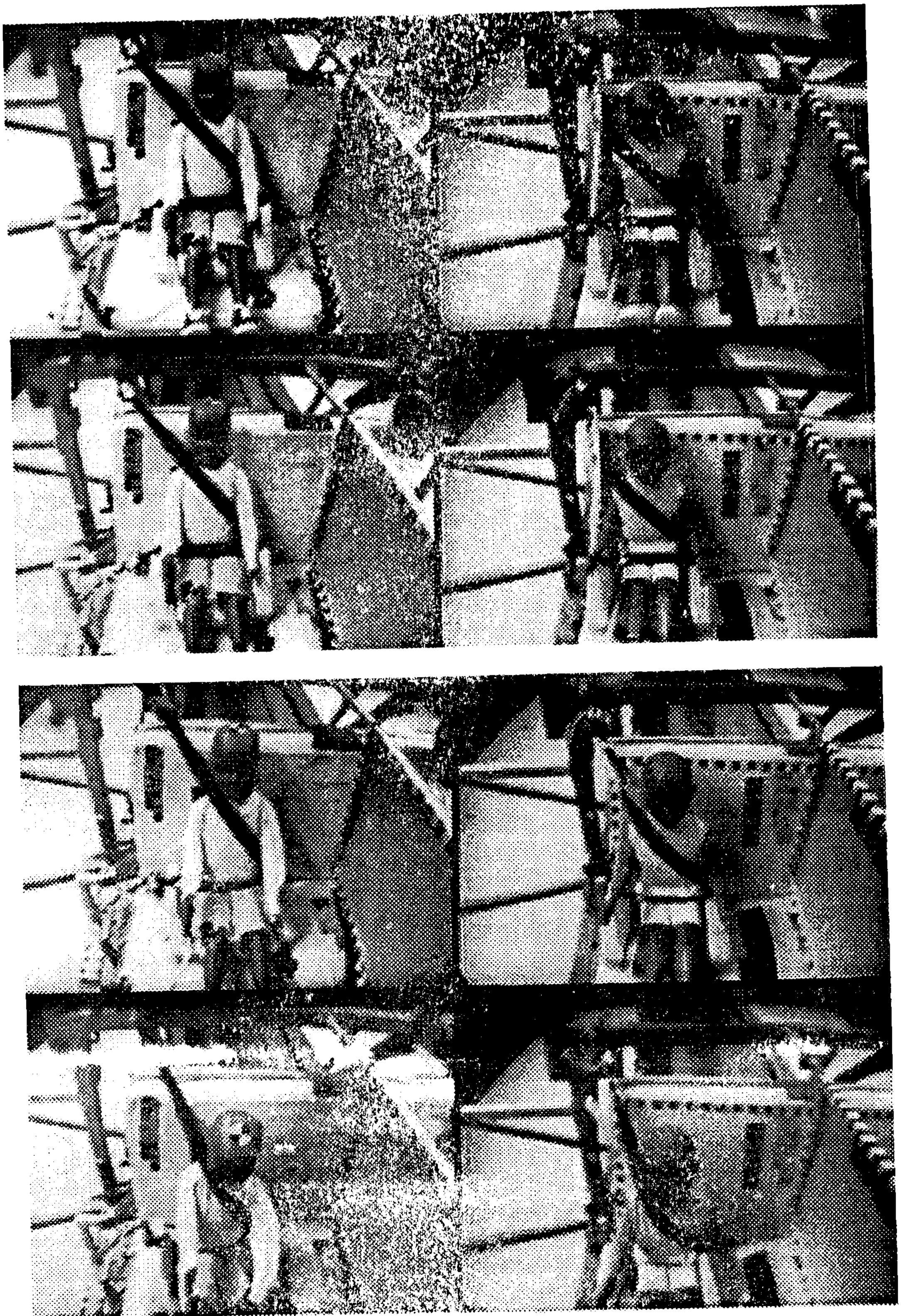
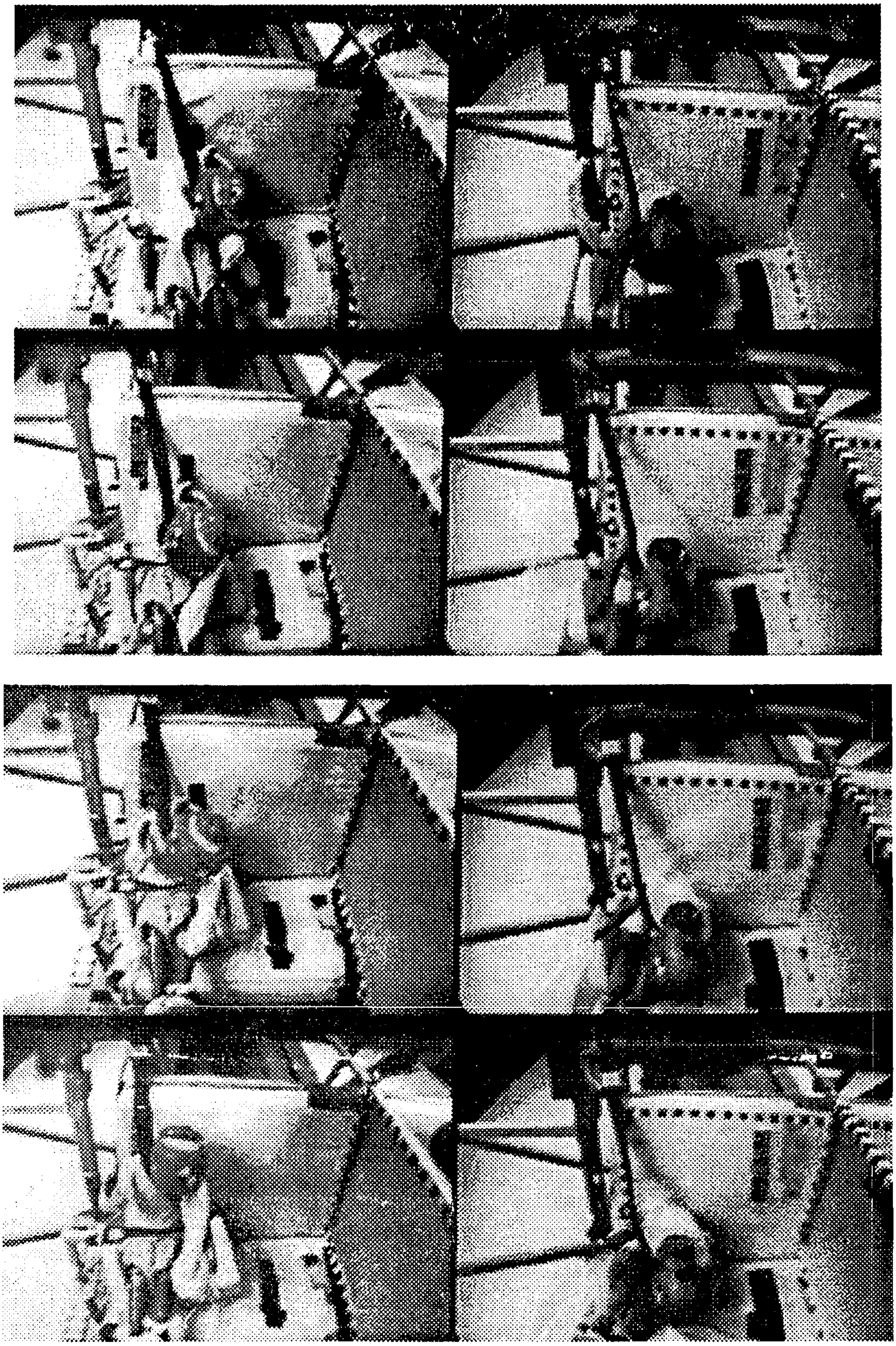


Figure 6. Effect of using belt fit device with belt positioning booster seat - front view

Booster Only | Booster With Child-Safer™



t=80 ms

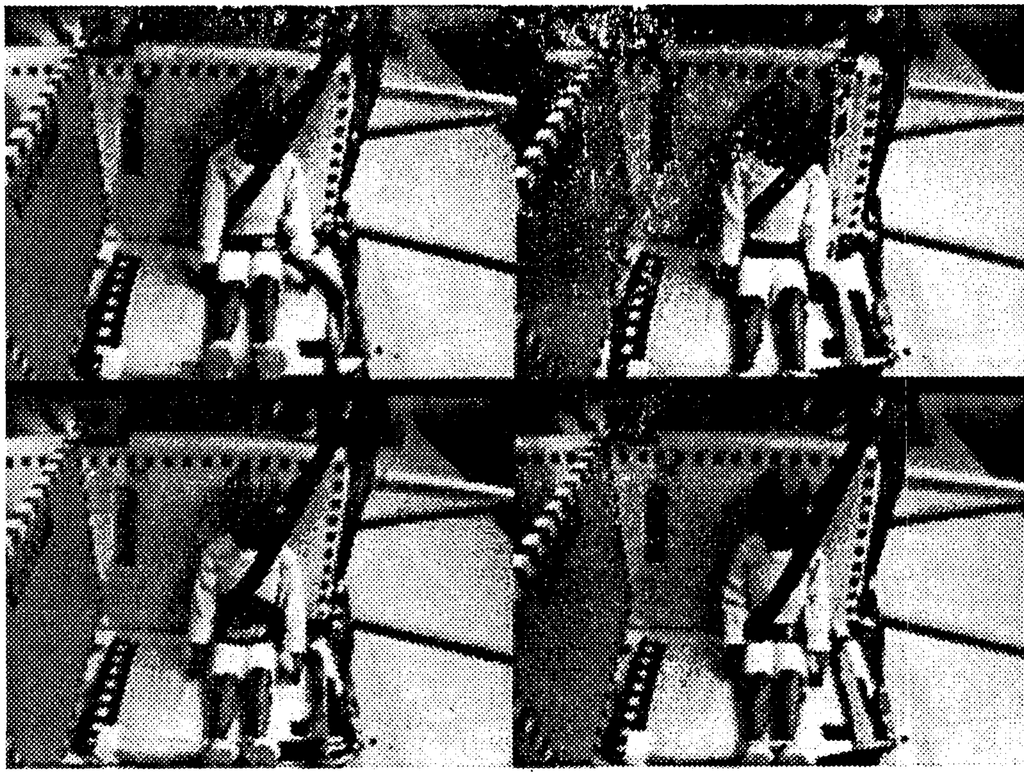
t=100 ms

t=120 ms

t=140 ms

Figure 6. (Continued) Effect of using belt fit device with belt positioning booster seat - front view

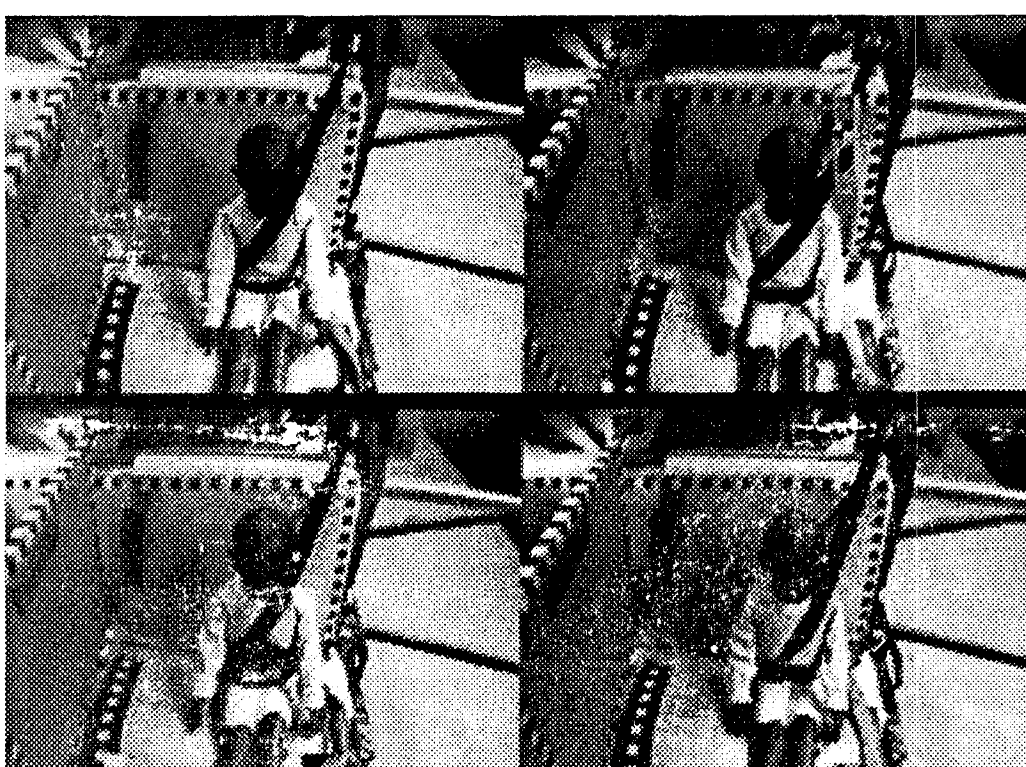
BL CS



t=0 ms

SF SA

BL CS



t=40 ms

SF SA

Figure 7. Kinematic Comparison of 3-year-old in standard frontal orientation -- Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL CS

t=80 ms

SF SA

BL CS

t=120 ms

SF SA

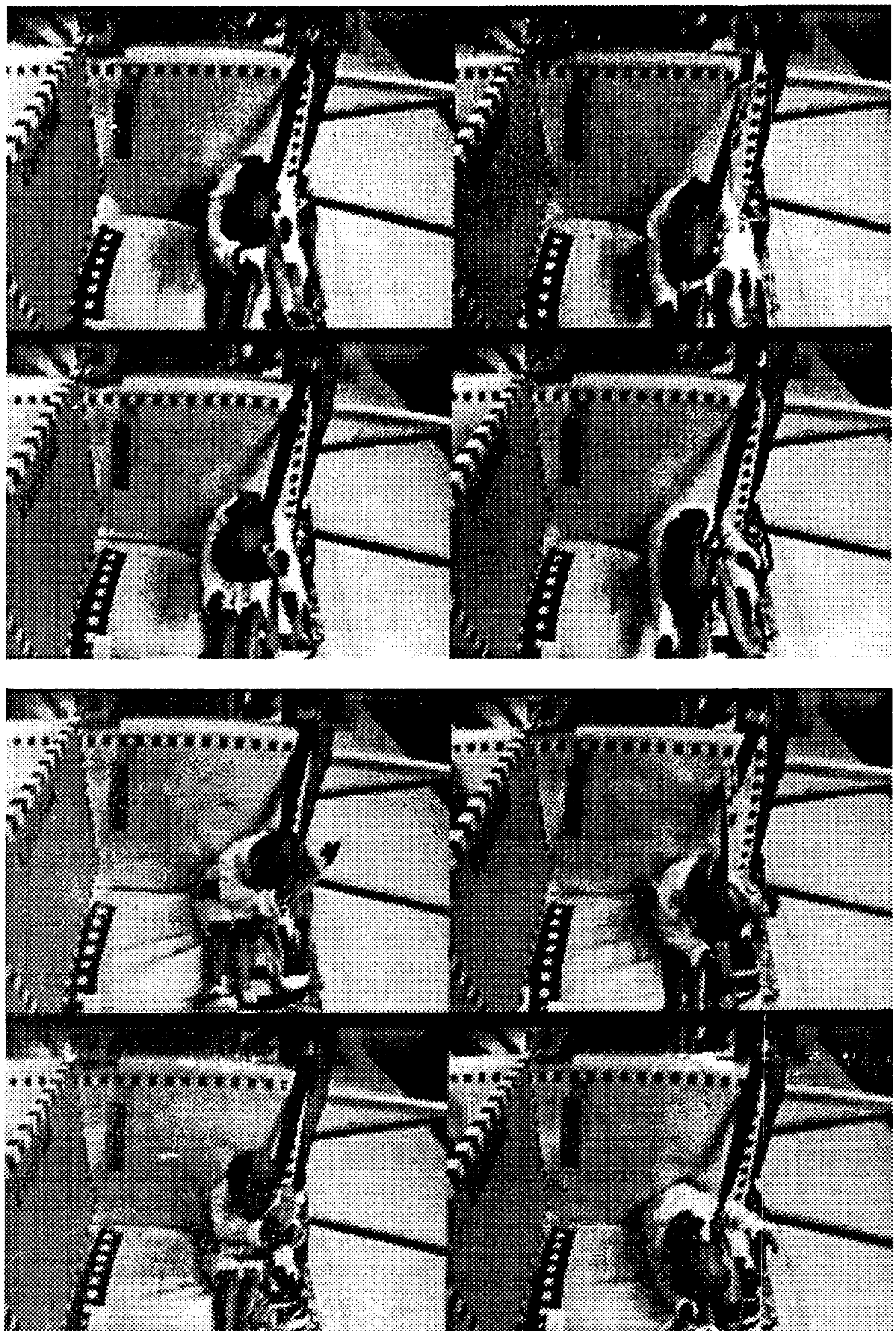


Figure 7. (Continued) Kinematic Comparison of 3-year-old in standard frontal orientation -- Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

began its rebound motion earlier for the baseline test condition than when tested with the belt fit devices, except for the SafeFit™. Also, the Child-Safer™ and the Seatbelt Adjuster™ devices allowed for more forward rotation and "roll-out" of the shoulder belt. These two motions appear to be primarily attributed to (1) the slack in the shoulder belt introduced with the Child-Safer™ routing, and (2) the initial positioning of the shoulder belt with the Seatbelt Adjuster™ (very little belt support on the inboard side of the lower torso, as observed in the other tests).

For the 3-year-old in the clockwise oblique orientation, the baseline and belt fit devices exhibited similar kinematics throughout the 120 ms. One variation was that the dummy exhibited slightly more forward rotation with the Child-Safer™, which in turn caused its rebound to be slightly later than for the other three test conditions.

For the standard frontal orientation, the 6-year-old dummy exhibited similar kinematics for the baseline and belt fit devices up through 40 ms. At 80 ms, the dummy's forward rotation in the tests with the Child-Safer™ and the SafeFit™ devices was more pronounced than for the other tests, which led to less rebounding action observed at the 120 ms time frame. The 6-year-old also tended to "roll-out" of the SafeFit™ device more than under the other three conditions. During the tests with the 6-year-old dummy and the buck oriented 15° clockwise ("into belt"), the kinematic responses for the dummy were quite similar for the baseline and belt fit devices. With the 6-year-old in the counterclockwise orientation, the belt fit devices resulted in more dummy "roll-out" of the shoulder belt than was observed in the baseline test. This phenomenon resulted in significant rotation of the head about the z-axis, which again, was not observed in the baseline condition.

For the 5^{th} percentile female dummy in the standard frontal orientation, the kinematics were quite similar for the baseline and the three belt fit devices up through 80 ms. At the 120 ms time frame, the test with the SafeFit™ device exhibited a different rebound motion than for the baseline and other two devices. The SafeFit™ device kept the lap belt from pulling over the abdominal region in as pronounced a manner as the belt did in the baseline and with the other two devices. This difference allowed the torso to rebound faster, which in turn caused complete submarining of the small female dummy to occur later in the event. For both the clockwise and the counterclockwise oblique tests with the 5^{th} percentile female, the kinematics for each orientation were quite similar for the baseline and the three belt fit devices up through 80 ms. In fact, the kinematics observed for the four test conditions in the counterclockwise orientation were similar through the 120 ms time frame. The main difference at the 120 ms time frame for the clockwise orientation was that the SafeFit™ device appeared to affect the rebound characteristics - the dummy rebounded sooner than it did in the baseline test and the tests with the other two devices. It appeared that the device again kept the lap belt from riding up over the abdominal region completely until later in the event, as it did in the standard frontal orientation.

In reviewing the performance of each individual type of belt fit device, the following observations were made:

- In six of the eight tests using the Child-Safer™, it performed as designed with the shoulder belt slipping out of the top portion of the slots, allowing the device to fall away from the dummy. This also introduced slack in the shoulder belt. In tests with the 3-year-old and the 5^{th} percentile female dummies in the standard frontal condition the Child-Safer™ did not fully disengage from the shoulder belt. Review of the high speed films showed that the dummies did not make contact with the device. No problems were observed as a result of the device not disengaging.
- Review of the high speed films showed that in all eight tests the SafeFit™ device remained in place and did not rip or tear, and no slack was introduced into the shoulder belt.
- In seven of the eight tests using the Seatbelt Adjuster™ device, it performed as expected. Upon loading of the safety belt, the device split apart, which introduced slack into the shoulder belt. During the test with the 3-year-old in the standard frontal condition the device did not break apart. This contributed to the shoulder belt slipping off the shoulder of the dummy.

CONCLUSIONS

Based on the research to evaluate the performance of safety belt comfort devices the following conclusions are made:

- Use of the Child-Safer™ device resulted in a general increase in dynamic responses, regardless of occupant size.
  - HIC values greater than 1000 were observed in 63% of the tests conducted with the Child-Safer™, while the 3 ms chest acceleration clip exceeded 60 g's in 25% of the tests. Head and knee excursion amounts during tests conducted with the child dummies were below the FMVSS No. 213 specified values of 813 and 914 mm, respectively. Tests conducted with the Child-Safer™ resulted in average increases in head excursion (27.3%) and knee excursion (17.8%) as compared to the baseline configuration for the 3-year-old dummy, regardless of impact orientation. Use of the Child-Safer™ with the 6-year-old dummy resulted in an average increase of 21.2% in the amount of head excursion and an average increase of 5.6% in the

amount of knee excursion, as compared to baseline tests.

- In the three tests conducted with the 5th percentile female dummy using the Child-Safer™ device, the device resulted in significant increases (0% to 51.5% higher) in the x- and z-axis upper neck loads. Use of the device also resulted in increased moments about the y-axis (40.5% to 83% higher) as compared to the baseline condition. Impact orientation did not appear to be a factor in this phenomenon.
- In six of the eight tests using the Child-Safer™ device, it performed as designed. The shoulder belt slipped out of the top portion of the slots, allowing the device to fall away from the dummy, but also introducing slack in the shoulder belt. In tests with the 3-year-old and the 5th percentile female dummies in the standard frontal condition the Child-Safer™ did not fully disengage from the shoulder belt. No problems were observed as a result of the device not disengaging.
- The manufacturer of the Child-Safer™ states in the literature that the device can be used in conjunction with a booster seat to aid in improving shoulder belt fit. The HIC value was 1575 and the 3 ms resultant chest acceleration was 61.6 g's for the 3-year-old dummy tested in the booster/belt fit device configuration, while the booster seat only test resulted in a HIC value of 906 and chest acceleration of 48.8 g's. In addition to the booster/belt fit device exceeding FMVSS No. 213 injury criteria, it resulted in severely different dummy kinematics. Due to the introduction of excess shoulder belt webbing (approximately 51 mm used to route the belt through the device) during the impact, the dummy's torso significantly rotated around the lap belt and almost contacted its lower extremities. The amount of head and knee excursion did not appear to be affected by the use of the belt fit device. Although the manufacturer states that the device can be used by people between 96.5 and 152.4 cm tall (the 3-year-old stands 97.5 cm), it is believed that a child at the lower height range is sufficiently small enough to still be using a toddler or booster seat. As for using the device with a booster seat, if the child cannot properly wear the shoulder belt without the device the child should still be using a toddler seat or, if using a small shield booster seat, the shoulder belt should be routed behind the child's torso.

- Increases in dynamic responses were observed in approximately half of the tests conducted with the SafeFit™ device.
  - HIC values greater than 1000 were observed in 50% of the tests conducted with the SafeFit™, while the 3 ms chest acceleration clip exceeded 60 g's in 12.5% of the tests. All head and knee excursion values were below the FMVSS No. 213 criteria. Use of the device with the 3-year-old dummy resulted in average increases of 11.1% and 15.6% in head and knee excursions values, respectively, in comparison to baseline tests. When the SafeFit™ was used with the 6-year-old dummy, an average increase of 11.8% in the amount of head excursion and an average decrease of 1.1% in the amount of knee excursion were observed.
  - In the tests conducted with the 5th percentile female dummy using the SafeFit™ device, the device resulted in a 41.5% increase in the x-axis neck load and a 22% increase in the z-axis upper neck load when tested in the 15° clockwise offset ("into belt") and the standard frontal configurations, respectively. All other combinations of neck load/impact configurations resulted in either a slight reduction, or no change, in neck loads as compared to the baseline tests. Use of the device also resulted in an increased moment about the y-axis (45.5% higher) when tested in the standard frontal configuration. For both offset tests, use of the SafeFit™ had little effect on the neck moment results in comparison to the baseline tests.
  - In all eight tests using the SafeFit™, the device remained in place and did not rip or tear and no slack was introduced into the shoulder belt.
- Minimal increases in dynamic responses for the three sizes of dummies when tested with the Seatbelt Adjuster™ were observed.
  - HIC values greater than 1000 were observed in 12.5% of the tests conducted with the Seatbelt Adjuster™, while 3 ms chest acceleration clip values did not exceed 60 g's in any of the tests. Use of the device resulted in average increases of 12.8% and 6.9% of head and knee excursion amounts, respectively, for the 3-year-old dummy. With the 6-year-old dummy, use of the device resulted in an average increase of 6.3% in the amount of head excursion and an average decrease of 1.8% in the amount of knee excursion as compared to baseline tests.
  - In all three tests conducted with the 5th percentile female dummy using the Seatbelt Adjuster™ device, the device resulted in slight increases (12.5% to 18%) in the z-axis neck loads. The x-axis neck load increased by 32.5% when tested in the 15° clockwise offset ("into belt") configuration. Use of the device also resulted in increased

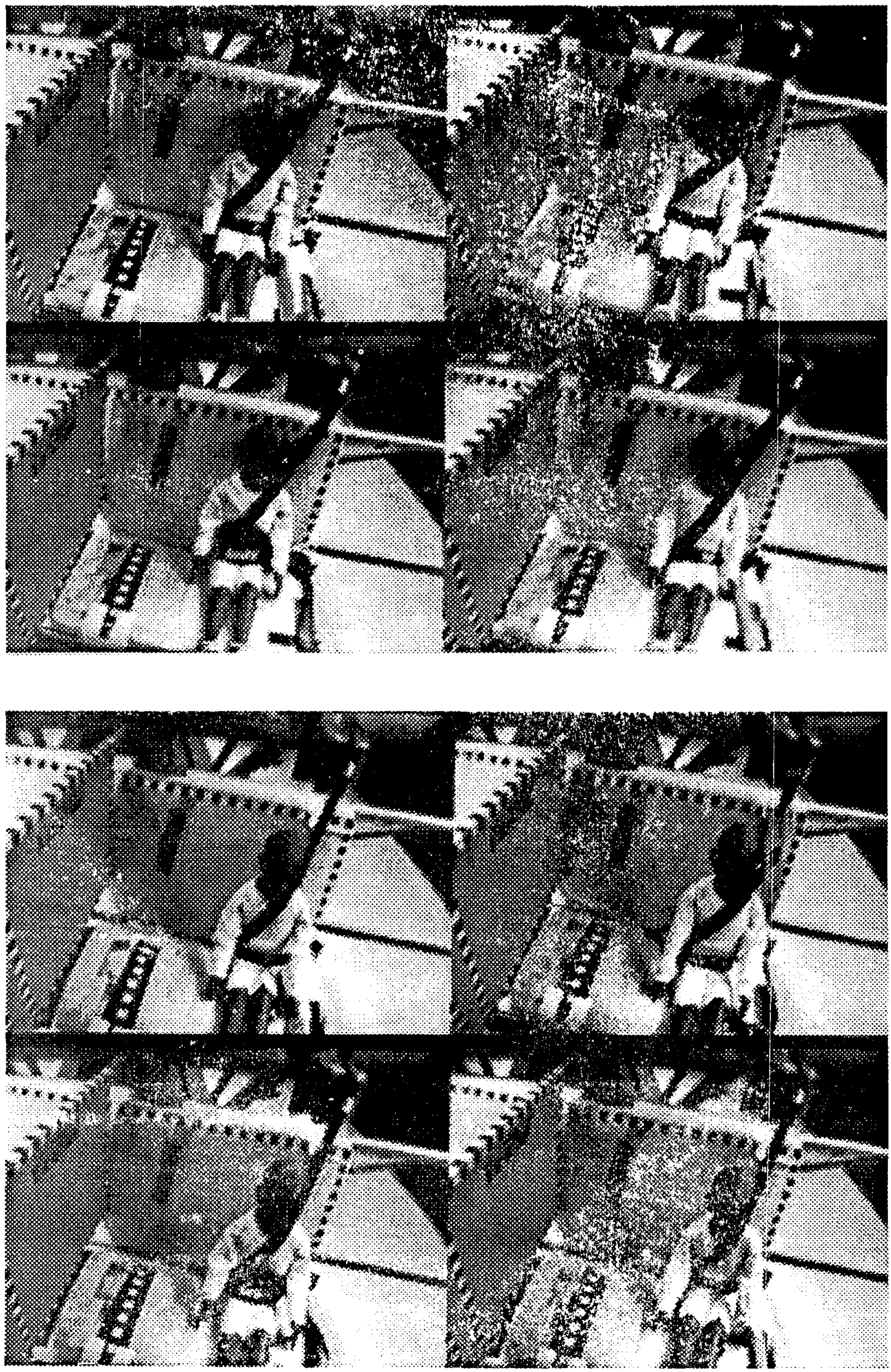


Figure A-1. Kinematic comparison of 3-year-old in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

moments about the y-axis (15% to 21% higher) when tested in the 15° clockwise offset and standard frontal configurations, respectively, but resulted in a decreased moment (14.3%) when tested in the 15° counterclockwised configuration.

- In seven of the eight tests using the Seatbelt Adjuster™ it split apart, which introduced slack into the shoulder belt. During the test with the 3-year-old in the standard frontal condition, the device did not separate, which contributed to the shoulder belt slipping off the shoulder of the dummy.

- Review of the kinematic responses for the 3- and 6-year-old and 5th percentile female dummies, from time t=0 to t=120 ms, reveals the following:
  - Use of all three belt fit devices tended to increase the amount of forward rotation for both the 3- and 6-year-old dummies as compared to the baseline tests, regardless of impact orientation.
  - The Child-Safer™ and the Seatbelt Adjuster™ devices allowed for more "roll-out" of the shoulder belt when tested with the 3-year-old dummy. This motion appears to be primarily attributed to (1) the slack in the shoulder belt introduced by the belt routing required for the Child-Safer™, and (2) the initial positioning of the shoulder belt with the Seatbelt Adjuster™ (very little belt support on the inboard side of the torso, as observed in the other tests). During the standard frontal test with the Seatbelt Adjuster™, the shoulder belt slipped off of the 3-year-old dummy's shoulder, which was due to the flange not breaking away from the clip as it is designed to do.
  - The SafeFit™ device tended to cause the 6-year-old dummy to "roll-out" of the shoulder belt to a greater extent than when tested in the baseline configuration or with the other two devices.
  - The SafeFit™ device had the most significant effect on the kinematics of the 5th percentile female dummy. The device tended to keep the lap belt from pulling over the abdominal region in as a pronounced manner as the belt did in the baseline test and with the other two devices. This difference allowed the torso to rebound faster, which in turn delayed complete submarining of the small female dummy until later in the event.

The apparent leading motivation behind the development of these types of devices is to improve lap/shoulder belt fit on the occupant. It is the authors' opinion that, although this is a worthwhile intent, the performance of the vehicle's restraint system should not be detrimentally affected by the use of such a device. All of the devices evaluated in this study produced some degradation in the performance of the lap/shoulder belt system as compared to baseline conditions, depending on the size of the occupant and the impact orientation.

With the promulgation of the final rule on FMVSS No. 208, "Occupant Crash Protection" (59 FR 39472, August 3, 1994) requiring that Type 2 safety belts be either (1) integrated with adjustable vehicle seats, or (2) equipped with a means of adjustability to improve belt fit and comfort, it is anticipated that increased belt usage will occur, particularly among those occupants who currently find wearing their belts uncomfortable. With the increase in belt comfort due to OEM equipment, it is anticipated that the need for aftermarket belt fit devices will decrease.

REFERENCES

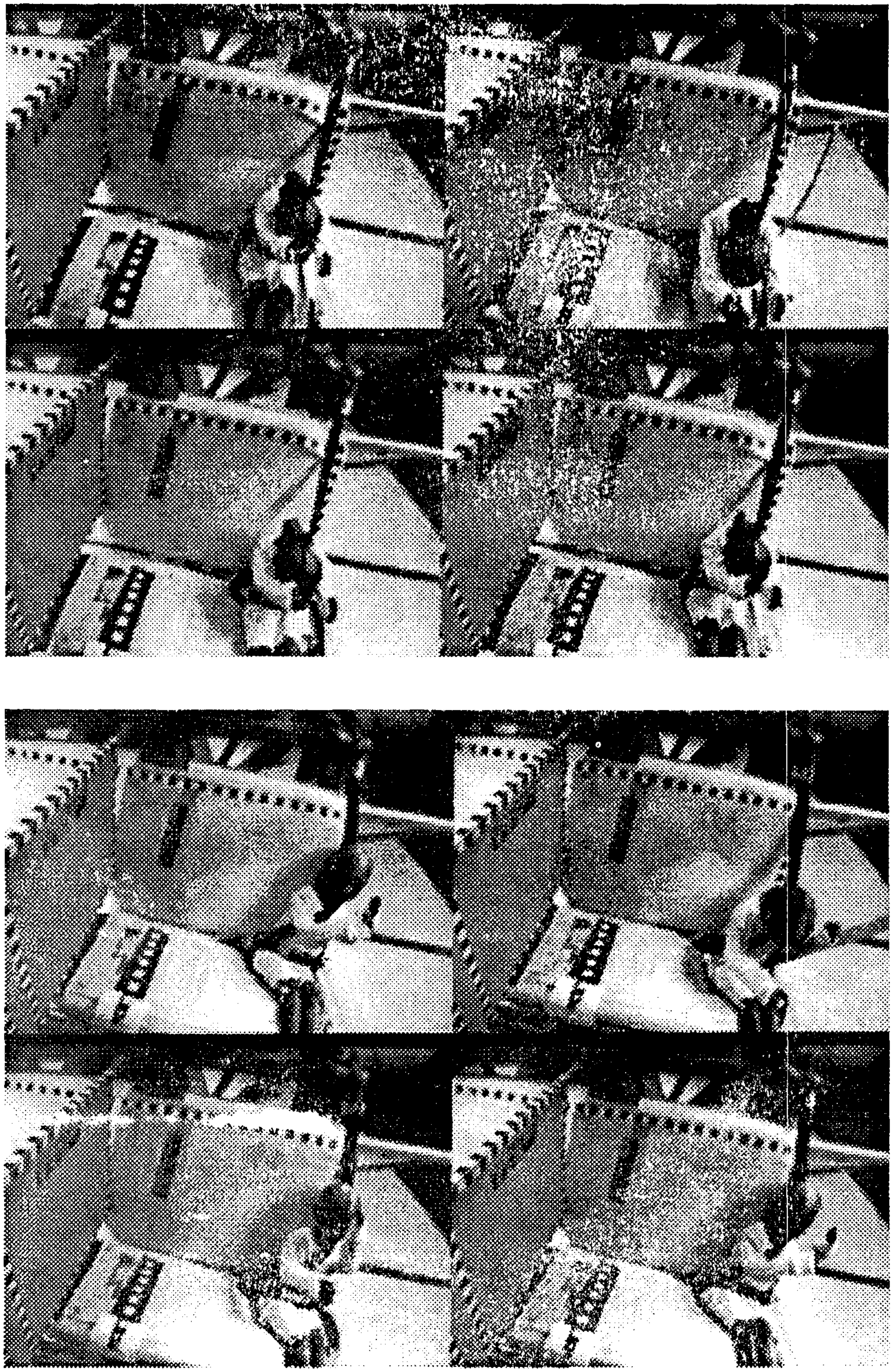
1. Federal Register / Vol. 58, No. 170 / Friday, September 3, 1993 / Proposed Rules, pg. 46936-7

2. Howe, J. Gavin, Chambers, Fletcher K., and Sullivan, Lisa K., "Assessment of Vehicle Interior Dimensions and Lap/Shoulder Belt Fit", NHTSA Final Report, DOT HS 808 003, October 1992

3. Howe, J. Gavin, and Sullivan, Lisa K., "Evaluation of Belt Positioning Booster Seats and Lap/Shoulder Belt Test Procedures", NHTSA Final Report, DOT HS 808 005, October 1992

APPENDIX

The appendix contains timed kinematic sequences for 3-year-old, 6-year-old and 5th percentile female dummies with and without belt fit devices.



BL CS

t=80 ms

SF SA

BL CS

t=120 ms

SF SA

Figure A-1. (Continued) Kinematic comparison of 3-year-old in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

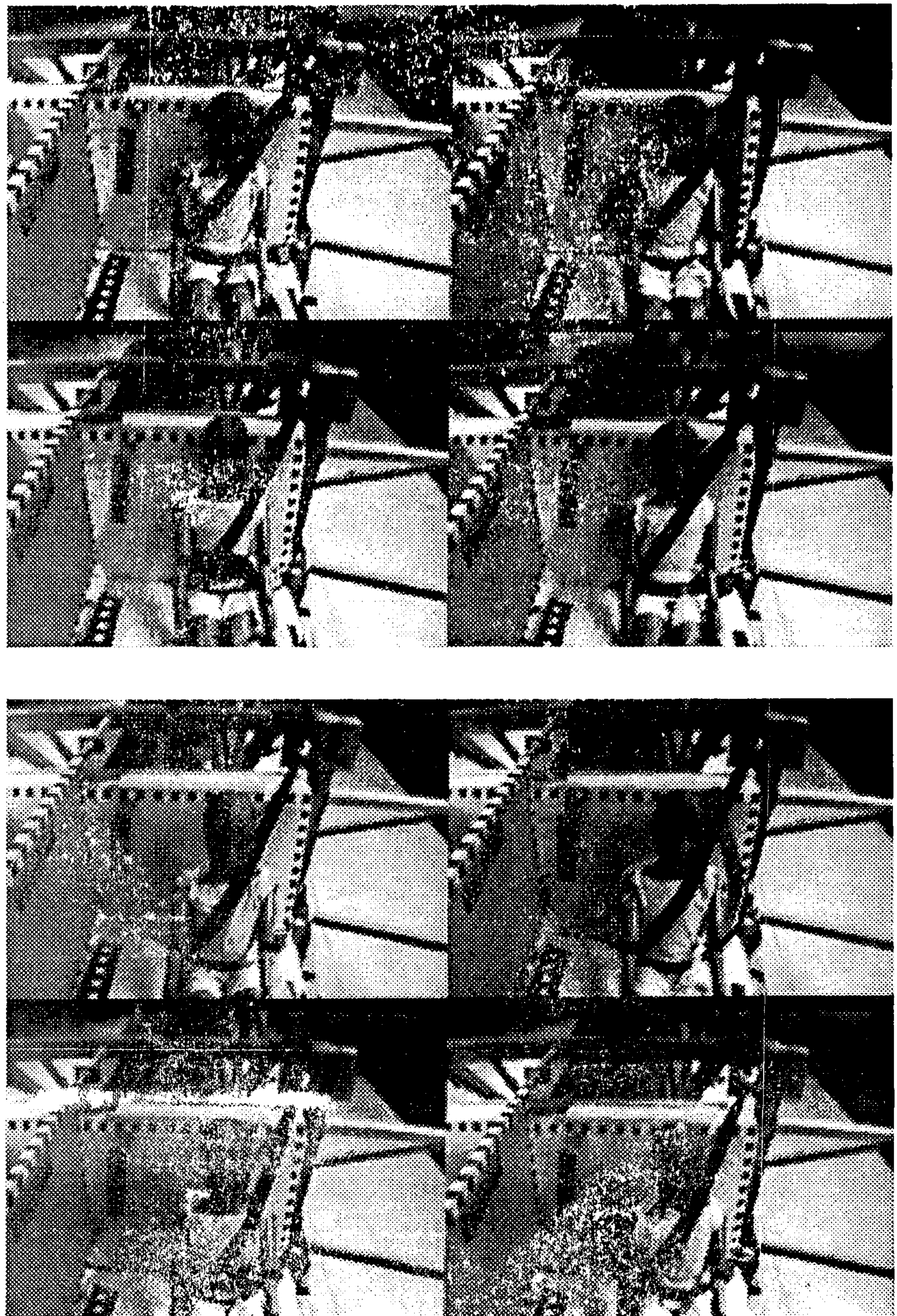


Figure A-2. Kinematic comparison of 6-year-old in standard frontal orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

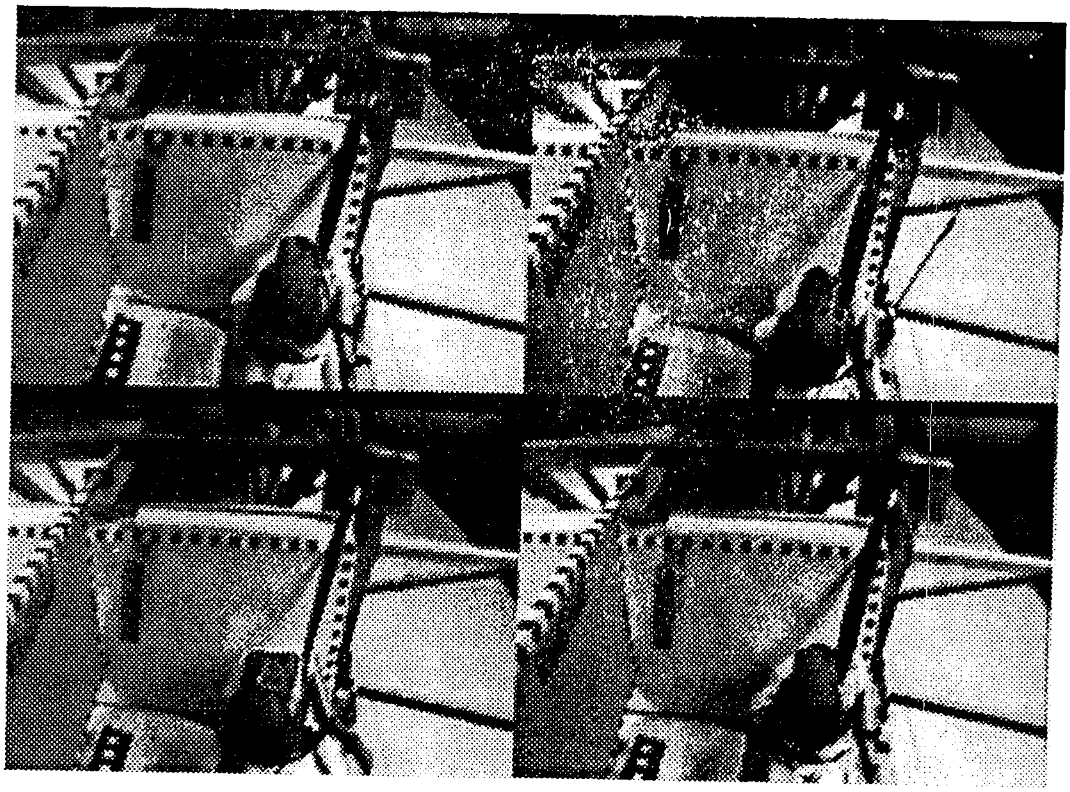
BL

CS

t=0 ms

SF

SA



BL

CS

t=40 ms

SF

SA

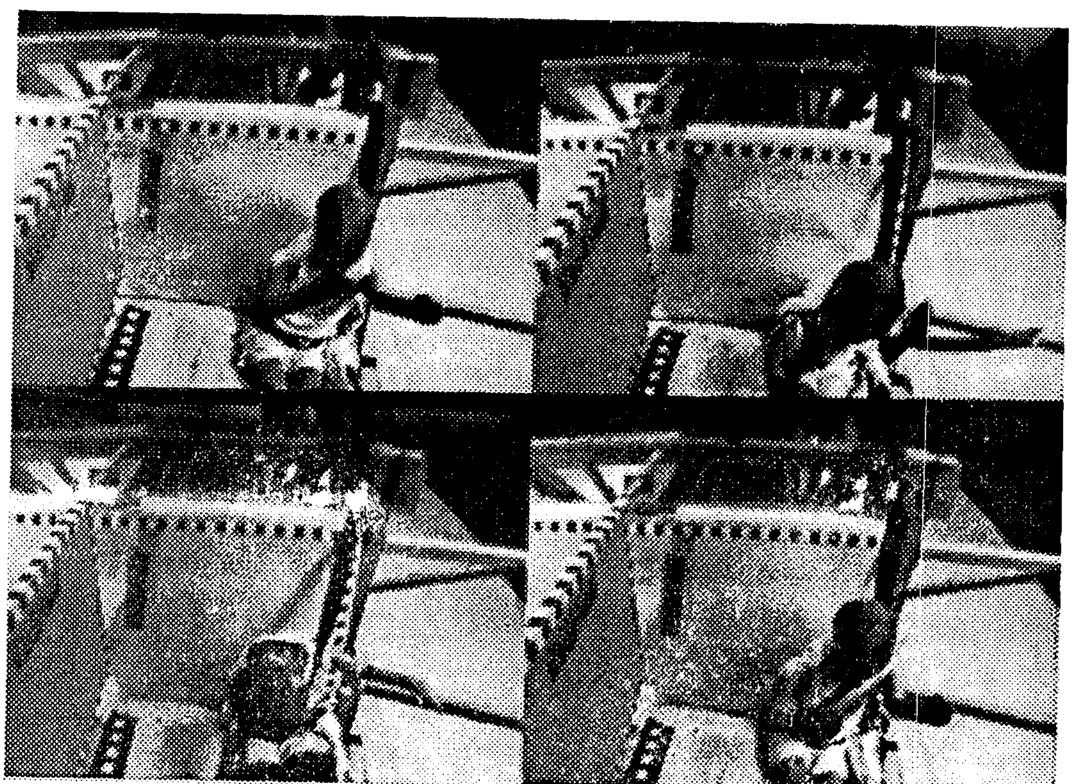
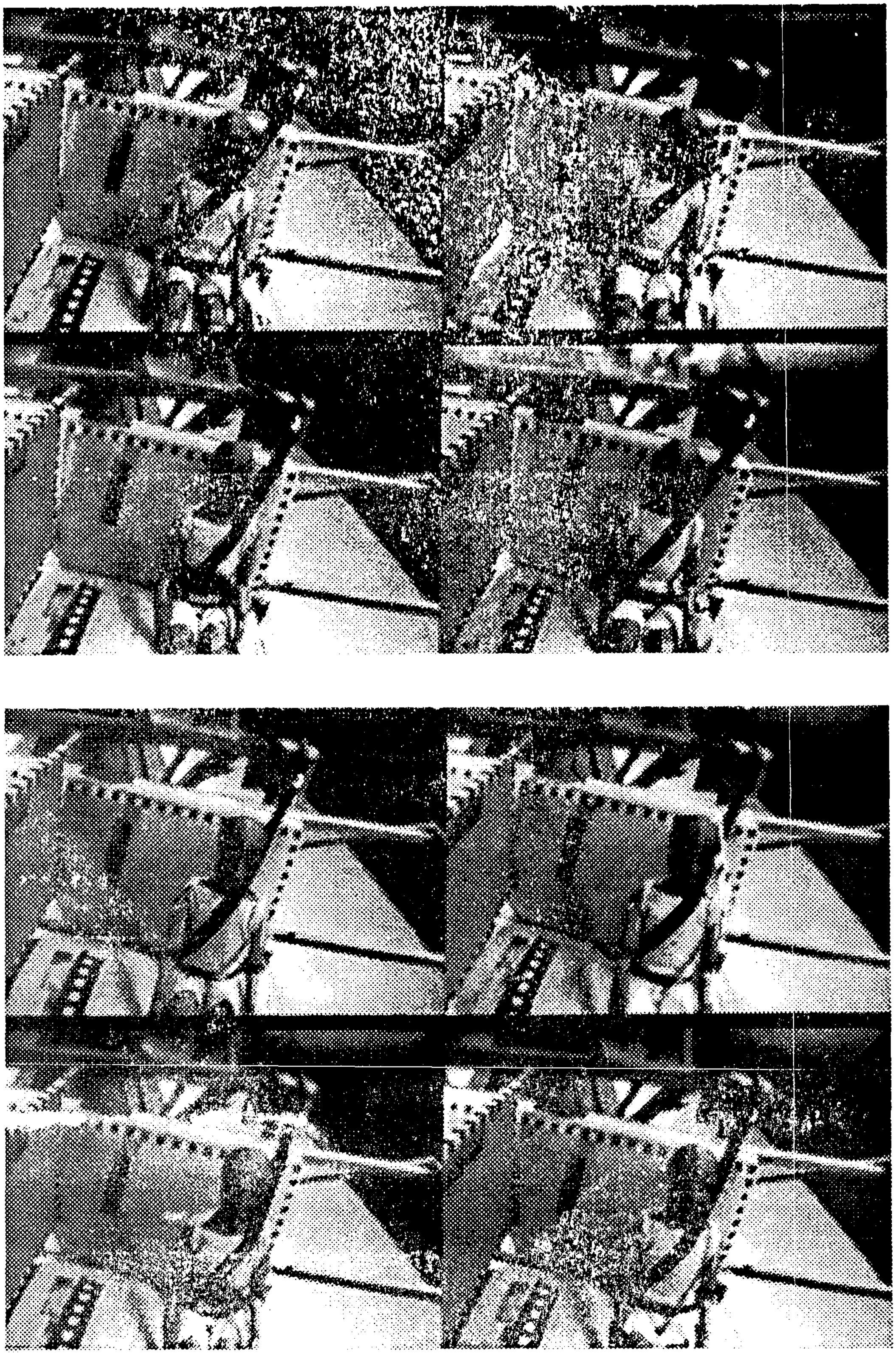


Figure A-2. (Continued) Kinematic comparison of 6-year-old in standard frontal orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)



BL CS

t=0 ms

SF SA

BL CS

t=40 ms

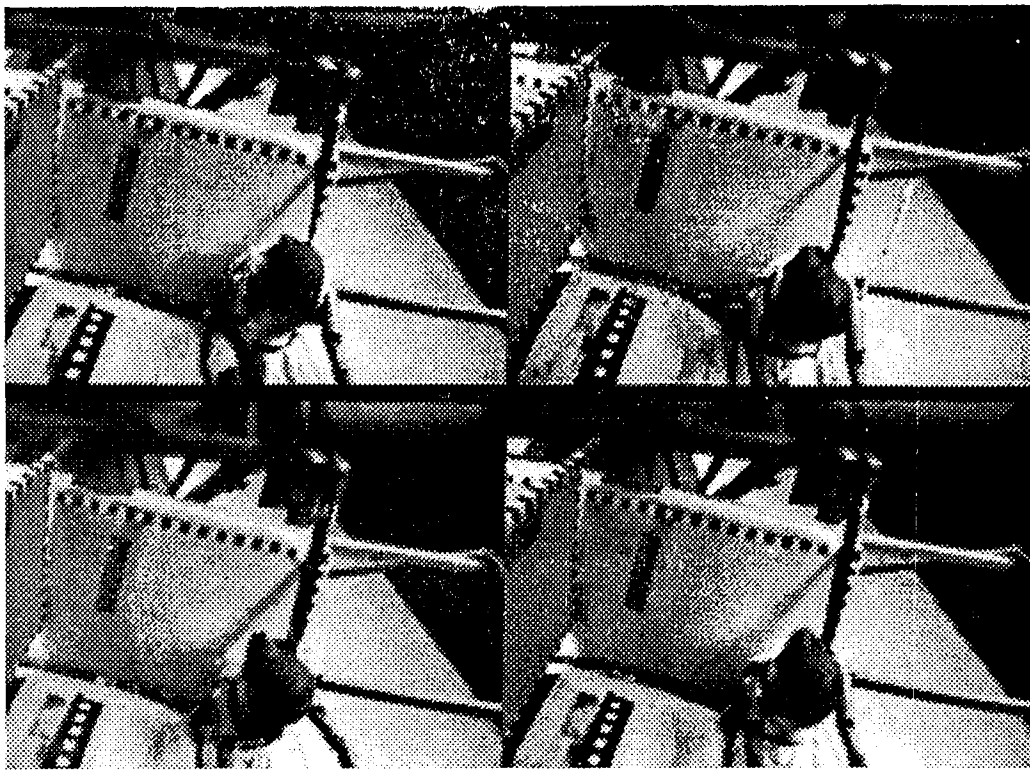
SF SA

Figure A-3. Kinematic comparison of 6-year-old in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL CS

t=80 ms

SF SA



BL CS

t=120 ms

SF SA

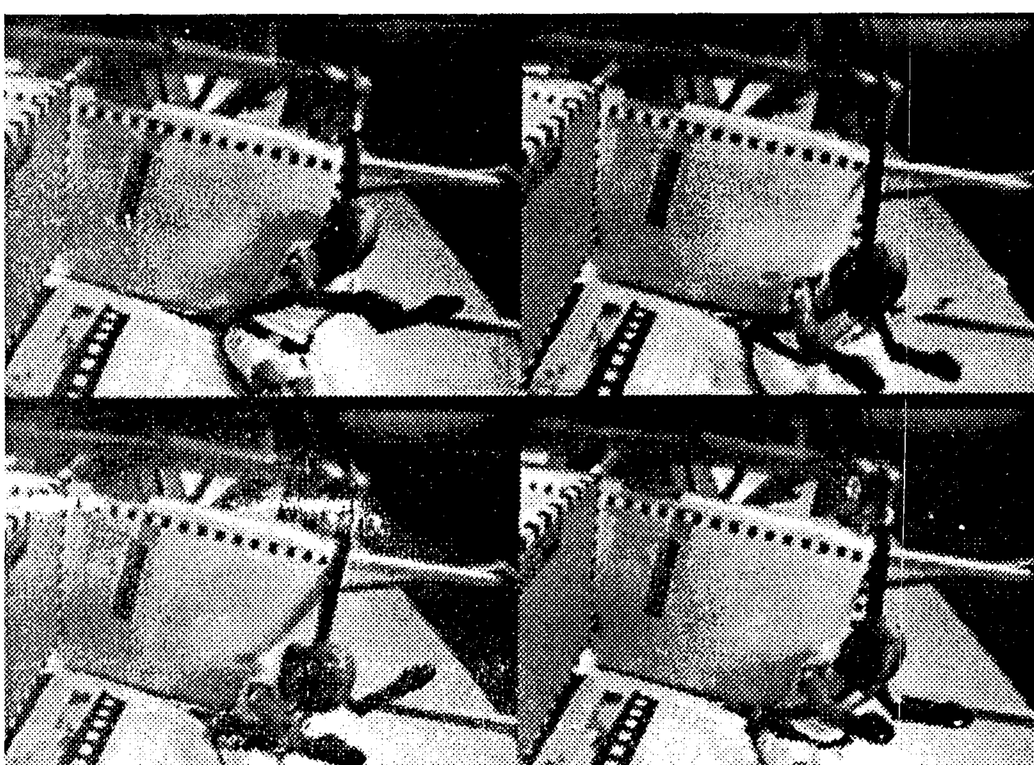
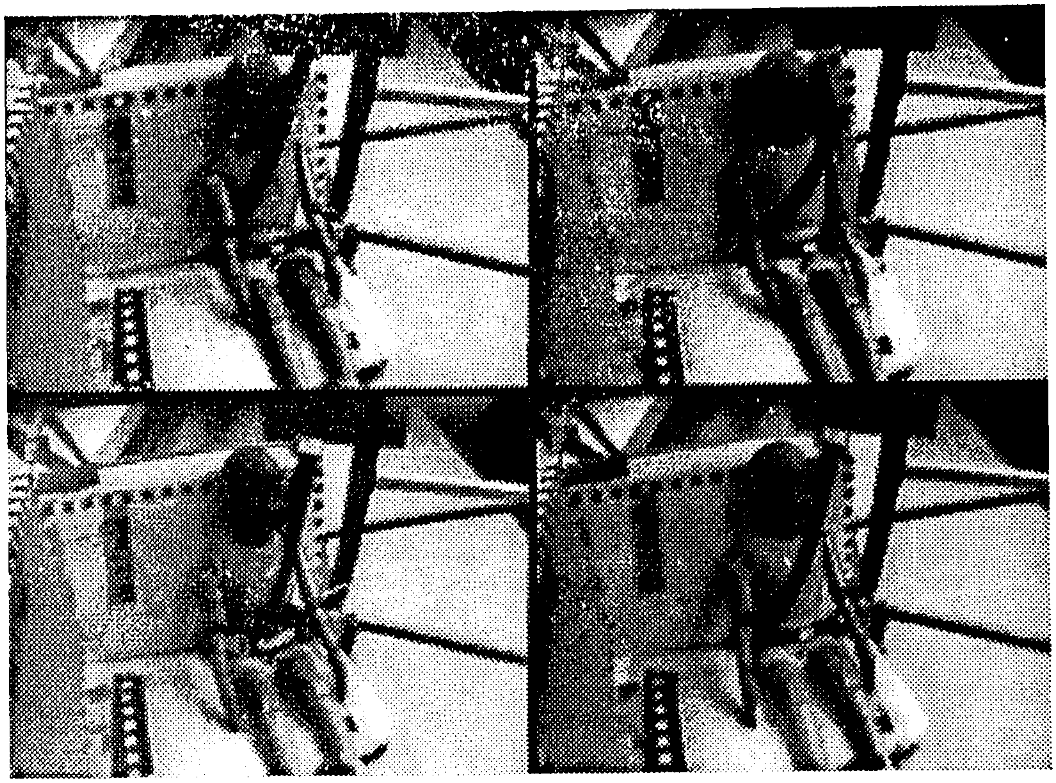


Figure A-3. (Continued) Kinematic comparison of 6-year-old in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL CS

t=0 ms

SF SA



BL CS

t=40 ms

SF SA

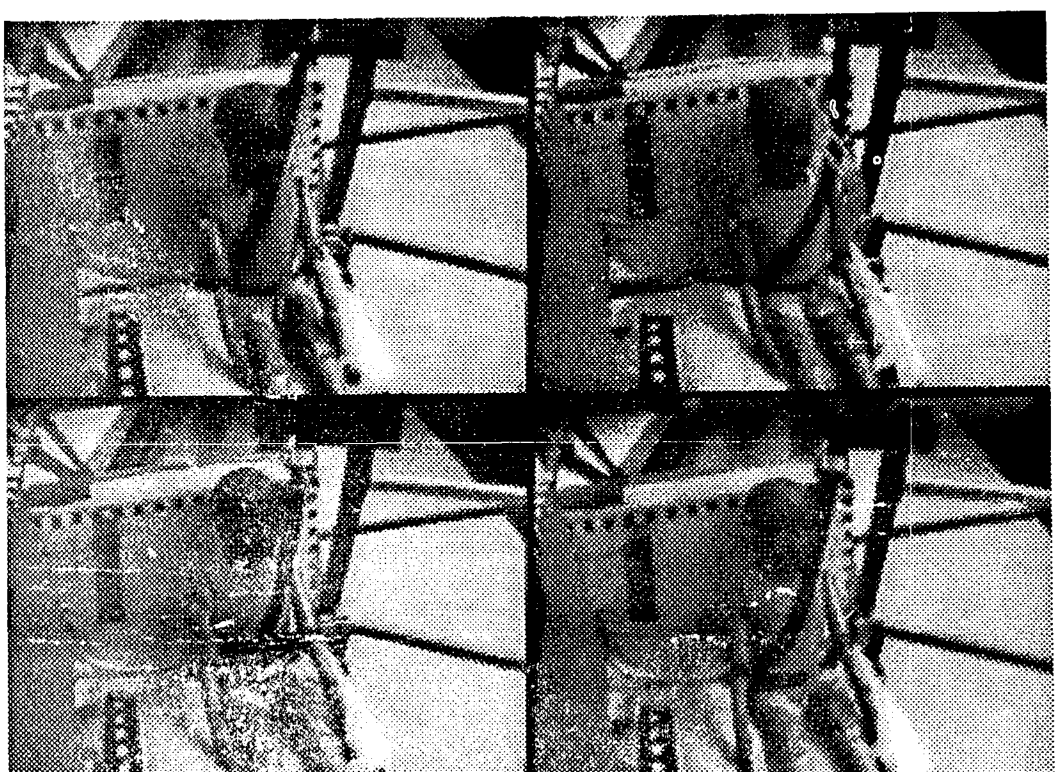
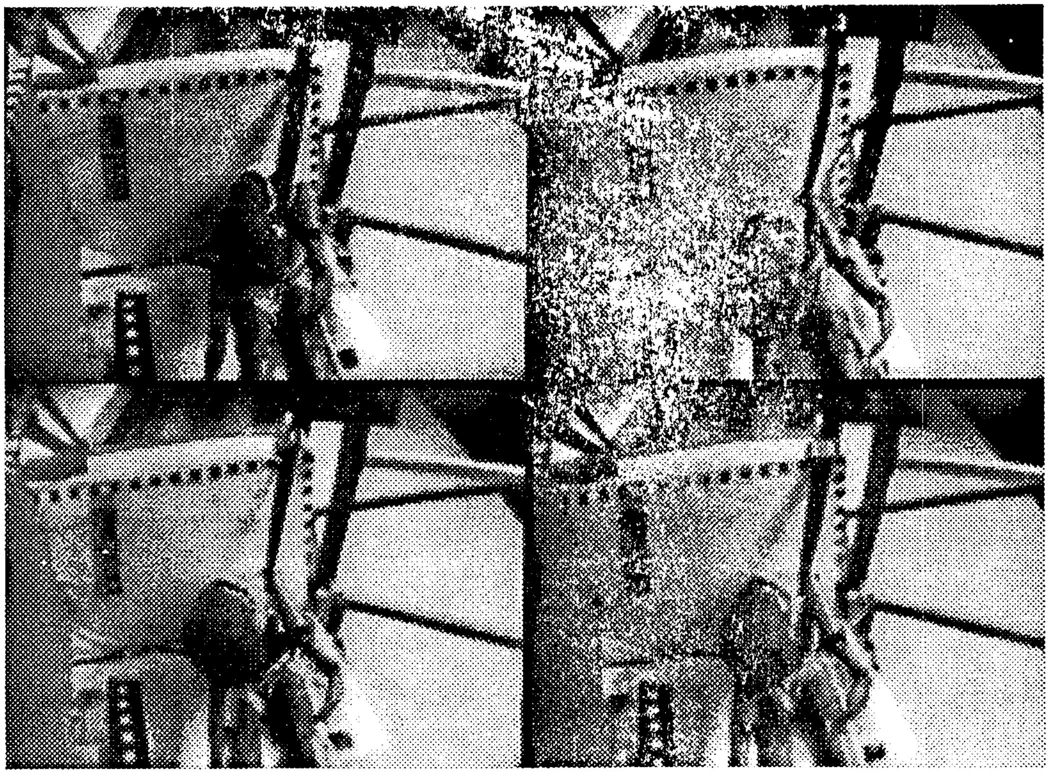


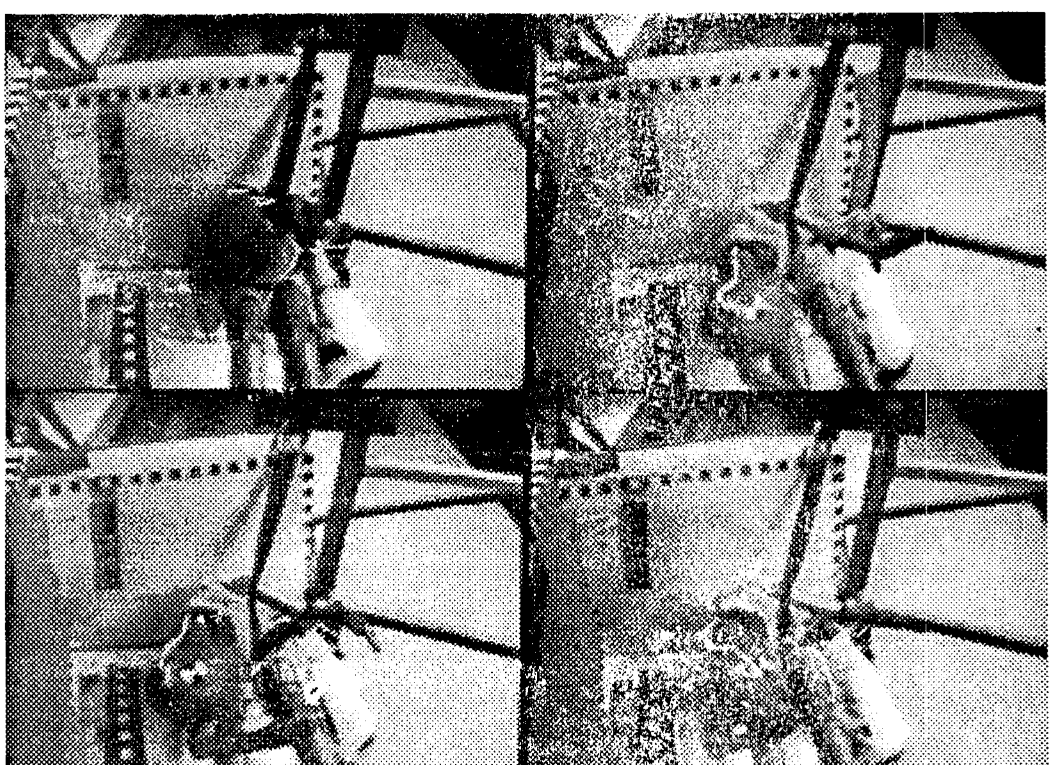
Figure A-4. Kinematic comparison of 6-year-old in counterclockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)



BL CS

t=80 ms

SF SA

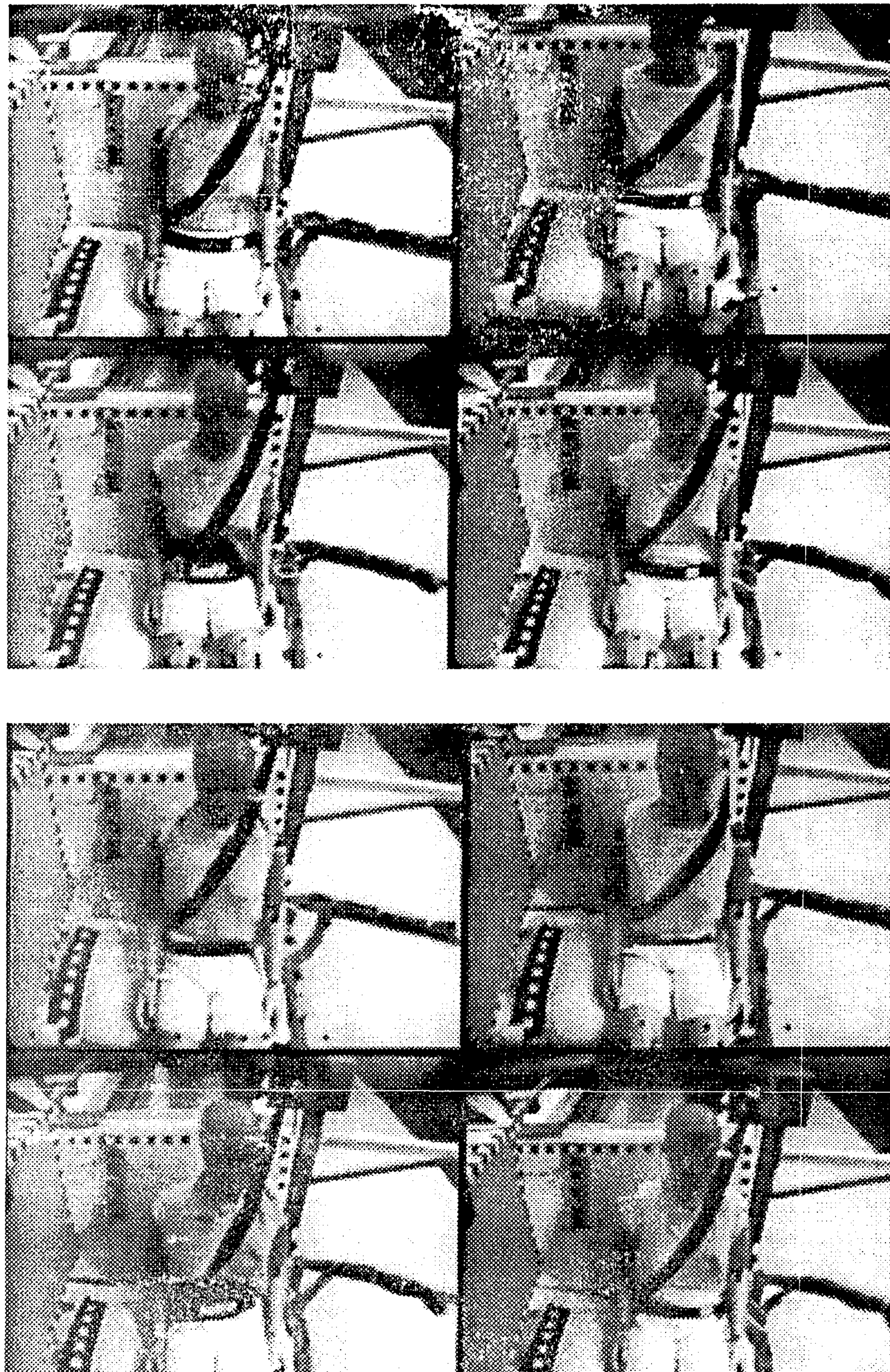


BL CS

t=120 ms

SF SA

Figure A-4. (Continued) Kinematic comparison of 6-year-old in counterclockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)



BL CS

t=0 ms

SF SA

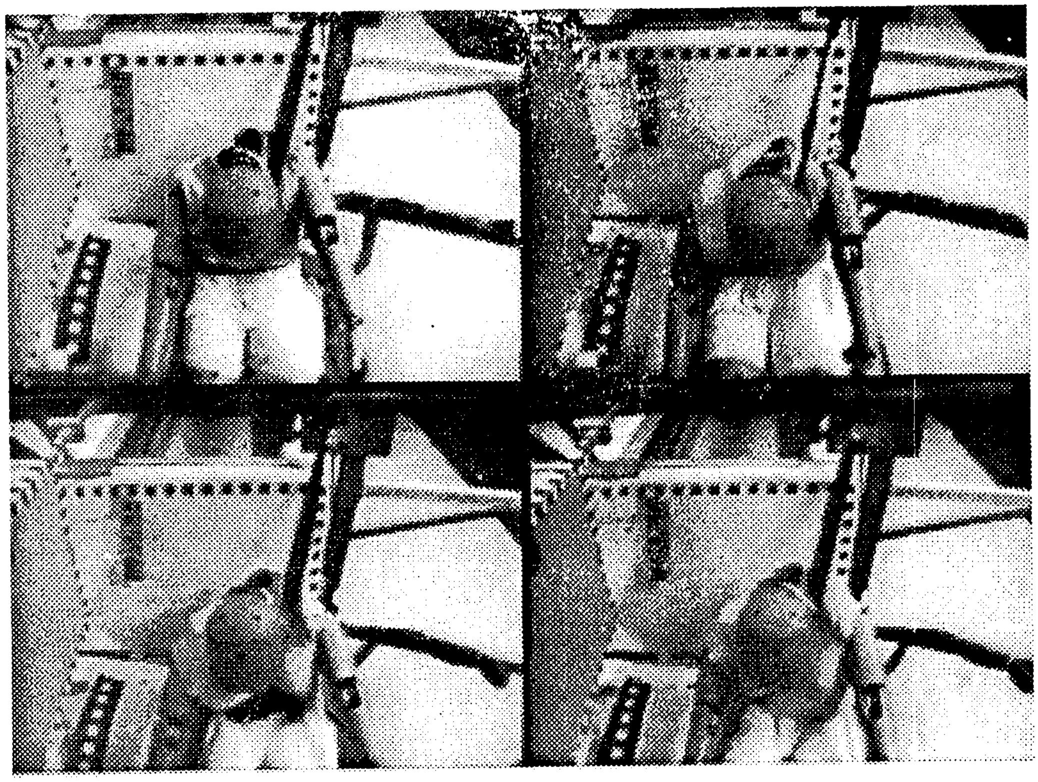
BL CS

t=40 ms

SF SA

Figure A-5. Kinematic comparison of 5th percentile female in standard frontal orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

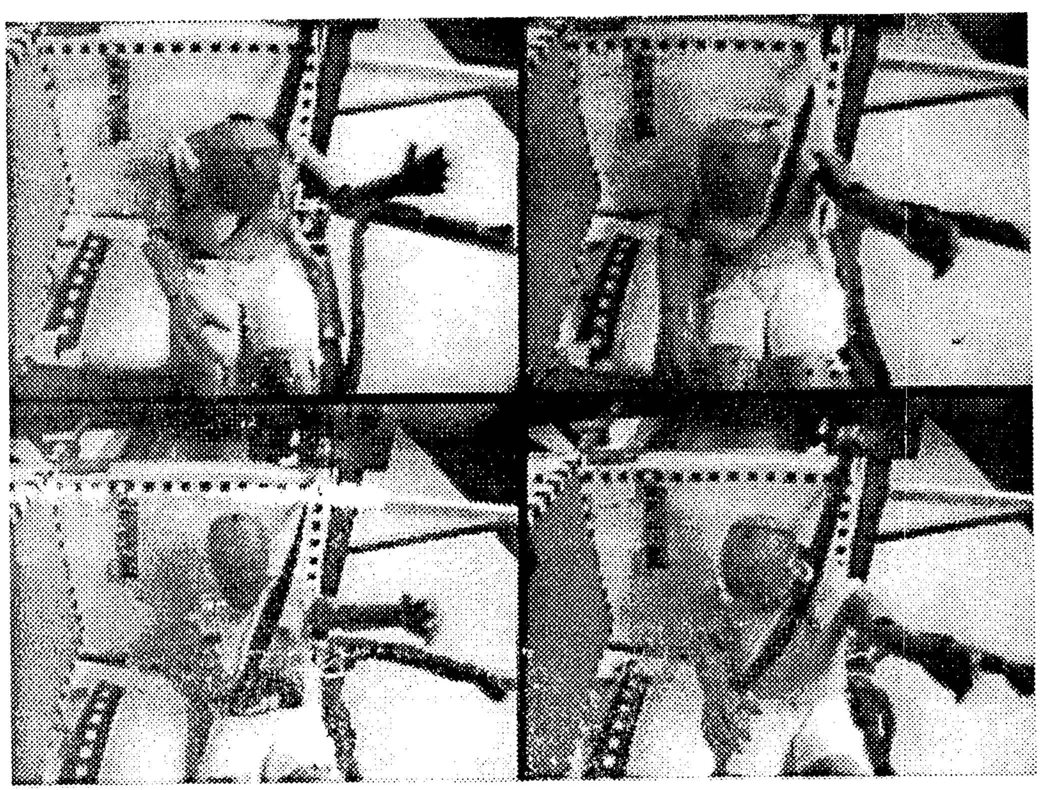
BL CS



SF SA

t=80 ms

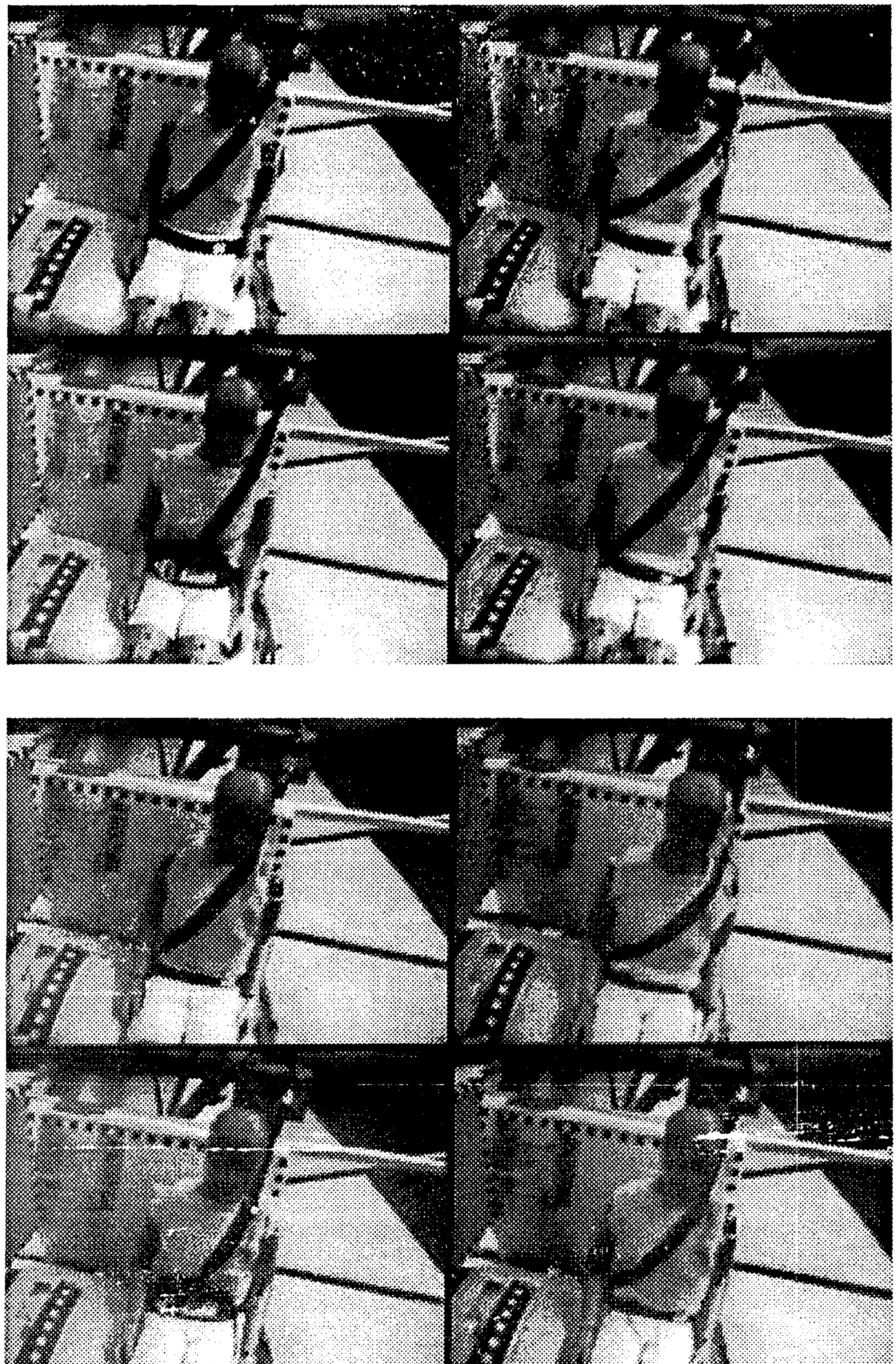
BL CS



SF SA

t=120 ms

Figure A-5. (Continued) Kinematic comparison of 5th percentile female in standard frontal orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)



BL CS

t=0 ms

SF SA

BL CS

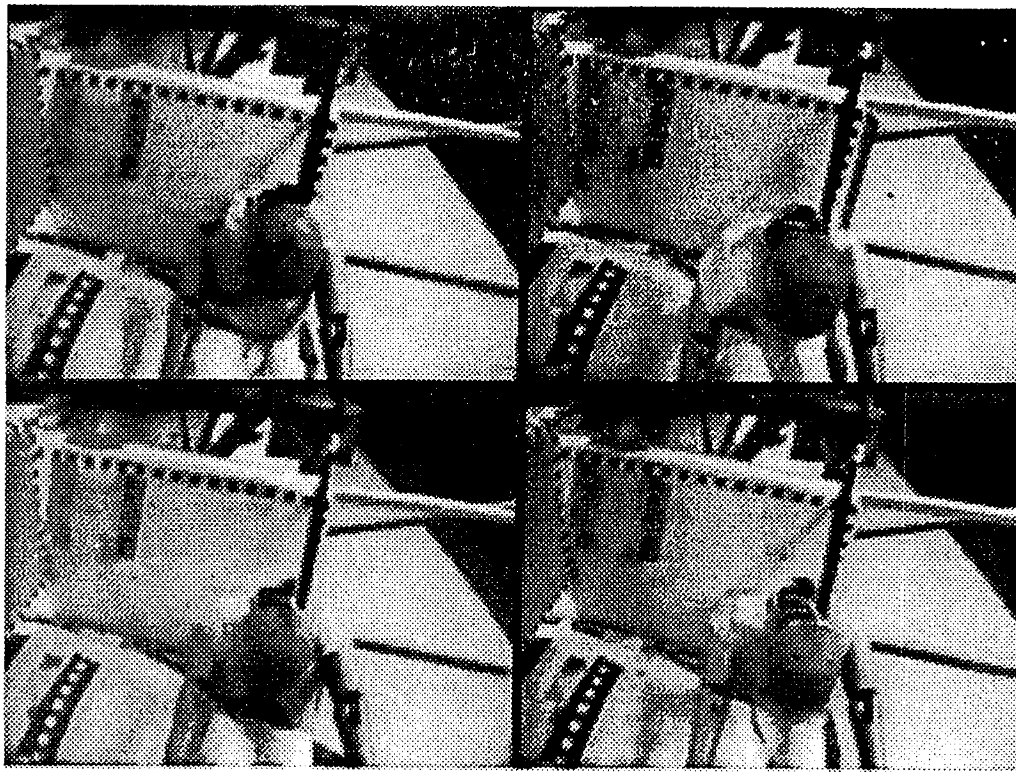
t=40 ms

SF SA

Figure A-6. Kinematic comparison of 5th percentile female in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL

CS



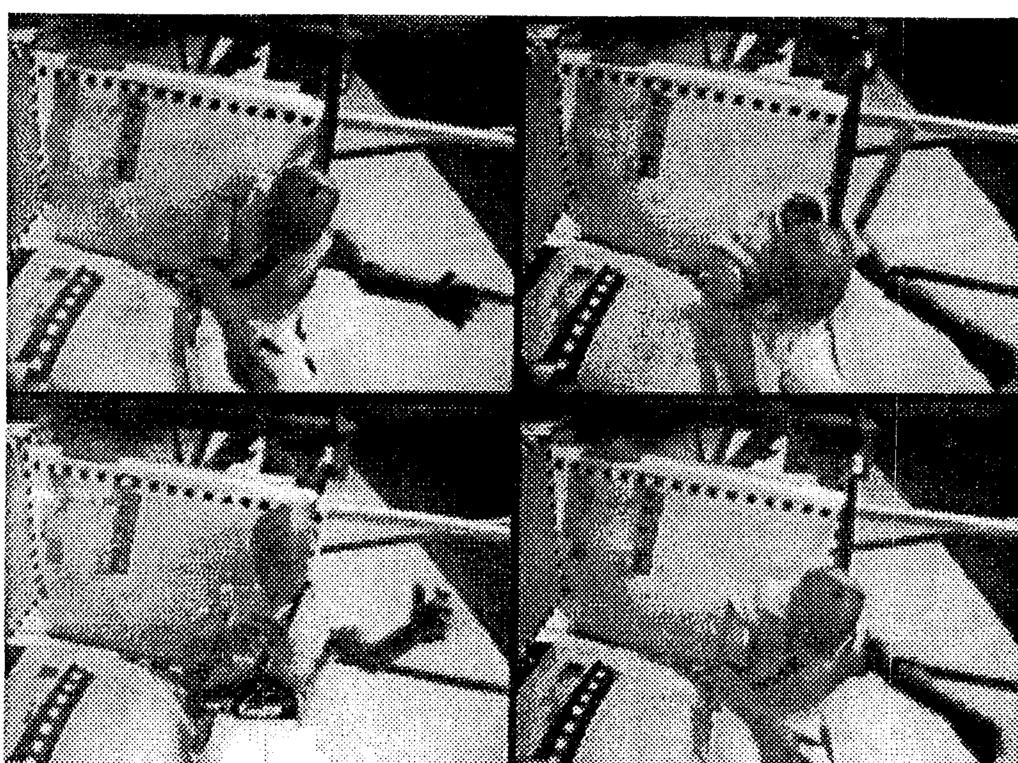
t=80 ms

SF

SA

BL

CS



t=120 ms

SF

SA

Figure A-6. (Continued) Kinematic comparison of 5th percentile female in clockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL CS

t=0 ms

SF SA

BL CS

t=40 ms

SF SA

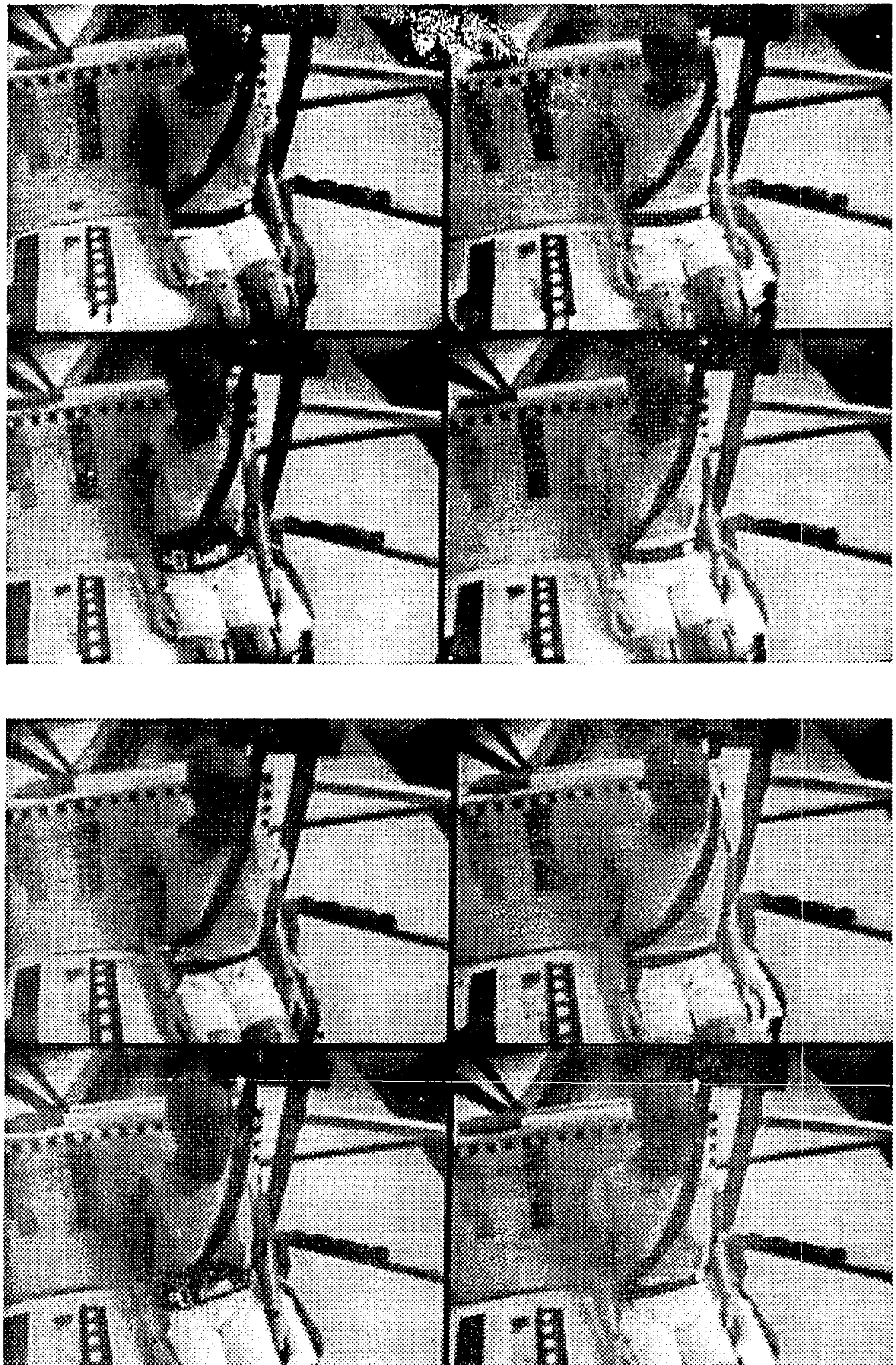
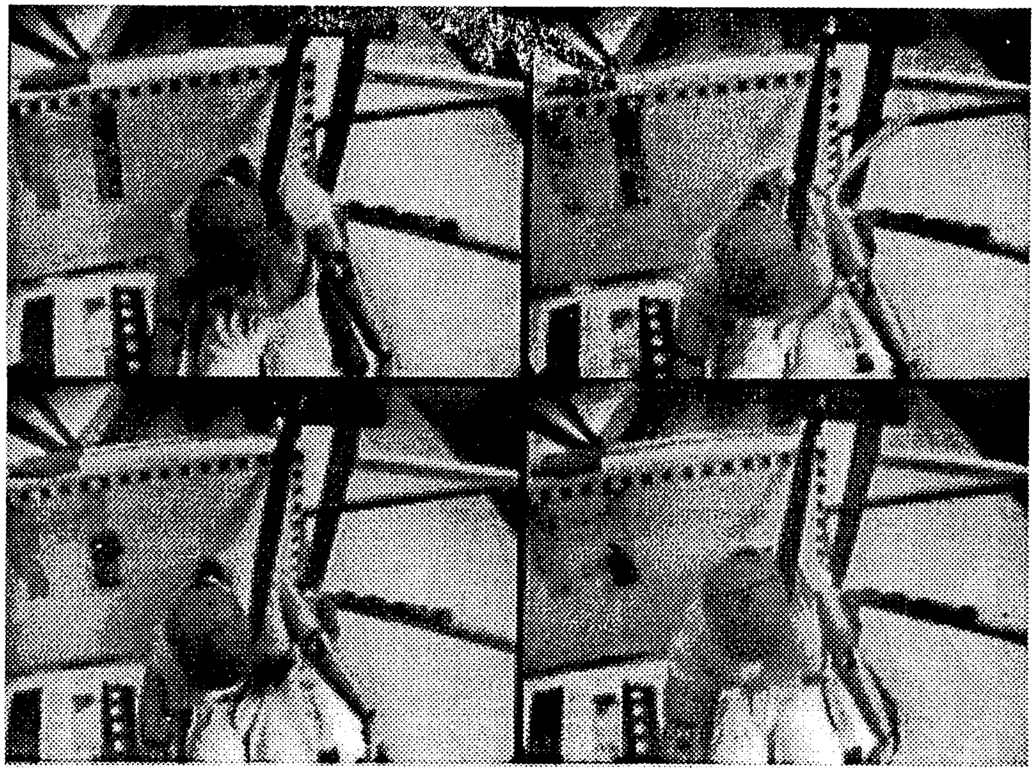


Figure A-7. Kinematic comparison of 5th percentile female in counterclockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

BL CS

t=80 ms

SF SA



BL CS

t=120 ms

SF SA

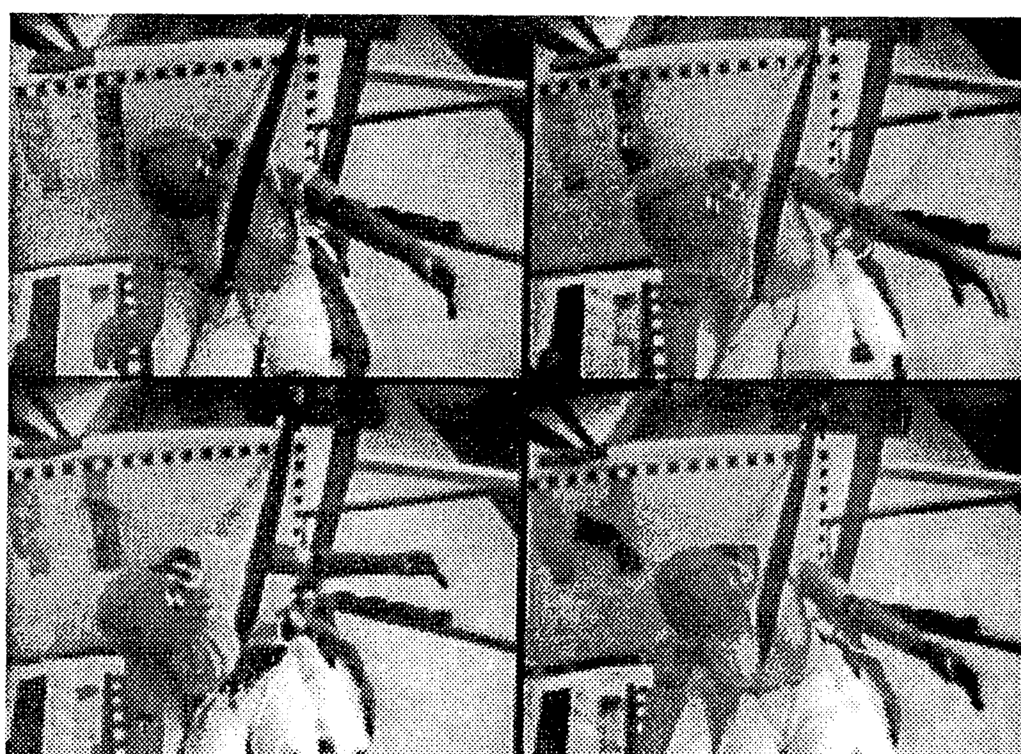


Figure A-7. (Continued) Kinematic comparison of 5th percentile female in counterclockwise oblique orientation - Baseline (BL), Child-Safer™ (CS), SafeFit™ (SF), and Seatbelt Adjuster™ (SA)

SIDE IMPACT TO CHILDREN IN CARS
EXPERIENCE FROM INTERNATIONAL ACCIDENT ANALYSIS AND SAFETY TESTS

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ABSTRACT

In the ISO TC22/SC12 working group 1 "Child Restraint Systems" the risk of side impacts to children in cars was declared an important working item and an ad-hoc group was established to analyse this field.

This paper summarises the first experience and activities of this ad-hoc group "Children in Cars - Side Impact Studies". The group started in 1993 an international inquiry at accident research units to cover characteristics and injury patterns of children in cars depending on seating position, age and kind of restraint systems used.
The resulting international database covers at present 83 side impacts of children in cars from 0 to 4 years and 56 accidents of children between 5 and 12 years where the children suffered an injury severity of MAIS 2+.

Based on the results from the accident data and the sampling of full scale and sled tests new test configurations have been developed.
The paper includes suggestions for further work with side impact test procedures, which could be a basis for future safety standards.

INTRODUCTION

Up to now the interest in improving child restraint systems (CRS) has focused on frontal crashes.
For child restraint systems, the requirements of the ECE Reg.44 having been established in 1981. At present, only Australia and New Zealand have standards for dynamic testing of CRS in lateral collisions (1).

But side collisions are a major problem. From different accident research units, it was reported that critical or fatal injuries of CRS-protected children in side collisions show about the same importance as in frontal collisions (2,3,4). Therefore, there is an interest in evaluating the risk of injuries to children in side impacts and in analysing side impact performance of child restraint systems. Proposals for an international standard of uniform test criteria should be developed. This task has been given by the ISO TC22/SC12 Working Group 1 "Child Restraint Systems" to the ad-hoc group in which members of 8 countries are represented. The members of this ad-hoc group are listed in annex 1.

INTERNATIONAL COOPERATION IN ACCIDENT ANALYSIS

Method of Sampling Accident Material

Side impacts to restrained children in cars, protected in a CRS form a major proportion of the children's risk in car although they are not frequent in relation to the number of traffic accidents. The accident databases even of big research units are not sufficient to analyse reliably the injury mechanisms and the resulting safety proposals.
Therefore, an international comparison of existing data was considered to be necessary.
For this general overview, 54 different accident research units were asked to check their data banks for accidents with unrestrained/restrained children in lateral car collisions, by using a questionnaire.

But for realistic proposals of an international safety standard a deeper understanding of injury mechanisms to

children is necessary. Therefore, a world-wide in-depth data collection of side impacts with injured children MAIS 2+ was carried out. Ten institutes, which are listed in annex 3, reported 139 cases, which were documented on the ISO accident standard evaluation form ISO/TC22/SC12/WG1 N305.

The general accident statistics and the collection of cases is based on different sampling procedures in five countries with different car populations. Therefore, this material cannot show an unbiased portrait of the whole lateral impact situation world-wide. But these data show the injury mechanisms and the biomechanical risks to children on the basis of much higher accident numbers than it has been possible up to now.

Results of General Statistics

The aim of this survey is to determine from a large sample whether the risk of side impacts to children in cars is overrepresented or not.

Even if the sample size of all car accidents reported by different institutions (Annex 2) is relatively high, the numbers are reduced considerably if this material concentrates on restrained children only, as seen in table 1.

Table 1.
General accident database

	impact location		
sample	**all**	**lateral**	**%**
total car crashes	69,267	15,629	22.6
children involved	8,004	1,475	18.4
restrained children	3,948	673	17
MAIS 3+ restrained children	296	102	34.5

The proportion of lateral accidents with MAIS 0-6 injuries varies between 17% and 23%. But focusing on MAIS 3+ (severe to fatal) injured restrained children (0-12 years) the proportion increased to 35%. This clearly demonstrates the high injury risk for severe and fatal injuries to restrained children in lateral collisions.

Results from in-Depth Accident Studies

Accident Numbers

The ad-hoc group decided that side impact protection standards, reflecting the real accident risk, should aim to reduce especially the occurrence of MAIS 3+ cases in particular.

But concentrating on these serious cases only would have raised the risk of a "negative selection" by excluding cases where child restraints were effective. The material has therefore been extended to MAIS 2+ injuries of restrained children in side impacts.

Again, it should be mentioned that this accident material from different countries is based on different sampling methods and consists both of accident evaluation on the spot and in-depth retrospective analysis. But even from this possibly biased material, the collision characteristics and the injury mechanisms could be analysed. Resulting countermeasures have to be incorporated in the test standards proposed for the future.

Table 2 shows the basis of the in-depth accident database with lateral car collisions. To concentrate on the situation with correct protection of children in CRS, cases with unrestrained children, misuse of CRS/ejection have been excluded as well as cases of catastrophic intrusion of the cars where protection by CRS seemed not to be practicable.

This procedure again reduced the material available to 69 selected cases (remaining as a data base for further evaluation). These cases represent the basis for the subsequent tables.

Table 2.
In-depth MAIS 2+ lateral accident material

		Selected cases	
Age	**total**	**CRS**	**belt**
0-4	83	27	6
5-12	56	2	34
0-12	139	29	40

Categorising of Impact Conditions

The first question is which types of collision predominate in the side impact material and which types of deformation occur.

Perpendicular impacts were the most frequent observed (table 3). In 83% of the selected cases the reconstructed collision angle was between 60 and 90 degrees.

Table 3.
Collision angle of the selected MAIS 2+

	30°	60°	90°	120°
No.	8	17	36	3
%.	12 %	27 %	56 %	5 %

A major proportion of the crashes was formed by rectangular loading, cases with 30 degree angle of impact showing a lower percentage. Thus, the 90 degree crash configuration represents the highest risk exposure.

The reconstruction of the contact speed of the crashes or the assessment of the crash intensity caused difficulties, as delta v or EES calculations were not available for the whole material. Therefore, the speed of the striking vehicle had to be chosen as a reference value (table 4). 70% of the selected cases showed a velocity of the striking vehicle up to 50 kph.

Table 4.
Impact velocity of the striking vehicle

kph	-30	-50	-80	>80
No.	14	12	9	2
%	38 %	32 %	24 %	6 %

More detailed information is available in the accident material, but cannot be presented in a general form due to the limited number of cases up to now.

The average weight of the opponent car was 1,060 kg. With the exclusion of the US cases (many pick-up trucks) the average weight drops to 990 kg.

Of particular importance for the assessment of the impact loadings to the CRS is the deformation profile of the struck car side.

The deformation patterns were categorised into three main patterns. These are depicted in table (5).

Table 5.
Typical examples of side impact deformations

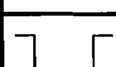
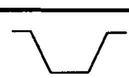
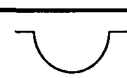
Type	square shape	v - shape	pole - shape
			

Table 6 indicates that the most frequent deformation contour of the impacted car was square shaped (49%), but v-shaped deformation patterns were observed in 39% of accidents.

Table 6.
Type of deformation

Type	square shape	v-shape	pole shape	other
No.	25	20	5	1
%	49 %	39 %	10 %	2 %

A pole shape was registered in only 10% of the accidents. A realistic side impact test procedure should simulate the effect and behaviour of the incoming door during the side intrusion process, too.

Exposure of the Children

There were 20 child fatalities among the "69 selected cases". Table 7 shows the distribution of the injury severity by MAIS values (5) and Table 8 the distribution of the children among the relevant age groups.

Table 7.
MAIS values

MAIS	2	3	4	5	6
No.	22	15	6	18	8

Table 8.
Relevant age groups

Age	0	1	2	3	4	5	6
No.	4	10	4	10	4	7	3

Age	7	8	9	10	11	total	N/A
No.	6	3	6	5	6	68	1

Table 9 indicates the distribution of the children sitting on the struck/non-struck side. This shows that the major risk as expected occurs on the struck side (67%), but also that the protection criteria of children on non-struck side position should be considered.

Table 9.
Impact location

	Struck side	Centre	Non-Struck side
No.	45	6	16
%	67 %	9 %	24 %

The sample comprised mainly forward facing CRS (ECE group I) and 3-point belted children (with or without booster cushion). Rearward facing configurations of CRS could be observed in 6 cases.

The frequency of injury at AIS 2+ and AIS 4+ are given by body area in table 10. For injury severity AIS 2+ head injuries predominate by far, followed by injuries to thorax, extremities and cervical spine. Critical injuries (AIS 4+) for the head again were the most frequent with 40% of the children experiencing head injury. The other important body areas were thorax (10% with AIS 4+ injuries) and cervical spine (11%).

Table 10.
Injury distribution

body region	No.	AIS 2+	No.	AIS 4+
head	50	72 %	28	40 %
thorax	14	20 %	7	10 %
abdomen	11	9 %		
pelvis	3	9 %		
Cspine	9	13 %	8	11 %
Tspine	1	2 %		
Lspine	1	2 %		
Upper X	12	18 %		
Lower X	12	17 %		

(n = 69 = 100%)

A detailed analysis of this case material with injury combinations and medical/biomechanical findings should be published at the 40th STAPP Car Crash Conference.

Discussion

The accident material showed that the protection of CRS in side impacts has to cover a crash severity equivalent to an impact speed of up to 50 kph. The intrusion of the side door area has to simulate square or v-shaped deformation contours and impact angles between 60 and 90 degrees. Therefore, an angled impactor could reflect the reality in the test methods proposed.

Side impact testing should concentrate on child restraint systems ECE group 0 and group I as these exclusively systems offer the potential of providing side protection by the CRS, whereas the other CRS groups are influenced by the side stiffness of the car and its door interior characteristics.

The accident experience shows that the type of restraining the CRS in the car and the movement during the side impact loadings strongly involve the loadings to the child. The stopping distance of the intruding door is a factor affecting the loadings to the CRS itself. From real accidents, the door intrusion lies by about 400 mm and this should be reflected in a proposed test standard.

The injury mechanism of the children on non-struck side positions has to be analysed further. Following that it will be decided later if the non-struck side position should also be included in the testing procedure. For the time being the activities should focus on the struck side.

Injuries to head, cervical spine and thorax are the most outstanding sources of serious injuries and therefore these measurements have to be integrated in the proposal of a test impact standard. But also the observation of the child's movement by video analysis seems to be an important source of information for risk assessment.

INTERNATIONAL EXPERIENCE IN DYNAMIC CRASH TESTING

Possibilities and Limits of Testing

Following the definition of real accident crash conditions, the group decided to collect any information which is generally available for side impacts with CRS. 9 institutions have responded to a questionnaire and have outlined the advantages and disadvantages of different test procedures.

The results are summarised in table 11. The conclusions were that options other than a simple single-sled configuration should not be pursued for reasons of producing practicable test procedures.

Table 11.
Results from CRASH TEST questionnaire

	Advantages	**Disadvantages**
FULL SCALE CAR IMPACT	Very realistic effect of vehicle construction	Very expensive time consuming poor repeatability defined average vehicle
BODY SHELL DYNAMIC INTRUSION	CRS-seat interaction accurate effect of vehicle construction	Expensive Complex Limited tests due to need to replace body shell
BODY SHELL STATIC/NO INTRUSION	CRS-seat interaction accurate May reflect injury circumstances for centre or non-struck occupant	Still expensive Static or no intrusion effect unknown may give misleading results Does not reproduce the real injury mechanisms for most serious injury/fatal side accidents for struck side occupants
TEST BENCH ON SLED WITH INTRUSION	More economic and simple Better reproduction of injury mechanism Generally applicable results Easier photographic coverage	Requires test series to determine kinematics and parameters Intrusion velocity profile artificial - difficult to generate „typical" realistic velocity profile simultaneously with sled deformation pulse
TEST BENCH ON SLED NO INTRUSION	Lowest cost Easiest procedure	Does not simulate critical parameters in side-impact Main injury mechanisms not reproduced at all Hard to interpret results and to verify CRS performance

This inquiry confirmed that in many different institutes of several countries side impacts have been tested but the conditions differ substantially. This underlines the necessity of an international standard.

On the other hand, from the different test conditions, the advantages and problems of the methods used could be learned. The group therefore collected information available for full-scale and sled tests.

Compared to frontal crashes, experimental investigations of side impact crashes are more complex - particularly regarding the interaction between the car, the CRS and its occupant.

The child comes into contact with the intruding structure of the inner door area (striking object) either directly or through the CRS. Therefore, the relative behaviour of the vehicle and of the child restraint, the (head) kinematics of the child and its interaction with the car's inner structure are of major influence. Also the injury mechanism in different seating configurations (forward and rearward facing, different attachments like ISOFIX, CANFIX, influence of top-tether etc.) should be reproduced in a simple, practicable and easily reproducible test system.

An additional problem is that no child dummy of the appropriate size and that has been developed for side impacts is available at present. For current dummies the shoulder might be too stiff and the pelvis too fragile. The experience with adult side impact dummies SID and EURO-SID development and scaling techniques (6,7,8) should be transferred to child dummies.

For the present work of the ad-hoc group it was decided that at first a realistic and practicable test method should be developed and then, as a second step, the selection of which child dummy to be used the biofidelity and biomechanical tolerances have to be addressed in the interim. The tests have to be made with the most suitable child-dummies available.

Collection of Existing Full-Scale Tests

As the closest approximation to real life accidents in which protection is required, full-scale tests should give the basic physical information for the development of test parameters.

At present information on full-scale tests from members of the ad-hoc group have been used as a basis for the sled test procedure. In future, information from full scale test of other institutions, where available, should be integrated. The reported full-scale tests and their test characteristics are shown in table 12.

Six full-scale side-impact tests were performed at 50 kph by TRL using the EEVC side-impact test procedure. A car-to-car crash test was performed by TÜV Bayern-Sachsen.

Table 12.
Full-scale tests and their test characteristics

Test Facility	Test	Angle [°]	Velocity [kph]	CRS Type ECE Group	Major findings
Folksam	Full Scale	90	48-56	Group 0,I rearward facing	- door velocity 40 and 45 kph - intrusion 40-50 cm - lateral a_{max} = 110 g - chest a_{max} = 50 g - head contacts door
TÜV	Full Scale car to car crash	90	50	Group I forward facing	- max. intrusion 55cm - HIC 380 - thorax a_{max} = 50g
TRL	Full Scale Deformable EEVC Barrier Tests	90	50	Group I forward facing ISOFIX	ISOFIX head acceleration was much less than with conventional CRS Door intrusion angled

Car-to-Car Tests, FOLKSAM Research, Stockholm

The Swedish full-scale tests correspond to the observations in the FOLKSAM accident research (9,10). Children in rearward facing child restraints up to the age of 3 years were involved. The mechanism observed in real accidents were fractures of the head when rotating out of the child restraint and hitting the intruding door or in some cases even hitting the hood of the striking car.

All these accidents had a relatively high severity with an estimated change of velocity of 30 to 40 kph and with an estimated closing speed of 50 to 70 kph. The angle of the striking and struck car was mostly around 90 degrees.

For the set-up of the tests it is important that the intrusion recorded in real accidents was between 55 and 65 cm and the CRS was pushed into the car by the intruding door by 35 to 45 cm. Thus, the most important parameters were considered to be the velocity of the intruding door and the intrusion characteristics.

The test configuration of the full-scale tests were:

- impact angle 90 degrees
- striking car hits B-pillar of struck car
- impact velocity of striking car between 48 and 56 kph
- rearward facing CRS positioned in the front passenger seat and in the struck-side rear seat.
- the CRS was instrumented with three accelerometers and a dummy TNO P3 was instrumented in the head and chest

An example of a full-scale test at FOLKSAM is shown in figure 1.

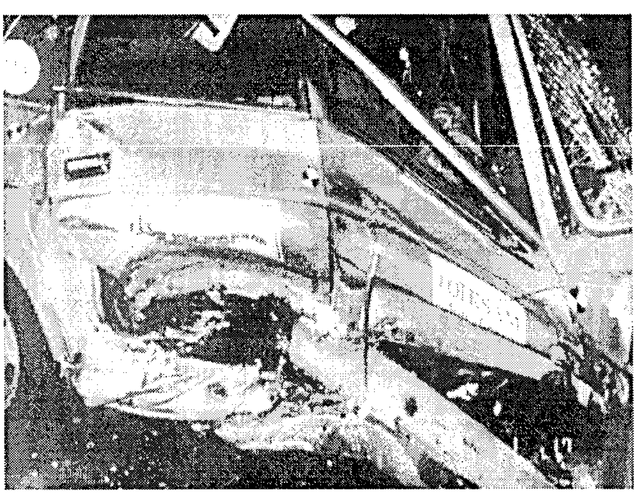


Figure 1. Typical shape of the side of the struck vehicle at Folksam.

Starting from the test closing speed of the striking vehicle (48-56 kph), the door velocity was between 40 and 45 kph, when it hit the CRS. The intrusion of the lower part of the CRS was between 40 and 50 cm.

In the front seat from the intruding door contact with the CRS, a high lateral acceleration of maximum 110 g to the CRS resulted. The padding of the interior of the CRS used in the tests reduced the maximum acceleration to 50 g in the dummy's chest. The head rotated out of the CRS and hit the sill of the intruding side door. This caused head acceleration of 190 g.

Car-to-Car Test, TÜV Bayern-Sachsen, Munich

One car-to-car crash with 50 kph at an angle of 90 degrees was performed (figure 2).

The maximum intrusion of the Alfa was 55 cm, the 18 month FTS child-dummy was sitting in a forward facing CRS on the rear seat struck side.

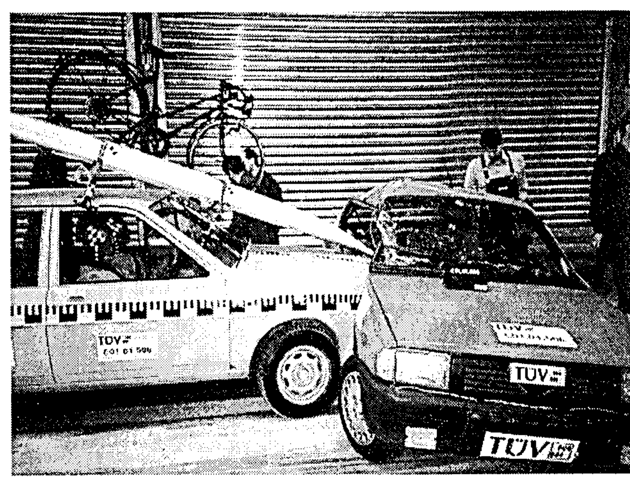


Figure 2. Car-to-car crash at TÜV Bayern-Sachsen.

The calculated HIC was 380 and the maximum thorax acceleration was about 50 g. There has been no contact to the intruding door.

Car to Deformable EEVC Barrier Test, Transport Research Laboratory (TRL), Crowthorne

The test set-up of TRL is shown in figure 3.

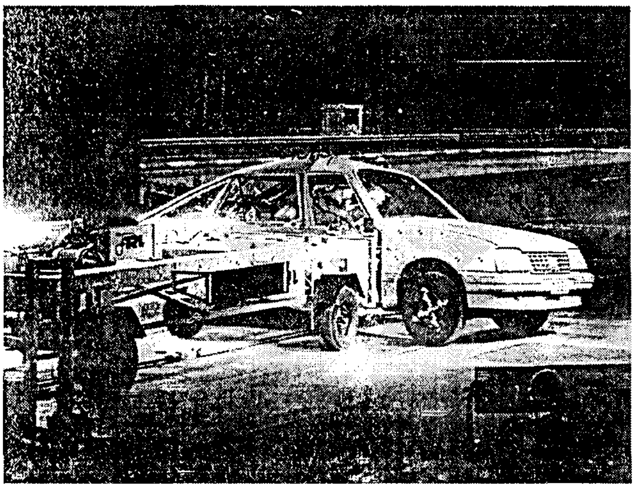


Figure 3. Full scale side impact test with deformable barrier at TRL.

Beside testing CRS in side-impacts, this series was aimed at comparing the performance of rigidly attached four-point ISOFIX-CRS with that of conventional CRS using safety belts for fixation (11).

Figure 4 shows the lateral acceleration of the CRS (struck-side), comparing conventional and ISOFIX-CRS.

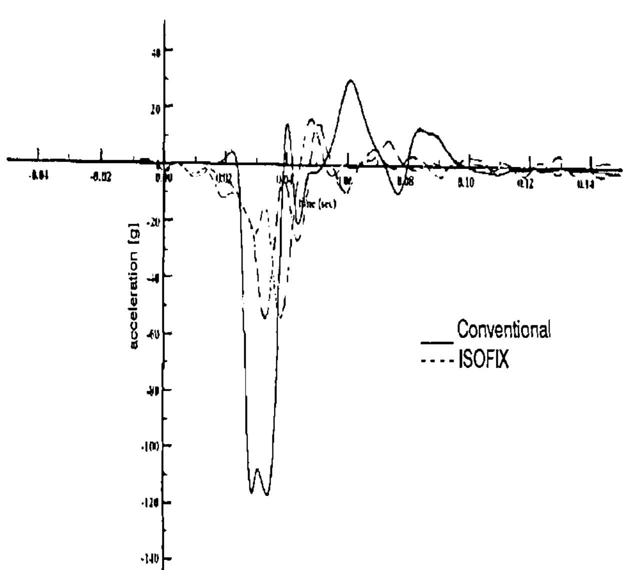


Figure 4. Lateral acceleration of the CRS for the struck side tests at TRL.

The peak acceleration of the ISOFIX seat was less than that for the conventional seats. This effect was repeated on the non-struck seating position.

Figure 5 shows the resultant head acceleration for the dummy in conventional and ISOFIX-CRS for the struck- and non-struck seating positions respectively.

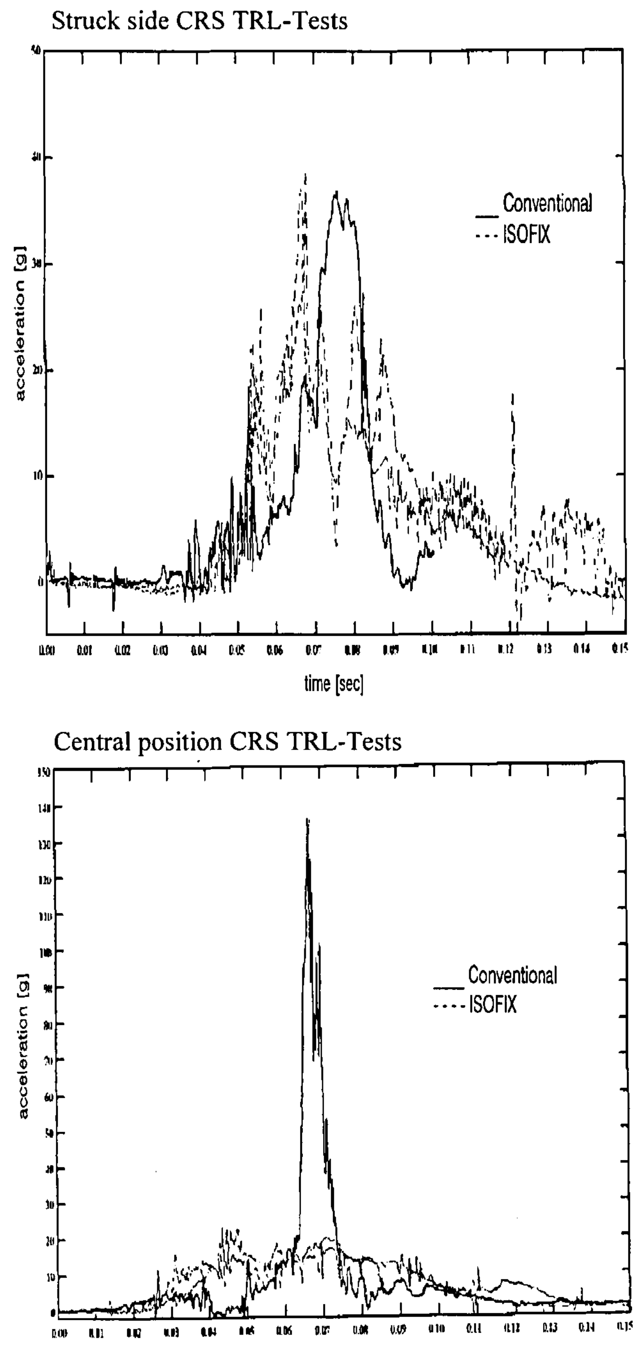


Figure 5. Resultant head acceleration Tests at TRL.

For the struck-side tests, the peak head accelerations were of the same order, but for the non-struck seating positions the head accelerations for the ISOFIX-seats were much less than for the conventional CRS.

Findings from Full-Scale Tests

Car-to-car testing with a velocity of 50 kph of the striking vehicle is indispensable. It is noted that the direct intrusion to the CRS amounts between 40 to 50 cm.

Every contact of the child dummy to the intruding door leads to very high, mostly non tolerable accelerations. The distance from CRS to inner door panel influences the lateral intrusion of the CRS.

The mounting of the child seats influences the peak accelerations of the CRS. Rigid attachments such as ISOFIX show positive effects in non-struck side position for the acceleration of the dummy contact against CRS or to the inner door structure. The padding of the CRS plays a major role in reducing the thorax accelerations. The tests have confirmed that rigid ISOFIX or CANFIX attachments are beneficial.

There are also offers of test institutes to incorporate CRS in their side impact tests. This procedure should come into common use, as with relatively low additional costs the knowledge of side-impact loadings to CRS could be substantially increased.

Component Tests with Single-Sled Procedure

A number of different sled-based tests using different principles have been reviewed by the ad-hoc group. These test programmes were started independently of this ISO activity but they have been extended on a voluntary basis to give more information for this research work. This is especially true for the extensive test work of TNO, but also for RTA (12).

Table 14 summarises the sled-tests which have been available for the work of the ad-hoc group up to now.

The test specifications are given in this figure and references to recent publications are indicated.

Road Traffic Authority (RTA), Sydney, Australia

As a dynamic test standard for lateral collisions exists in Australia, RTA has continuous and comprehensive experience with side-impact testing of CRS.

CRS have been tested in a vehicle body on rebound sleds (26 tests) and with conventional sled-testing with an impactor (44 tests). This allows a comparison of results between the movement in a realistic vehicle body-environment and in impactor testing. The sled/impactor tests cover different seat types such as infant carrier, conventional CRS, CANFIX, top-tether influence ect. . The results have been published (12); so it is not necessary to discuss them in detail.

It was found that different CRS types arrive at different head movements and therefore different risk of head contact to the intruding door. The top-tether had no significant effect in protecting the head in a lateral collision.

Rigid attachment, like CANFIX, significantly improves the performance of child restraints in a side-impact. This is a strong indication that by technical measures of CRS-design and type of attachment benefits may be expected from standardised side test procedures, even if it is difficult to influence directly the head contact risk and the rotation of the head out of the CRS.

FOLKSAM Research, Stockholm, Sweden

The test method, developed 1990, uses a ECE-R44-02 sled, rotated by 90 degrees (9,10). As stopping device a fixed door panel was mounted. The pulse-shape was similar to the R44-pulse, the test configurations are shown in table 13. Different CRS, both rearward and forward facing, of group 0, I, II have been tested.

Table 13.
Folksam test configuration

Test speed	42-43 kph
Stopping distance	35-40 cm
Pulse shape	16g for 60 ms total duration 100 ms

Table 14.
Summary of single-sled-test results

Test facility	Test	Angle [°]	Velocity [kph]	CRS Type ECE Group	Major findings
RTA	Single Sled	45, 90	32	Group 0,I CANFIX, top tether	- top tether had no effect in protecting the head - CANFIX improves the performance of child restraints
Folksam	Single Sled with simulated door	90	40-45	Group 0,I,II rearward and forward facing	- chest a_{max} = 70 g - head: a_{max} = 120 g (without side protection) a_{max} = 70 g (with side protection)
TNO	Single Sled			Group 0,I rearward and forward facing	
Series 1	without simulated door panel	45, 90	32		head movement crabbed configuration impossible to simulate
Series 2	with simulated door panel	90	32		very high chest acceleration, head contact with door
Series 3	with simulated door panel, 400mm distance between panel and CRS	90	50		fully destroyed CRS, extreme head and chest accelerations
Series 4	with modified simulated door panel; 0mm distance between panel and CRS	70, 90	32		new door panel gives higher head and same chest accelerations as in former tests
TRL, Middlesex University	Single Sled with hinged door	90	25-50	Group I forward facing	dummy responses are of the same order as in the car tests further analyses of CRS armrest interaction seems necessary

Typical dummy results for the chest were about 70 g, depending on the structure of the CRS. The acceleration values for the head were around 120 g in a CRS without side collision protection and around 70 g with side collision protection with sidewings.

The tests were intended to improve the side-collision protection. As the most important factor, the CRS design should keep the head of the child inside the CRS, which is especially possible for rearward facing seats. It was also found to be important that CRS are strong enough to take care of the loadings in lateral impacts and to have padding for energy absorption inside the CRS. The typical movement of the head in a CRS without side impact protection is shown in figure 6.

Figure 6. Movement pattern of the head in a side impact at Folksam.

TNO, Road Vehicle Research Institute, Delft, The Netherlands

The TNO tests are focused to analyse

- how existing dynamic test equipment could be used without major modifications for the new side impact tests and
- where the limits of meaningful testing are with respect to impact velocity and stopping distance of the simulated door panel relative to CRS.
- the possibilities of an angled impactor, simulating the incoming door.

Four different test series were conducted with a single-sled test method (figure 7).

- *Test series 1*
  Evaluation of the dummy responses in 45 and 90 degrees impacts, impact velocity of 32 kph, without a simulated door panel. Test series no.1 was conducted in order to compare the difference in dummy responses between a 45 degrees impact with a forward and lateral movement of the CRS and a 90 degrees impact with only a lateral movement of the CRS.

- *Test series 2*
  Evaluation of the dummy responses in 90 degree impacts, an impact velocity of 32 kph with a simulated door panel at different distances between the panel and the CRS. Test series no. 2 was carried out to analyse the difference in contact velocity between the (undeformed) simulated door panel and the CRS used in a forward facing configuration resulting from the different distances between the panel and the CRS.

- *Test series 3*
  Evaluation of the dummy responses in 90 degree impacts, impact velocity of 50 kph, with a simulated door panel at 400mm distance between panel and CRS. Test series no.3 has been conducted to compare the results of test series no.2 with respect to a higher impact velocity of approximately 50 kph in both configurations, forward and rearward facing.

- *Test series 4*
  Evaluation of the dummy responses in 90 and 70 degree impacts, impact velocity of 32 kph, with a modified simulated door panel at 0mm distance between panel and CRS, and a stopping distance of the trolley of 150mm.Test series no.4 has been set up to test the new door panel with a velocity of 32 kph and different stopping distances.

Figure 7. Four different test series with single sled method.

The trolley was decelerated according to the standard ECE deceleration curve for both impact velocities, 32 and 50 kph. The CRS/dummy approach the simulated door panel at a certain impact speed that depends on the distance "panel to CRS" at trolley impact.
TNO P3/4-dummy as the lower limit dummy and TNO P3-dummy as the upper limit dummy were used.

The CRS used is approved as an ECE group 0/I combination seat in rearward facing and forward facing configurations.

The first tests were designed to determine whether a forward component of velocity could be simulated by a 45° rotated seat. In the 45° angled impact, the head of the dummy easily ejects out of the CRS in forward facing configurations.

Comparing the same CRS in rearward facing configuration, head and chest resulting accelerations are higher, due to the different dummy kinematics. In the rearward facing configuration, the dummy is pushed into the CRS, while in the forward facing configuration the dummy ejects out of the CRS. The simulation of possible door contact is therefore essential for the realistic outcome of the test.

To analyse intrusion criteria, the different distances "CRS to simulated door panel" of 400 mm, 150 mm and 0 mm at trolley impact and a relative lateral intrusion (movement of CRS on test bench differed) with respect to the maximum stopping distance 0 mm, 130 mm and 260 mm of the trolley were tested. At the moment of contact between CRS and the simulated door panel, the contact speed is always equal to the impact velocity of the trolley (about 32 kph).

These test configurations lead to very high resultant chest accelerations - approximately 25% (400 mm) to 225% (0 mm) higher than the ECE-R44 limit of 55 g. Due to the head contact with the door panel, the head accelerations are higher for the 3/4 dummy than for the P3-dummy. Thus, the head position relative to the design of the simulated door panel, especially the vertical height, is very important for injury criteria of the dummy's head.

In the third series, the limits of the test specifications were analysed by increasing the impact velocity to 50 kph with a distance "CRS to door panel" of 400 mm.

In all the tests performed, the CRS was fully destroyed by the high contact speed of the simulated door panel, the resultant head and chest accelerations were extremely high.

Therefore, it became obvious that the direct 50 kph impact to the CRS does not correspond to the loadings from a car-to-car side-impact at 50 kph. The full-scale loadings have to be translated into a suitable method to the single-sled configuration.

In the fourth series, the results of the "second series" were extended, using a new modified simulated door panel, which showed that in comparable conditions realistic higher head and chest accelerations of about 30% occurred and thus it has been proven that shape and padding of the door have a strong influence on the test results.

Furthermore, the simulation of the incoming door by mounting the impactor under an angle of 20 degrees, surprisingly showed in general the same levels of head and chest acceleration as in the basic tests with 90 degrees. Even with a test seat rotated only five to ten degrees on the trolley, the fixed impact surface will crash the test seat's back cushion, during the stopping distance intrusion. Therefore, this aim of a simulated forward movement was not followed and the test concept should be with an angle of 90 degrees.

Findings from Single-Sled Tests

In sled tests, the problem of the stopping distances and the relative distance "door panel to CRS" turned out to be a decisive factor. This is influenced by the fact that in real accidents there is a movement of the struck-vehicle and therefore, also a lateral movement of the anchorage points, especially on the struck-side of the vehicle.

The most important problem was the hardware interaction between intruded simulated door panel and the 3-point-belt for the fixation of the CRS on the struck-side.

These sled-tests showed that due to the design of the test layout, a direct impact velocity to the CRS of 50 kph proved to be too high.

- The existing test results showed that on the one side full-scale tests were available, in which some reference values existed, but some injury risks and loadings to the CRS have to be assessed by movement analysis. Furthermore, the results did not reflect the protecting criteria of the CRS alone, as the characteristic side impact behaviour of the struck car and sometimes the striking object, too, have been superimposed on them.
- In contrary in sled-tests the loadings are well known, especially from additional TNO-tests, but sled tests are strongly influenced by the impactor and the relative distances chosen. Thus, it cannot be exactly assessed, to which side-impact conditions in a full-scale test the sled specifications would correlate.

At first the group intended to establish criteria on a "prima facie procedure", which should be a basis for an ISO Standard proposal of a simple-sled procedure. But the complicated nature of side impacts suggests that "this assessment of test parameter criteria" would not be sufficient to arrive at a reliable and internationally accepted standard.

TRL, with Middlesex University, then developed a sled-based test in which the simulation of the vehicle door was hinged at the and adjacent to the test seat backrest. In this way, the intruding profile increased in angle as the intrusion increased, duplicating that observed in accidents and crash tests. Also the door intrusion was not continuos but stopped after a predetermined displacement.

Sled Tests with Hinged Door, TRL and Middlesex University

A standard ECE R44 seat was mounted laterally on a sled. A door frame and a 25 mm door was mounted on a hinged frame which enabled the door to swing rearward (relative to the sled track) into a CRS (figure 8). As the sled decelerates, the door is pushed into the CRS by an impact beam. By changing the characteristics of the impact beam and a rubber bump stop, the loading values and the elastic displacement can be controlled.

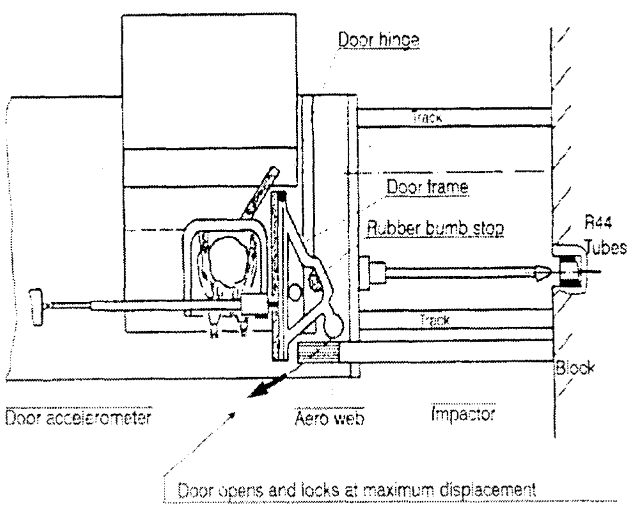


Figure 8. Test configuration at TRL and Middlesex University.

A series of 12 tests has been made which is primarily aimed at gaining experience with this new test method and adjusting the loadings corresponding to full-scale side impact tests.

The input conditions as shown in table 15 seem to achieve a dummy response and a maximum door acceleration of an acceptable order of overall severity. However, the inner door acceleration pulse time should be increased to arrive at higher energy input to the CRS.

Table 15.
Examples of first dynamic tests with hinged door

Test No.	3031	3035
Sled :		
Δ v [kph]	46.8	47.5
Stop [mm]	544	494
Decel [g]	19.7	22.7
Door:		
Accel [g]	142,1	108
CRS:		
Decel [g]	53.4	70.9
3ms accel. [g]:		
Chest res.	43.9	53.5
Head res.	81.9	60.1

Further testing will analyse the different initial space between door and CRS. Consideration will be given to the significance of arm rest interaction, which was shown to influence the dummy accelerations by creating different movement of the CRS.

Double Sled Tests - A Correlation Procedure

An intermediate step has therefore been chosen in order to translate the results of full-scale tests with help of a "double-sled procedure" into loadings to the CRS. The measurements in double-sled tests would have to be transferred to a simple single-sled-test procedure, which could then be used by all test institutions with their specific test equipment.

This new procedure of realistic side impact testing had been discussed in the group by the end of 1995. In the meantime, first test runs have been carried out (table 16). This test procedure has proven its benefits in evaluating the passive safety of structural components which are important in side crashes.

Table 16.
Summary of double-sled test results

Test facility	Test	Angle [°]	Velocity [kph]	CRS Type ECE Group	Major findings
Klippan	Double Sled	90	49	Group 0,I rearward facing	high head and chest acceleration
TUB	Double Sled	90	44	Group I forward facing	to be evaluated

Double-Sled Tests, Klippan, Sweden

An original sled of an ECE R44 test track has been equipped with a mock-up door, representing an intruding door structure (figure 9).

Furthermore, a second side impact sled has been designed to fit the ECE R44 track in order to represent a struck car with an installed CRS. This extra side-impact-sled has been equipped with a rotating platform, giving the possibility to put the ECE test-seat and thereby the installed CRS in various angles towards the striking door. The extra side-impact-sled has been equipped with braking means of its own in order to give the striking sled a desired crash pulse.

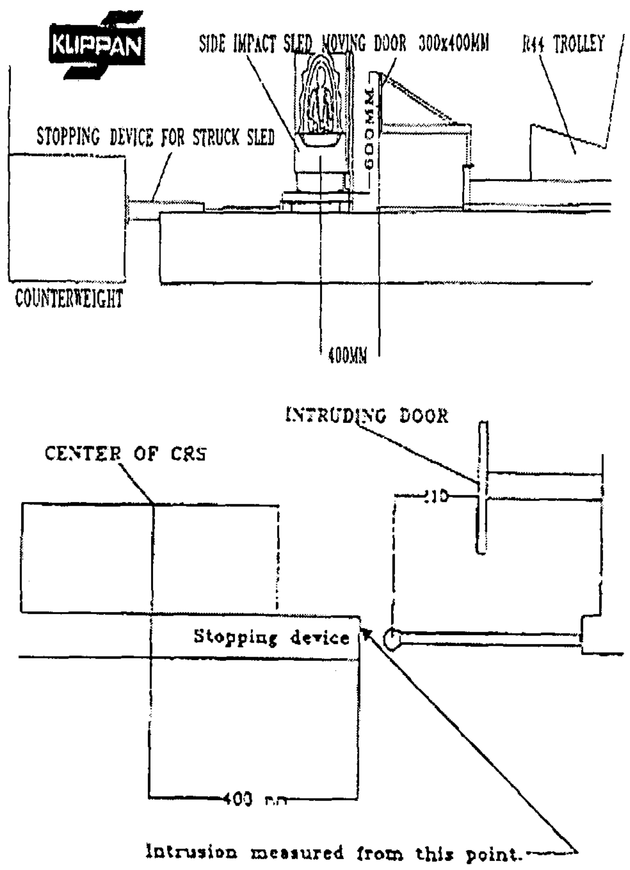


Figure 9. Schematic overview of the two-sled arrangement at Klippan.

An initial test run comprising five sled-tests with different child seats has been performed using this two-sled approach. Of the CRS tested, three units were of the type ECE R44 group 0 and two units of group I, rearward facing. The test parameters are shown in figure 10.

- Test speed of sled with door: 49±1 kph
- Door intrusion, 250-300mm measured from the centre of the installed CRS. Figure 9.
- Stopping distance of sled with intruding door 400±25mm.
- Test pulse of sled with intruding door . Max g 27.7 .
- Test pulse of extra side impact sled: Max g 61.5 .

Figure 10. Test parameters of Klippan.

For the tests a TNO P3-dummy has been used with recordings for head and chest. The results are shown in table 17.

Table 17.
Results of initial test run with the two sled method at Klippan

Test No.	Door intrusion	Acceleration levels Head [g]				
		X	Y	Z	Res	Res 3ms
1	270mm	32	168	31	169	133
2	285mm	49	135	36	142	127
3	260mm	27	122	44	126	108
4	280mm	60	151	39	152	110
5	285mm	38	156	34	161	122

Test No.	HIC	Acceleration levels Chest [g]				
		X	Y	Z	Res	Res 3ms
1	1,103	44	138	25	141	117
2	1,195	37	161	39	162	117
3	843	38	149	21	151	102
4	765	47	146	38	150	115
5	991	19	96	21	97	86

The two-sled arrangement, applied on the ECE R44 test track, seems to be rather suitable for simulating a car-to-car side impact.

The recorded acceleration levels in both head and chest of the dummy during the initial test run are, however,

found to be rather high compared to levels recorded in car-to-car tests.

An explanation for this may be that the given path of the struck sled is too severe. Other parameters which may be modified are the door velocity profile as well as door intrusion and door design.

Double-Sled Tests, Technical University of Berlin

As a part of an EC-project, a double-sled test method has been developed to evaluate the passive safety of structural components which are important in side crashes (13).

In the TU-Berlin procedure great importance was given to a flexible design of the test rig as far as the duplication of the final phase of the car's movement and the intrusion of the side structure into the car are concerned to ensure a good simulation of real life conditions. The characteristics of the test rig can be changed by equipping the band brake integrated into the sled, taking into consideration the influence of the rigidity of the seats in the cross direction and their effect on the intrusion reproduced. Other adjustable parameters are the masses of the sled, the selection of the friction elements and the contact pressure exerted on them by the impacted sled.

In order to adjust these various influences, the experimental simulation of the test rig was additionally coupled with a mathematical simulation, using the multi-body system MADYMO.

An expansion of this procedure is now being worked out in which the side structure components are mounted on a separate sled, thus allowing intrusions at an oblique angle, which changes with time, to be reproduced.

A first test series of 6 crashes with child seats has been made; the results have still to be analysed.

Findings from Double-Sled Tests

The first experience with the double-sled procedure showed the advantages of this component test procedure to reproduce, in a realistic way, the loadings from full-scale tests especially with regard to low cost application and easy reproducibility.

It seems possible to give the striking sled a desired crash pulse as well as to moderate the struck sled to reproduce the behaviour of a struck car by modifying the pulse or the weight of the struck sled. The repeatability of given door intrusion conditions has been kept within rather narrow limits. In extended test runs the crash pulse and the door velocity profile have to be adjusted to full-scale tests as well as the door intrusion and door design.

CONCLUSIONS

1) Severe to fatal injuries to children in correctly attached child restraint systems (CRS) are significantly overrepresented in lateral collisions.

2) High injury frequencies were observed to the head, neck and thorax. The head contact against CRS or to the inner door structure is of special importance.

3) Correct attachment of CRS in real accidents has a strong influence on the loading conditions. Too much slack in the attachments increases the injury risk. Tests have confirmed that rigid ISOFIX and CANFIX attachments show a better performance than conventionally attached CRS in lateral collisions.

4) To reflect the risks in real accidents, side impact testing to CRS has to correspond to a car-to-car crash of 50 kph and has to reproduce the door intrusion and design. Thus, the basic physical results of full-size crash testing of a 50 kph lateral car crash have to be transferred to a more reproducible sled test.

5) Crash pulse, stopping distance, door mass and padding have been analysed by different institutions by means of full-scale tests, single- and double-sled test procedures. By comparing the different results as indicated in this paper, proposals for an uniform test standard will be developed.

6) The forward movement of the head which may occur in pre-impact braking in forward facing systems is difficult to reproduce but should be considered in future work.

7) The test has to be developed for struck side positions, but the injury mechanism of the non-struck side positions should be analysed further. Preferably only one test should be developed of assessing rearward (ECE group 0/I) and forward (ECE group I) configurations, even if very different kinematics (forward movement of the head, CRS movement versus belt attachment geometry) have to be taken into consideration.

8) The aim of this ISO ad-hoc working group is to develop a proposal for a standardised side impact test procedure. To achieve this aim, based on the results of real accident analysis and full-scale vehicle impacts, double-sled systems should be used as an intermediate stage in the determination of required basic parameters of side impact testing, which should be used finally in a simpler single-sled test procedure.

9) At first, the method and the specifications of this standardised impact test procedure will be developed. In a second step the maximum tolerance limits to head, neck and chest will be defined. New child dummies with good biofidelity in side impact need to be developed quickly.

10) There is still an essential need for more research in biomechanical tolerance levels for children in lateral collisions.

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The advises of the ISO/TC22/SC12/WG1 "Child Restraint Systems" have been highly appreciated and it is expected that further contributions of test experience from industry and test institutions will be integrated in future work.

REFERENCES

1. Australian Standard 3629.1, "Methods of Testing Child Restraints".

2. Rattenbury, S.J.; Gloyns, P.F., "A Population Study of UK Car Accidents in which Restrained Children were killed", Joint AAAM/Stapp/IRCOBI Child Occupant Protection Symposium, San Antonio, November 1993.

3. Langwieder, K.; Hummel, Th., "Children in Cars - Their Injury Risk and the Influence of Child Protection Systems", Verband der Schadenversicherer e.V., Munich, 12th ESV-Conference, Göteborg, 1989.

4. Langwieder, K.; Hummel, Th.; "Biomechanical Risk Factors for Children in Cars and Aggravation by Misuse of Restraint Systems", Verband der Schadenversicherer e.V., Munich, Germany, 14th ESV-Conference Munich, 1994.

5. Abbreviated Injury Scale 1990 Revision, Association for the Advancement of Automotive Medicine, Des Plaines, IL, 1990.

6. Beusenberg, M.C.; Happee, R.; Twisk, D.; Janssen, E.G., "Status of Injury Biomechanics for the Development of Child Dummies", Joint AAAM/Stapp/IRCOBI Child Occupant Protection Symposium, San Antonio, November 1993.

7. Janssen, E.G.; Beusenberg, M.C., "Development of Mechanical Human Body Simulators - Crash Dummies", TNO Crash-Safety Research Centre, Crash-Tech, Munich, Germany, October 1994.

8: Thunnissen, J.G.M.; Happee, R.; Eummelen P.; Beusenberg, M.C., "Scaling of Adult to Child Responses Applied to the Thorax", TNO Crash-Safety Research Centre, IRCOBI Conference, Lyon, 1994.

9. Kamren, B.; Koch, M.; Kullgren, A.; Lie, A.; Tingvall, C.; Larsson, S.; Turbell, T.,"The Protective Effect of Rearward Facing CRS: An Overview of Possibilities and Problems with Child Restraints for Children Aged 0-3 Years", Joint AAAM/Stapp/IRCOBI Child Occupant Protection Symposium, San Antonio, November 1993.

10. Kamren, B.; Kullgren A.; Lie, A.; Sköld, B.A.; Tingvall, C., "Side Protection and Child Restraints - Accident Data and Laboratory Test Including a New Test Method", 13th ESV-Conference Paris, 1991.

11. Turbell, T.; Lowne, R.; Lundell, B.; Tingvall, C., "ISOFIX - A New Concept of Installing Child Restraints in Cars", Joint AAAM/Stapp/IRCOBI Child Occupant Protection Symposium, San Antonio, November 1993.

12. Kelly, P.; Brown, J.; Griffiths, M., "Child Restraint Performance in Side-Impacts with and without top tethers and with and without Rigid Attachment (CANFIX)", IRCOBI-Conference Brunnen, 1995.

13. Appel, H.; Heger, A.,; Meyer, L.; Lutter, G.; Pirschel, H.; Vetter, D., "Advanced Technologies for Automotive Seat Evaluation and Design", Technical University Berlin, 1995.

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PROTECTION OF CHILDREN ON BOARD VEHICLES
INFLUENCE OF PELVIS DESIGN AND THIGH AND ABDOMEN STIFFNESS ON THE SUBMARINING RISK FOR DUMMIES INSTALLED ON A BOOSTER

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ABSTRACT

The first part of this study endeavours to show that the design of the inter-spinal notch of the pelvises of impact test dummies is unrealistic and can therefore not be expected to reproduce satisfactorily the interaction between the seat belt and the child's pelvis.This part of the study leads to a shape and position recommendation for each dummy weight group. Part two attempts to define the crushing force pattern for the thighs and abdomen of children based on seat belt static compression tests .These recommendations led to modification of a TNO P series dummy. To measure forces in the abdomen during impact and predict a dummy injury risk, a load cell is placed just above the iliac crests of the modified pelvis. Tests performed with the modified dummy highlight the need to equip all boosters with side strap guides by illustrating the phenomenon of submarining for those boosters lacking such guides.To help the booster designer position satisfactorily the strap guides integral with the booster, an installation zone is recommended with reference to the 3-year child dummy.

INTRODUCTION

In 1994, an accident research study covering 1629 cases of children involved in collisions was carried out in France (1). This study showed that, while the obligation to fasten children with suitable restraint systems has improved overall safety for children, the effectiveness of the present systems is nevertheless still inadequate.
For children aged three years and over, using boosters (belt positionning systems excluding shield) in addition to the adult 3 points seat belt, accident research surveys tend to show that in frontal collisions cases of abdominal injuries are more frequent and more severe than for unrestrained children; these abdominal injuries are mostly caused by penetration of the lap belt into the abdomen (1)(2)(3)(4)(5)(6)(7).
This risk is not brought to light by the certification tests performed in accordance with the restraint system certification procedure (ECE Regulation R44).

STUDY OF PELVIS SHAPE REPRESENTATIVENESS FOR IMPACT TEST DUMMIES

In frontal impact, without direct intrusion on the child, the effectiveness of boosters depends mainly on the interaction of the seat belt with the pelvis. To reproduce this interaction satisfactorily, it is essential that the pelvis of the impact test dummy reproduce the geometry of the child's pelvis, and especially the shape and position of the line through the middle of the iliac wings from the anterosuperior spine to the iliac crest. This comparison is based on anthropometric measurements performed on volunteers, and on X-rays taken during consultations.

Anthropometric measurements were taken on a sample composed of 54 children aged between 30 and 148 months placed bare in seated position on the ground with their back resting against the wall.
For sake of comparison, the dummy dimensions were measured by the same procedure.
The dummies considered in this analysis are:
- TNO P series dummies aged 3 years, 6 years and 10 years
- PART 572 dummies aged 3 years and 6 years
- Hybrid III dummies aged 3 years and 6 years.

<u>Relation between the age and weight of the children in the sample</u> - One observes that the age and weight of the children in the sample are well correlated. The best prediction is obtained with a power type model ($r = .83$).
The relationship given in Figure 1 shows that the dummies of each age group have a standard weight which

is representative of the average weight of the children in the same age group in our sample

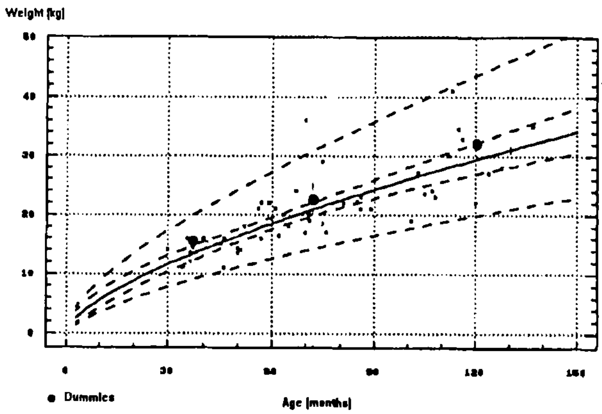


Figure 1 Regression between child age and weight

To verify the representativeness of our sample, we projected the regression curve plotted in Figure 1 onto the mean somatic growth curve for children (data supplied by Dr M. Sempre and G. Pendron, CECDE, Paris).
The projection shows that the weight of the children in our sample is representative of the average population of 3- to 10-year-old children.

<u>**Height of iliac crests (ICH) as a function of chil weight -**</u> The best prediction of the height of the iliac crests is obtained from the weight of the child using a power type model (r = .79).
Figure 2 illustrates this relationship. As an indication, the impact test dummies are also positioned.

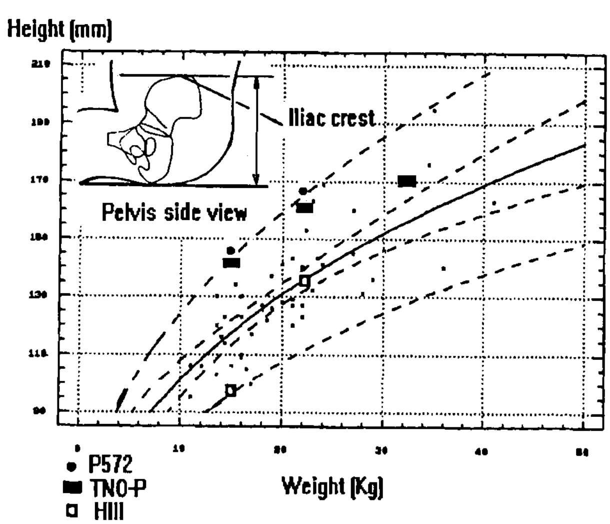


Figure 2 Regression between weight and height of iliac crests

<u>Iliac crests of 3-year dummies</u>
The iliac crests of the TNO P3 and PART 572 dummies are located at a height of 143 mm and according to the regression analysis should be brought to a height of 117 mm ± 5 mm.
The iliac crests of the Hybrid III dummy are at a height of 97 mm and according to the regression analysis should be brought to a height of 117 mm ± 5 mm.
<u>Iliac crests of 6-year dummies</u>
The iliac crests of the TNO P6 and PART 572 dummies are currently at heights of 160 mm and 165 mm respectively, and according to the regression analysis should be brought to a height of 135 mm ± 5 mm.
The iliac crests of the Hybrid III dummy are located at a similar height to that on the child, i.e. 135 mm ± 5 mm.
<u>Iliac crests of the 10-year TNO dummy</u>
The iliac crests of the TNO dummy are currently at a height of 170 mm and according to the regression analysis they should be brought to a height of 155 mm ± 7 mm. However, if we consider only those children weighing 32 kg ± 4 kg and aged 10 years ± 18 months, then the average height of the iliac crests for this sub-sample consisting of 4 observations is 168 mm with a standard deviation of 23 mm on the population.
The average age of this sub-sample is 124 months with a standard deviation of 9 months.
The average weight of this sub-sample is 32.5 kg with a standard deviation of 2.7 kg.
In can therefore be considered that the height of the dummy's iliac crests is satisfactory.

<u>**Distance for Antero superior Iliac spine (ASIS) as a function of child weight**</u> - The best prediction of the distance separating the anterosuperior spine from the back is obtained from the weight of the child using a power type model (r = 82). Figure 3 illustrates this relationship. As an indication, the impact test dummies are also positioned.

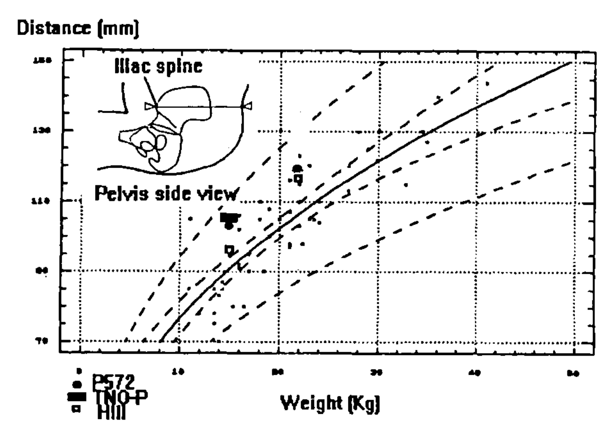


Figure 3 Regression of weight and distance between back and iliac spine

Iliac spines of 3-year dummies

The TNO P3 and PART 572 dummies have an iliac spine located at a distance of 105 mm from the back. According to the regression analysis in Figure 4 this distance should be brought to a distance of 90 mm ± 5 mm to be representative of a 15 kg child.

The Hybrid III dummy has an iliac spine satisfactorily located, i.e. at 94 mm.

Iliac spines of the 6-year dummy

Since the pelvis of the TNO P6 dummy does not reproduce the shape and position of the line running through the middle of the iliac wings from the anterosuperior spine to the iliac crest, it is impossible to record this dimension.

The P572 and Hybrid III dummies have an iliac spine located 118 mm from the back. For a 22 kg child the regression analysis predicts an average distance of 107 mm ± 5 mm. It can therefore be considered that the iliac spine of these dummies has a position representative of the 22 kg child.

Iliac spines of the 10-year TNO dummy

Since the pelvis of this dummy does not reproduce the shape and position of the line running through the middle of the iliac wings from the anterosuperior spine to the iliac crest, it is impossible to record this dimension. For a 32 kg child, the regression analysis predicts an average distance of 125 mm ± 7 mm.

Pelvis width (PLW) as a function of child weight - The "power" type functions appear as the most significantly predictive of pelvis width (r = .89). Figure 4 illustrates the PLW/WEIGHT relationship for children and, as an indication, the impact test dummies are also positioned.This figure shows that the pelvis width of TNO-3 year, 6-year and 10-year dummies, taken at the level of the iliac crests, always exceeds by between 15 mm and 20 mm the average width for children as plotted by regression analysis. On the whole, the dummies have a satisfactory pelvis width.

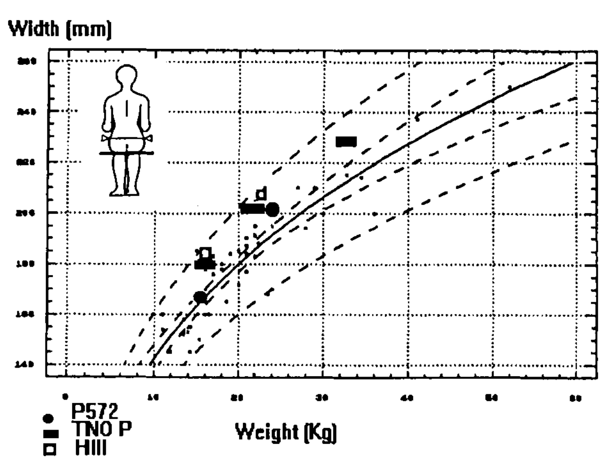


Figure 4 Regression between child weight and pelvis width

Abdomen thickness (ABTH) as a function of child weight - Figure 5 illustrates the linear regression (r = .65) between the thickness of the abdomen taken at the thigh level and the child's weight.

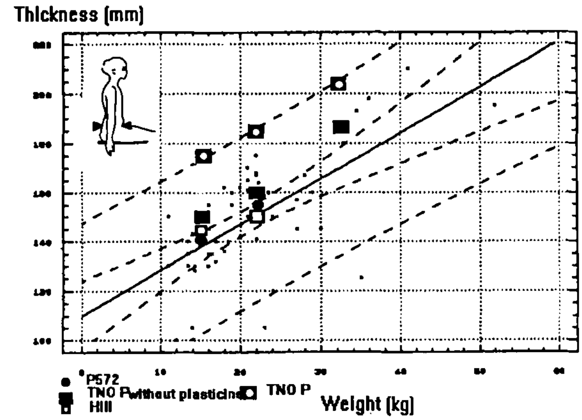


Figure 5 Regression between weight and abdomen thickness

This figure shows that the P572, Hybrid III and TNO P series dummies, 3-year, 6-year and 10-year, without plasticine in the abdomen, have an abdominal thickness representative of the children in the sample.

Statutorily (ECE R44), these dummies are used with a block of plasticine placed between the spinal column and the abdominal padding; the addition of this block generates a 25 mm - i.e. 25% - increase in the dummies' abdominal thickness, thus placing them on the boundary of the interval of confidence at 95% of the prediction (Figure 6).

Thigh thickness (THTH) as a function of child weight - Figure 6 illustrates the results of the power type function for THTH and WEIGHT (r = .82) and, as an indication, the TNO dummies are also positioned.

This value is preponderant because it influences the height differential between the iliac crests and the thighs, and hence the height available to the seat belt to restrain the pelvis.

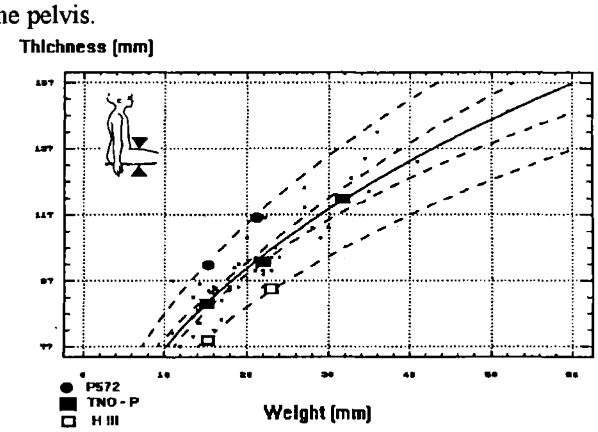


Figure 6 Regression betwen weight and thighs thickness

This figure shows that the thickness of the thighs of the TNO 3-year, 6-year and 10-year dummies is satisfactory by comparison with the children in the sample. On the other hand, the PART 572 dummies are on the upper boundary of the interval of confidence of the sample, with a thigh thickness 12 mm greater than in the regression analysis, while the Hybrid III dummies are on the lower boundary of the interval of confidence with a thigh thickness approximately 10 mm less than that of the children.

In the end, the height available to the seat belt to bear against the pelvis is characterized by the height separating the iliac crests from a tangent to the child's thighs.
On the current 15 kg and 22 kg regulatory dummies, this dimension is greatly increased (figure 7)
This increase is especially marked for 3-year dummies (15 kg), for which the value measured (see TNO P3) is virtually twice that for the child and is similar to the height between the iliac crest and the thigh of a child aged 10 year old, weighing 32 kg.

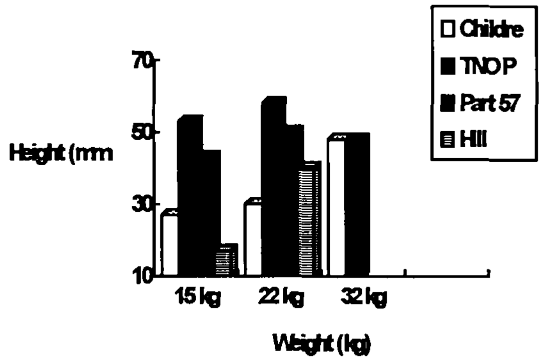


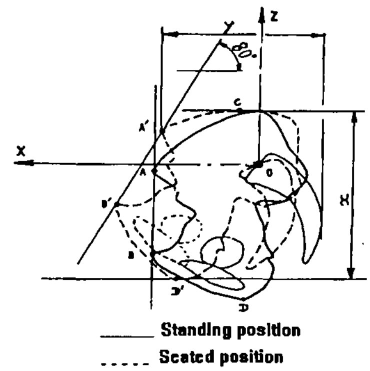
Figure 7 Height between thigh and iliac crest in function of the weight

For the 3-year-old child it appears that the seat belt has a distance of only 27 mm to restrain the pelvis, which is little given the width of current seat belts, namely 47 mm, and seat belt wearing play due to the thickness of clothing. It appears clearly that the regulatory dummies underestimate the capacity for seat-belt glance-off from the child's pelvis to its abdomen, and do not bring to light the risks inherent in the phenomenon of submarining.

Comparison of child pelvis X-rays with the designs of the dummies - 21 complete bust X-rays of children in standing position - front and side views - were supplied to us by the child orthopaedic surgery ward of the R. Debré Hospital in Paris. These full-scale X-rays are taken from the medical case histories of seven children.

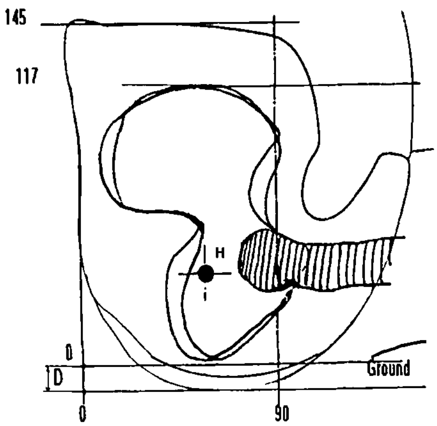
To assess the representativeness of dummy pelvis shape we modelled the bone contours on the child X-rays and projected these contours onto the scale drawings supplied by the dummies manufacturers.

Definition of the pelvis seated position in side view
The X-rays show that the "standing" position of the child's pelvis, viewed in side projection, can be indicated by the fact that the pelvis is maintained in a position in which the anterosuperior iliac spines (A) and the upper part of the pubic symphysis (B) are contained in a vertical plane just like the adult pelvis .

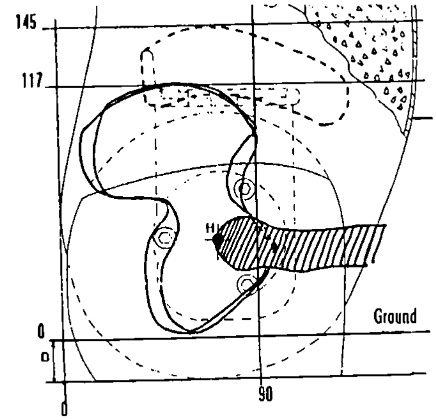


Based on X-rays of the adult placed in seated position, Leung (9) defines the inclination of the pelvis (see figure above).Based on a sample of 10 subjects the author observes that the angle of the straight line passing through (A) and (B) ranges between 69° and 90° relative to a horizontal, with a mean calculated value of 81°.
We have assumed that this inclination was the same for the children.
Accordingly, we have assessed the representativeness of the dummy pelvises mainly from the side views.

Definition of the dummy seating reference.
For the dummies, the drawings supplied do not take into account crushing of the pelvis padding under the weight of the dummy placed in seated position on a rigid surface. To allow for this crushing we have calculated the difference between the height of the iliac crests measured on the dummies and the value read on the drawings supplied by the manufacturers. This difference shown on the drawings defines the dummy seating line. Vertically (Z axis), the child pelvises are placed so that the ischia (D) are at a tangent to the dummy seating line. Horizontal lines plotted at 117 mm, 135 mm and 170 mm above the seating line illustrate the mean position of the iliac crests for children weighting 15 kg, 22 kg and 32 kg respectively. Horizontally (X axis), the child pelvises are placed so that the anterosuperior iliac spine (B) is tangent to a vertical line which defines its mean position relative to the back, namely 90 mm for the 15 kg child, 105 mm for the 22 kg child and 125 mm for the 32 kg child.



D= Pelvis crushing under the dummy's weight
Figure 8 Side view of TNO P3 pelvis compared with pelvis of 2 children normalized for a standard weight -15 Kg



D= Pelvis crushing under the dummy's weight
Figure 9 Side view of Part 572 3 years pelvis compared with pelvis of 2 children normalized for a standard weight -15 Kg

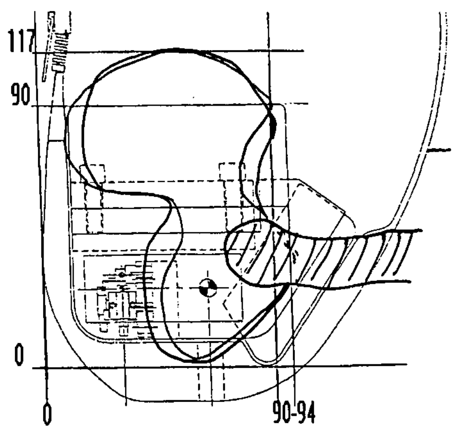


Figure 10 Side view of H III - 3 years pelvis compared with pelvis of 2 children normalized for a standard weight -15 Kg

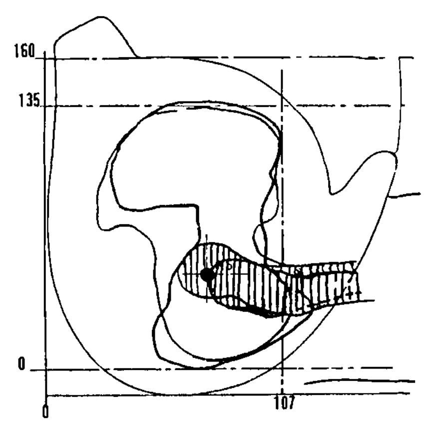


Figure 11 Side view of TNO P6 pelvis compared with pelvis of 2 children for a standard weight -of 22 kg.

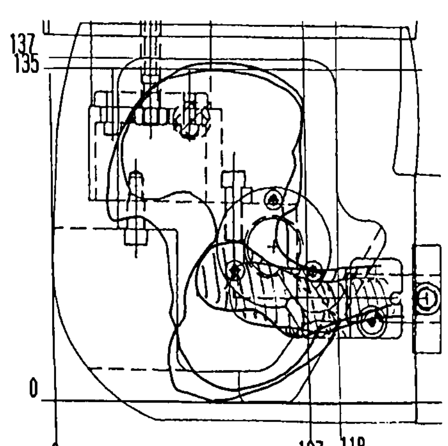


Figure 12 Side view of HIII 6 years old pelvis compared with pelvis of 2 children for a standard weight -of 22 kg.

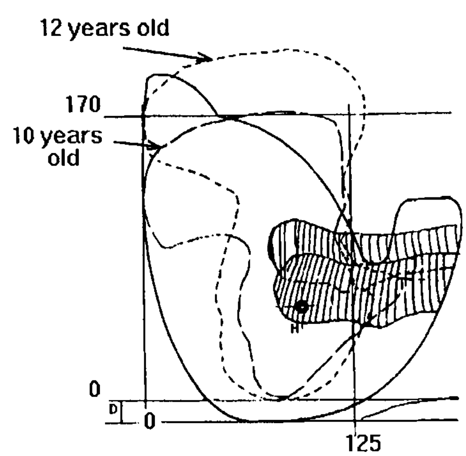


Figure 13 Side view of TNO P10 pelvis compared with pelvis of 2 children for a standard weight -of 32 kg.

To assess the representativeness of the 3-year dummies we took into account the following X-rays:
- Child case history No. 90 10 04 930, age 47 months - weight 18 kg
- Child case history No. 92 23 33 064, age 48 months - weight 18 kg
The two children adopted as a reference have an iliac crest height greater than the average for children aged 36 months and weighing 15 kg (average value = 117 mm). This difference can be explained by the children's greater age (47 and 48 months) and weight (18 kg). To correct these side views we applied to them a reducing factor of 0.93, which is the ratio between the average height of the iliac crests for an 18 kg child (weight of the children) and the average height of the iliac crests for a 15 kg child (standard weight of dummy). The corrected side views are compared with the drawings of the pelvis for the TNO P3, P572 and HIII 3-year dummies (see figures 8, 9 and 10).
To assess the representativeness of the 6-year dummies we took into account the following X-rays:
- Child case history No. 90 10 04 930, age 60 months - weight 22 kg
- Child case history No. 95 34 79 870, age 66 months - weight 22.5 kg
The superposition of the pelvises on the drawing of the TNO P6 dummy is shown in Figure 11and figure 12 for the P572. On the side views one observes that the two children adopted as a reference have an iliac crest height close to the average for children aged 72 months and weighing 22 kg.
To assess the representativeness of the 10-year dummies we took into account the following X-rays:
- Child case history No. 94 30 05 871, age 113 months - weight 35 kg
- Child case history No. 94 32 68 274, age 139 months - weight 41 kg
The superposition of the child's pelvis on the drawing of the TNO P10 dummy is shown in Figure 13.
On the side views one observes that case No. 94 30 05 871 has an iliac crest height close to the average for children aged 120 months and weighing 32 kg.
This good representativeness is to be related to the child's age (113 months) and weight (35 kg).The figures show clearly that as regards the shape of the dummy pelvises, the design of the inter-spinal notch is generally unrealistic and can therefore not be expected to reproduce satisfactorily the interaction between the seat belt and the child's pelvis. One also notes that the pelvis of the TNO dummies has a stiff protuberance starting from the pubis and rising up to the anterosuperior iliac spine; this protuberance has no anatomical significance and should therefore be eliminated, especially since it interferes with the seat belt notably in the event of pelvis rotation, which encourages dummy anti-submarining by creating a moment opposite to the direction of rotation of the pelvis in a frontal impact. From a front view the design of the iliac wings of TNO P series and Hybrid III dummies can be considered satisfactory ; this is not the cases for the PART 572 dummies. With a view to testing the effectiveness of the booster strap guides in preventing the seat belt from passing over the abdomen (before or during impact), this study leads us to modify in priority the pelvis of a TNO P3 dummy, because given the low height of its iliac crests relative to the thighs (27 mm), it is the most unfavourable case.It should be remembered that boosters are devices designed to restrain children from ages 3 to 10 years.
To detect the force applied to the abdomen we equipped it with a dynamometric platform placed just above the iliac crests.The overall design of the modified pelvis is shown in Figure 14.

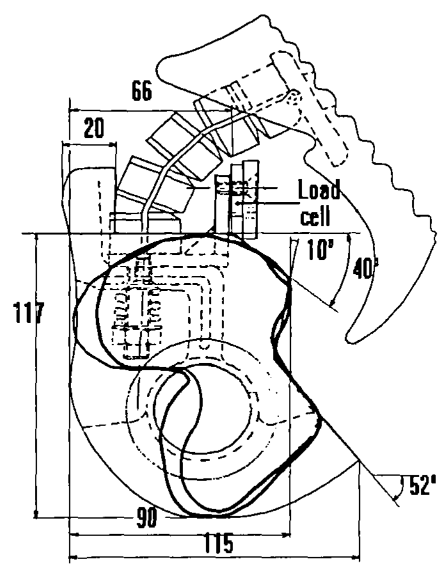


Figure 14 Pelvis side view of modified TNO P3 compared with 2 children normalized for a standard weight of 15 kg

In the second part of this study an experimental process will now be put in place to record the force/crushing characteristic of the abdomen and thighs on dummies and on child volunteers. This work should lead to the construction of a prototype dummy abdomen and thighs to be adapted to our modified TNO P3 dummy.

CHARACTERIZATION OF THE STIFFNESS OF CHILDREN'S THIGHS AND ABDOMEN

In order to reproduce the phenomenon of submarining, it is essential that the impact test dummies reproduce the interaction between the seat belt and the thighs and abdomen. Thighs which are excessively stiff tend to promote seat belt slippage by not allowing it to

become anchored in the soft tissue deformation caused by the vertical compression force exerted by the strap. For the same reasons regarding the iliac spine, it is also necessary to reproduce the natural stiffness of the abdomen. To gather this information we performed static compression tests on child volunteers.

Method - The child with its body clothing is seated on a rigid plate with its lumbar column well supported by a wooden plank positioned at 90° relative to the ground.
The child's feet are dangling in the air.
The thighs and abdomen are subjected to compression by a seat belt of the 2-point type, 47 mm wide and of characteristic elongation 10% under a one-tonne load.
The seat belt is subjected to tension manually by means of a winch, applying the load at a very slow speed.
Seat belt penetration is measured by means of a laser centred on the centreline of the child. The resultant force applied by the strap is also measured.
The load is limited to 50 daN for the thighs.
The load is limited to 25 daN for the abdomen.

- Table 1 - Anthropometry of the child volunteers

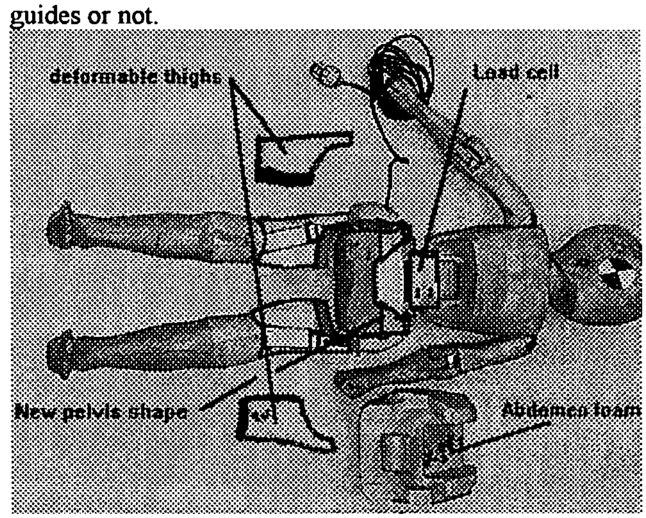
Case No.	Age	Sex	Weight (kg)
EL	30	M	14
SC	50	F	14.3
MC	75	M	18.5
PL	61	M	21
JC	105	M	23.5
ML	115	F	34.5

Thigh compression test -The seat belt is positioned flat on the bare thighs of the child and the edge is in contact with the child's abdomen. Strap force/penetration in the thighs is illustrated in Figure 15. One observes that the initial stiffness of the thighs of the children aged 3 to 10 years shows relatively little scatter; for this reason all the recordings form a corridor in which the thighs of the 3-to-10-year impact test dummies must be situated in order to be considered as representative in terms of initial stiffness. Tests were also performed in the same conditions on the thighs of the impact test dummies; the results, presented in figure 16, show clearly that the 3 year old dummies thighs are far too stiff ; it's the same obsevation for the 6 and 10 year old dummies. We machined the thighs of our modified TNO P3 dummy to insert in them deformable test specimens enabling the characteristic crushing force set by the corridor to be complied with.Padding test specimens of various densities were tested. Compliance with the corridor is illustrated Figure 16.

Abdomen compression test -The seat belt is positioned flat on the bare abdomen of the children and the edge is in contact with the thigh; in this position the seat belt is opposite the iliac spine of the children's pelvis. The pattern of strap force/penetration is illustrated in Figure 17. One observes that the initial stiffness of the abdomen of the children aged 3 to 10 years shows relatively little scatter; for this reason all the recordings form a corridor in which the 3-to-10-year impact test dummies must be situated in order to be considered as representative. Figure 18 show clearly that the 3 year old dummies have an abdomen which is far too stiff ; it's the same obsevation for the 6 and 10 year old dummies. For the TNO P6 and P10 dummies the strap comes into contact with the pelvis protuberance and the strap must be raised by at least 15 mm to glance off this rigid shape and apply loading to the deformable abdomen.We built a mould of the abdomen of our modified TNO P3 dummy with a view to forming test specimens of a shape which would enable the crushing force characteristic set by the corridor to be complied with. The thickness of this new abdomen at the level of the iliac spine is in conformance with the average for 15 kg children, namely 135 mm. The iliac spine is therefore recessed by 45 mm in the abdomen. Conformance with the corridor is monitored up until seat-belt contact with the iliac spine. Test specimens of paddings of various densities were tested. Compliance with the corridor is illustrated Figure 17.

COMPARISON OF THE TNO P3 STANDARD AND MODIFIED ON VARIOUS BOOSTERS

Having illustrated the shortcomings regarding the pelvis shape and the stiffness of the thighs and abdomen, we wanted to see the influence of the modifications performed on the impact behaviour of the dummy placed on various types of boosters whether equipped with strap guides or not.

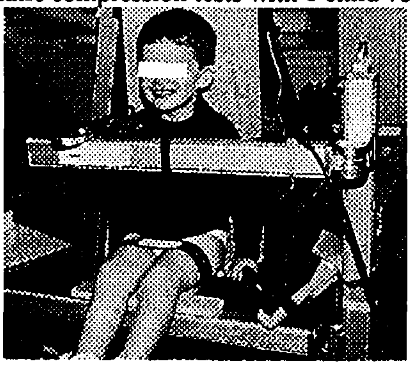


TNO P3 modified with abdominal sensor

For this purpose we carried out a series of frontal crash tests at Union Technique de l'Automobile et du Cycle, a

STUDY OF THIGH STIFFNESS FOR CHILDREN OF 3 TO 10 YEAR OLD

- 12 static compression tests with 6 child volunteers



RESULTS OF STATIC COMPRESSION TESTS ON THE THIGHS WITH LAP BELT

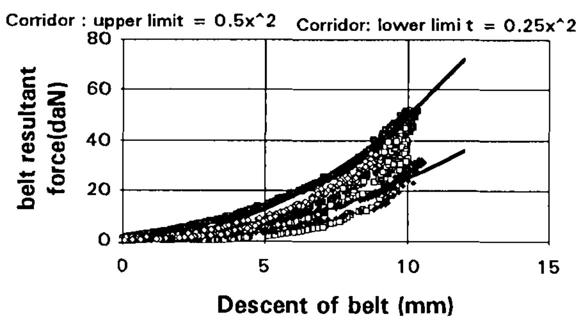


Figure 15

COMPARAISON OF CHILD DUMMIES (3 YEAR OLD) THIGHS STIFFNESS WITH VOLUNTEER CORRIDOR

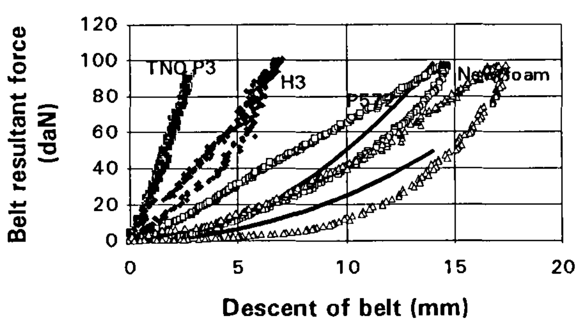
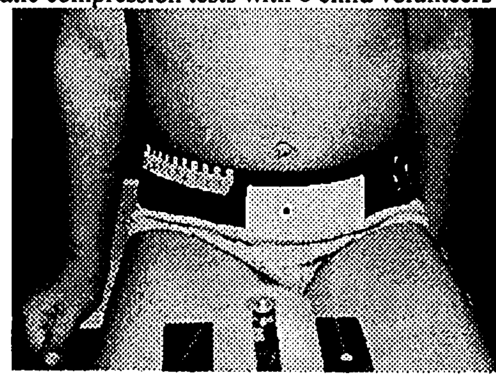


Figure 16

STUDY OF ABDOMEN STIFFNESS FOR CHILDREN OF 3 TO 10 YEAR OLD

12 static compression tests with 6 child volunteers



RESULTS OF STATIC COMPRESSION TESTS ON THE ABDOMEN WITH LAP BELT

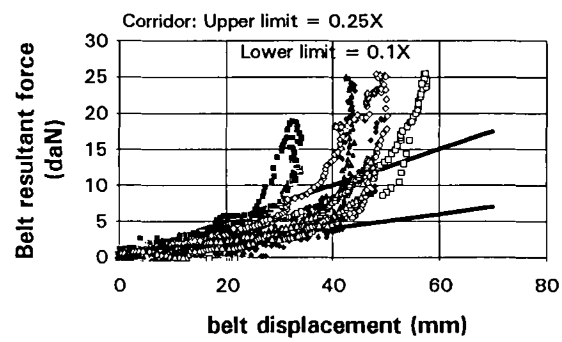


Figure 17

COMPARAISON OF CHILD DUMMIES (3 YEAR OLD) ABDOMEN STIFFNESS WITH VOLUNTEER CORRIDOR

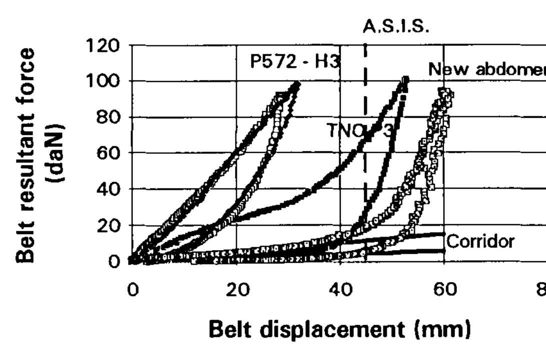


Figure 18

French organization authorized to perform certification tests. The comparative tests between the TNO standard P3 and the prototype TNO modified P3 were performed in accordance with the procedure of ECE Regulation R44-03. The boosters used in the tests are products certified by the ECE R44 procedure. The various types of booster used are illustrated in Figure 19. The test matrix is given in Table 2.

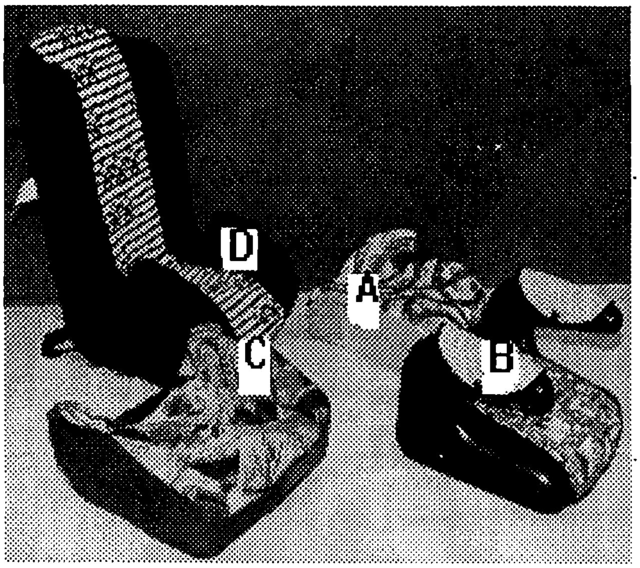


Figure 19

Table 2: Matrix of ECE R44 03 frontal crash tests

Type of booster	TNO standard P3	TNO modified P3
Seated on regulatory bench seat	C1	C5-C6
booster A	C2	C7
booster B	C3	C8
booster C	C4	C9
booster D	-	C10
booster E (same as A but integral with the test rig)		C11
booster F (same as A but strap guide placed 50 mm lower than the seating line)	-	C13

The main results of these tests are given in Appendix 1. In identical test conditions one observes that the changes to the dummy have no notable influence on the maximum head excursion, the resultant thorax acceleration during 3 ms and the maximum forces in the seat belt. One observes on the film that the shoulder of the dummy, whether modified or not, frequently glances off the seat belt (see comments in Appendix).

Out of eight tests with modified dummy restrained by the seat belt with or without booster, one observes that in four cases the seat belt did not glance off the shoulder, and these three cases are associated with strong dummy submarining. This glance-off is due to the position of the upper anchorage point, which is not favourable to good restraint because its strap is too eccentric in the transverse direction relative to the dummy and not sufficiently retracted to be representative of the side rear positions of Renault vehicles equipped with a belt pulley system.

Table 3 - Position of the upper belt pulley anchorage point (C) / point H

	X-mm	Y-mm	Z-mm
ECE R44 - 03	-293	-300	540
Mean for side rear positions of Renault vehicles equipped with a belt pulley	-466	-244	567
Difference	-173	-56	27

In fact, the strap is well positioned on the shoulder when the 3-year dummy is seated directly on the bench seat and on the contrary predisposed to glance off the shoulder as soon as the 3-year dummy is elevated. This glance-off is no doubt more pronounced with 6-year and 10-year dummies.This sliding contributed to loading the abdomen by the inferior part of the shoulder belt (see test C7). Another factor contributing to this problem of glance-off is the excessive stiffness of the thorax of this dummy. For the TNO standard P3 dummy, whatever the conditions of restraint, analysis of the film shows no slippage and/or stress on the lap-belt strap above the dummy's iliac crests. This is also confirmed by the post-impact position of the dummy and strap and by the absence of markings in the plasticine block placed in the abdomen. On the other hand, when the modified P3 dummy is seated on the C and D boosters which have no guide of lap belt , one observes very strong penetration by the lap-belt strap in the abdominal region located above the Iliac crests (see appendix 2). In these cases the force applied to the abdomen is very great and is directly attributable to incorrect initial positioning of the lap-belt strap, which is flat on the abdomen. When the modified dummy is directly on the bentch the force applied on the abdomen are limited by the excessive stiffness of the thorax . The excessive stiffness differential between the thorax and the new abdomen can result in:

- an unrealistic transfer of force between the seat belt's lap and shoulder straps,
- a major and unrealistic abdominal compression force during bending of the thorax (8).

These tests confirm that the role of a booster is above all to force the seat belt into a correct initial position, i.e. flat on the thighs and to keep ot in that position during impact. The abdominal measurement show that the lap belt guide has divided by 2 the force applied on the abdomen comparatively to the boosters without guide.

DEFINITION OF A STRAP GUIDE LOCATION ZONE FOR GROUP 2 AND 3 CHILD BOOSTERS

Due to the immature shape of the pelvis in children aged 3 to 10 years, and to prevent the lap-belt strap from slipping onto the abdomen, the adult seat belt must be forced to pass over the base of the child's thighs throughout the impact. In this seat belt position, restraint is provided mainly by compression of the thighs. Given the present position of the seat-belt anchorage points in cars, this seat-belt position is impossible. To ensure good passage of the seat belt it is therefore essential that the booster be provided with two side strap guides well positioned relative to the pelvis of the 3-year-old child which represents the most unfavourable case. A strap guide well positioned for a 3-year-old child is especially so for a 6- or 10-year-old child. This lap belt guidance design could be a reversed T-shape installed in the side panels that would preclude any risk of submarining.

Static verification of the correct positioning of the strap guide window - The booster is placed on the regulatory bench seat (ECE R44) and the TNO P3 3-year dummy, without its abdominal padding, is installed on the booster in accordance with the regulation. The positions of the upper and rear edge of the window (Figure 20) are measured by means of a rigid plastic ruler, 3 mm thick and 50 mm wide, simulating the seat belt.

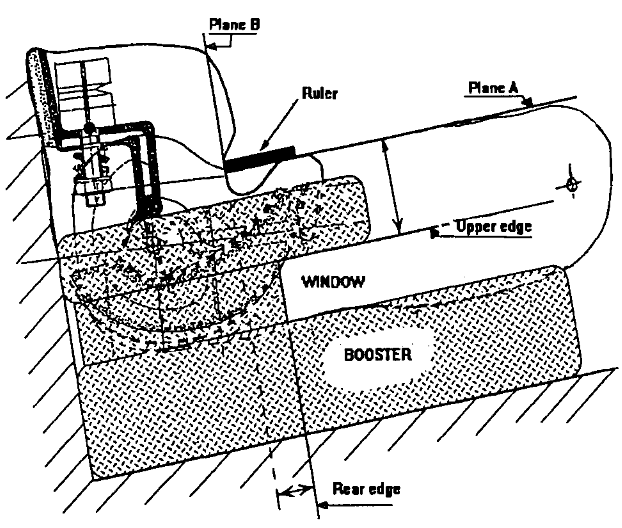
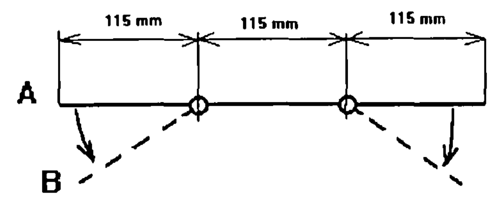


Figure 19 Definition of lap belt guide location zone for boosters

This ruler is provided with two pivot points enabling switchover from position A to position B.



Ruler

The ruler is positioned on the thighs with its edge bearing against plane B, or the rear edge of the window (figure 19).

Conformance of upper edge positioning
Criterion: The seat belt when taut will be flat on the thighs of the child if the upper edge of the window is located lower than the plane (A) tangent to the thighs, and the lower this edge is located the better the child will be restrained. Plane A is the maximum acceptable limit at which the upper edge of the window may be considered well positioned, i.e. at a maximum height of 90 mm relative to the ischia.
Verification: If the ruler can be positioned horizontally, then the criterion is not complied with and the positioning is considered incorrect.

Conformance of the window rear edge positioning -
Criterion: The rearmost limit is the plane tangent to the iliac spine of the pelvis of the 3-year-old child, i.e. 15 mm to the rear of plane B of the TNO P3 dummy. To avoid creating excessive play in the shoulder belt, moreover, the forward positioning of the rear edge of the window must be limited; a maximum authorized forward positioning of 40 mm relative to plane B is defined, corresponding to the position of the iliac spine of a 10-year-old child, i.e. a maximum forward positioning of 40 mm relative to plane B of the TNO P3 dummy.
Verification: If the ruler comes to bear against plane B it is verified that the distance X separating this plane B from the rear edge of the window is less than 15 mm. - If the ruler comes to bear against the rear edge of the window it is verified that the distance X separating this edge from rear plane B is less than 40 mm.

Conformity of the static procedure with the dynamic tests results: This criterion is complied with by boosters A, B, E and F for which the dummy sustains no stress applied by the lap-belt strap to the abdomen in dynamic testing. This criterion is not complied with when the dummy is seated on the bench seat or on boosters C and D; in these cases major stress applied by the strap to the abdomen is observed in dynamic testing.

CONCLUSION

The effectiveness of restraint systems designed for child passengers in motor cars is evaluated using dummies.

Based on anthropometric and radiological measurements this study aims to demonstrate that the present design of dummy pelvises is by no means representative of children aged between 3 and 10 years and under-estimates or even masks the risk of abdominal injury by seat-belt compression.

It is also demonstrated that the stiffness of the thighs and abdomen at the level of the iliac spine is excessive and therefore does not reproduce the interaction of the seat belt with these segments.

For these segments, shape and stiffness recommendations are suggested with a view to improving the biofidelity of 3-year, 6-year and 10-year impact test dummies.

Following these recommendations a prototype TNO P3 dummy was modified.

The dynamic tests with the modified dummy show a risk of abdominal injury by compression of the lap-belt strap for boosters available commercially and not equipped with a strap guide, or when the dummy is placed directly on the regulatory bench seat. This risk, inherent in the absence of or poor positioning of the strap guides, is not detected by tests with the regulatory dummy.

To help the booster designer, a positioning is recommended for the strap guide window relative to the child. A static verification method with the TNO standard P3 dummy is proposed. This method is by no means a substitute for dynamic tests to prevent the risk of abdominal injury, because in spite of correct positioning of the strap guide there may be a phenomenon of dummy submarining due to other factors (strap guide not strong enough, seating surface too flexible, etc.).

For tests with a good booster, one observes systematically that the strap glances off the shoulder; this glance-off is promoted, among other things, by the excessive thorax stiffness of the TNO P3 dummy.

In the future, therefore, some flexibility should be lent to the thorax, and this requires defining the crushing pressure characteristic of the children.

We believe that the position of the upper anchorage point used in the regulation 44-03 is a factor causing the shoulder strap to glance off the dummy when the dummy is placed on a booster; we believe that its relevance and its compatibility with good restraint of dummy 50th percentile should be verified.

Further tests are needed, on the one hand to assess the reliability of the load cell with a view to retracing unambiguously the abdominal risk, and on the other hand to identify the force threshold beyond which there is a danger for the child.

ACKNOWLEDGMENTS

We should like to thank Doctor Souchet and Professor Bensahel of the orthopaedic surgery ward of R. Debré Hospital, Paris, for their precious aid.

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The views expressed in this paper are those of the authors alone and should not be interpreted otherwise.

REFERENCES

(1) Beusenberg , Brun-cassan « Automotive accident and injury data of children - literature survey and database analysis »January 5, 1995 CDWG / N25-R

(2) Got , Analyse accidentologique de la protection des enfants dans les véhicules automobiles en france (1992 / 1993)- document interne

(3) Bastiaanse,Malta « Evaluation of the dynamic test requirements for child restraints according to the EEC 44 regulation » Proceedings of the 7th international Ircobi conference 1982

(4) Tarrière-Thomas-Cassan Got-Patel « From three years old to adult size - How to ensure child protection in automobile accidents.

(5) Kelleher-Walsch « Sled test-Comparisons of Child Restraint performance » Proceedings of the 22nd Stapp car conference - 1978

(6) Tarriere - « Securité des enfants en voiture - Nouveaux dispositifs de retenue » Journal de pédiatrie et de puericulture n° 2 - 1995.

(7) Tarriere - « Children are not miniature adults » Bertil Aldman lecture Ircobi conference 1995.

(8) INRETS paper presented at the STAPP AAAM IRCOBI specialist meeting on "Child occupant protection".

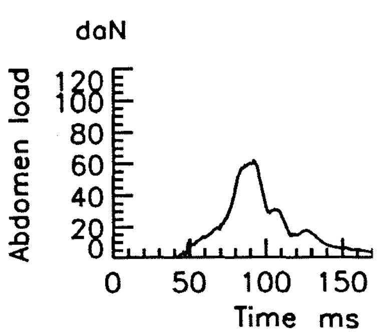
(9) Leung Action Thematique programmée - Sécurité des véhicules - Critère de sous-marinage Rapport final marché 78 043

Appendix 1 Results of ECE R44-03 type frontal impact tests with TNO modified P3 and standard P3 dummies

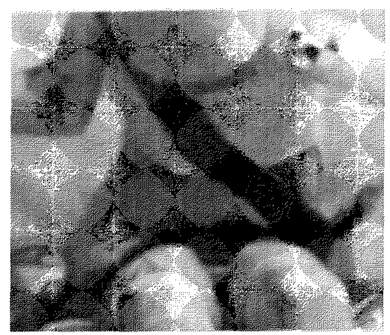
N°	HIC 36 ms	Resultant head acceleration (G)	Max. head excursion (X) point Cr (mm)	Resultant thorax accel. 3 ms (G)	Thorax accel. 3 ms vertical (G)	Pelvis accel. 3 ms vertical (G)	Initial position of lap-belt strap	Lap-belt movement during impact	Final position of the lap-belt strap	Strap glance-off from the shoulder
C1	734	84	300	65	33	31	Flat on the abdomen and the edge in contact with the thighs	The strap passes over the pelvis protuberance at T = 46 ms but continues to bear on the iliac spine	Flat on the abdomen and the edge in contact with the thighs	No
C2	441	63	310	42	19	21	Flat on the thighs and the edge in contact with the abdomen	The strap passes over the pelvis protuberance at T = 56 ms but remains flat on the thighs	Flat on the thighs and the edge in contact with the abdomen	Yes, at t = 60 ms
C3	666	87	282	43	23	23	Half-flat on the thighs and on the abdomen	The strap passes over the pelvis protuberance at T = 60 ms but remains flat on the thighs	Slipped between the abdomen and the pelvis protuberance with the edge in contact on the iliac spine	Yes, at t = 60 ms
C4	590	76	247	52	23	26	Flat on the abdomen and the edge in contact with the thighs	The strap passes over the pelvis protuberance at T = 51 ms but continues to bear on the iliac spine	Flat on the abdomen and the edge in contact with the thighs	No
C5	677	84	_	65	33	32	Flat on the abdomen and the edge in contact with the thighs	Major penetration by the strap in the abdomen and above the iliac crests (T = 48 ms) (see photo)	Strap found inserted in the abdomen and above the iliac crests, especially on the belt pulley side	No
C6	772	81	325	67	37	41	Flat on the abdomen and the edge in contact with the thighs	Major penetration by the strap in the abdomen and above the iliac crests (T = 61 ms)	Strap found inserted in the abdomen and above the iliac crests, especially on the belt pulley side	No
C7	406	73	353	40	23	25	Flat on the thighs and the edge in contact with the abdomen	The strap remains flat on the thighs throughout the impact	Flat on the thighs and the edge in contact with the abdomen	Yes, at t=60ms
C8	500	71	-	41	16	39	Flat on the thighs and the edge in contact with the abdomen	The strap remains flat on the thighs	Flat on the thighs and the edge in contact with the iliac spine	Yes, at t=50 ms
C9	905	87	244	52	32	37	Flat on the abdomen and the edge in contact with the thighs	Major penetration by the strap in the abdomen and above the iliac crests with strong pelvis rotation (see photo)	Strap found completely inserted in the abdomen and above the iliac crests	No
C10	696	86	293	52	23	35	Flat on the abdomen and the edge in contact with the thighs	Major penetration by the strap in the abdomen and above the iliac crests with strong pelvis rotation (see photo)	Strap found in the abdomen and above the iliac crests	No
C11	346	94	351	50	20	27	Flat on the thighs and the edge in contact with the abdomen	The strap remains flat on the thighs throughout the impact	Flat on thighs and edge in contact with the abdomen	Yes, at t=60 ms
C13	353	171	408	38	16	25	Flat on the thighs and the edge in contact with the abdomen	The strap remains flat on the thighs throughout the impact	Flat on thighs and edge in contact with the abdomen	Yes, at t=60 ms

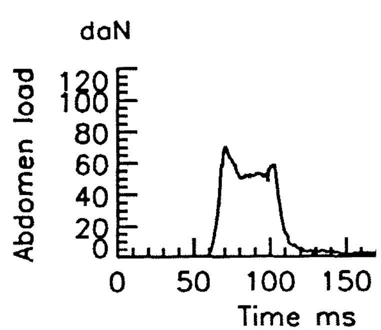
Appendix 2 - Hight speed movie showing the way of the lap belt before the test and at the time of the maximum load measured inside the abdomen of the TNO P3 modified

Test C5 - dummy seated on the bentch

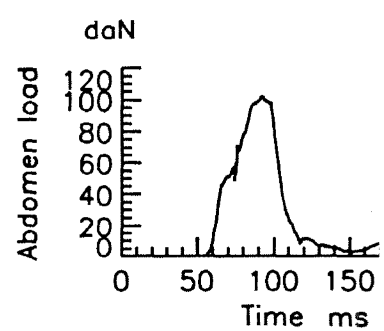


Test C7 dummy seated on the booster A (with lap belt guides)

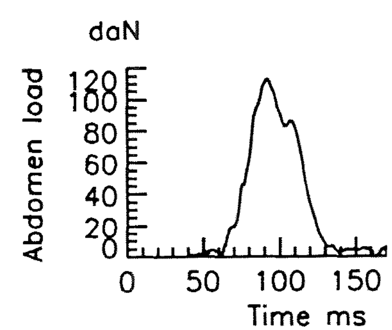




Test C9 dummy seated on the booster C (with lap belt guides)



Test C10 dummy seated on the booster D (with lap belt guides)



ADULT SEAT BELTS: HOW SAFE ARE THEY FOR CHILDREN?

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Paper Number 96-S7-O-04

ABSTRACT

Investigation of crashes involving 121 children aged up to 14 in adult three-point lap/shoulder (lap/sash) belts showed that irrespective of age they were generally well protected even in severe frontal crashes, and none sustained belt-induced inertial neck injury. The prime cause of injury among these children was contact with the interior surfaces of the car, predominantly in side impacts. Lap-belted children sustained a higher proportion of belt-induced abdominal injuries and a similar proportion of head injuries despite mostly being seated in centre positions away from the side of the car. Sled tests with 18-month, three-year-old and six-year-old dummies produced data consistent with the conclusion that adding torso restraint slightly increases the risk of minor (AIS 1 or 2) neck injury, but has the major benefit of reducing the risk of serious head and abdominal injuries. The conclusion of this work is that adult lap/shoulder belts do not present a significant risk of injury to young children.

INTRODUCTION

A point of interest for many years has been the extent to which children may be placed at risk by using adult belts, because of the incompatibility of the size and shape of the typical child with the geometry of the typical seat-belt installation.

In an early study of restrained children by the Traffic Accident Research Unit in New South Wales (Vazey, 1977), a selection of reasonably severe crashes involving 65 case occupants were examined to provide evidence that would address the question posed by Snyder and O'Neill (1975): *"Are 1974/1975 automotive belt systems hazardous to children?"*. At that time in the United States, and to a considerable extent even now in that country, few children were restrained in adult belts that had shoulder belts incorporated. In Australia, however, lap/shoulder belts had been required in outboard positions both front and rear since 1971, quite independently of mandatory-wearing requirements.

Snyder and O'Neill had noted that in Australia the original legislation requiring the use of seat belts did not apply to children under eight years, but they wrongly concluded that the reason was concern for the safety of children using adult belts. In fact, at least in NSW it was for administrative reasons associated with the age of legal responsibility, and soon all passengers over the age of one year had to be restrained in a seat belt, including an adult lap/shoulder belt for children if that was the only restraint available.

The conclusion of the 1977 NSW study and those that succeeded it (Corben and Herbert, 1981) was that in practice children appeared to be afforded good protection by adult three-point lap/shoulder (lap/sash) belts, even down to two years of age, as long as the restraint was properly adjusted. At that time few seat belts in the rear positions had automatically adjusting and locking retractors, whereas modern cars are now so equipped. When firmly restrained in well-adjusted belts, the children were found to withstand crash forces as well or better when wearing adult restraints than adults in the same car, even in crashes of 50 km/h change of velocity (delta-V).

The importance of this question has diminished over recent years with the ever-increasing availability and use of dedicated child restraints (including booster seats to be used with adult belts) that are much more appropriate for different ages and sizes of children. Nevertheless, many children still use adult belts alone, and clearly in many cases seat-belt restraint is not optimal for small occupants.

To review issues of child occupant protection, a field crash investigation study undertaken through 1993 was aimed at studying crashes involving vehicle passengers

aged 14 years or under.*

Table 1.
Summary of Results: NSW Study, All Restraints

	Child restraint		Lap/ shoulder belt		Lap-only belt		No restraint	
MAIS	N	%	N	%	N	%	N	%
0	28	39.4	11	9.1	5	14.3	0	0.0
1	30	42.3	83	68.6	21	60.0	6	31.6
2	7	9.9	13	10.7	3	8.6	3	15.8
3	1	1.4	7	5.8	2	5.7	5	26.3
4/5	2	2.8	1	0.8	1	2.9	0	0.0
6	3	4.2	6	5.0	3	8.6	5	26.3
Total	71	100.0	121	100.0	35	100.0	19	100.0
MAIS 2+	13	18.3	27	22.3	9	25.7	13	68.4

Among the main research questions were these:

- What injuries, especially to the neck, were occurring despite the use of restraints?
- How was restraint effectiveness related to the age of the children?
- How might effectiveness be improved?
- What were the effects of misuse, if any?
- In very severe crashes, which children were surviving, and why? Did their survival give any guidance on the tolerance to injury of children?

The study aim was to include for analysis the following cases:

- all fatally injured child occupants from throughout the State;
- any child occupant involved in a crash in which another occupant was killed anywhere in the State;
- and all child occupants presenting (but not necessarily admitted) to hospitals accepting trauma patients in the greater metropolitan Sydney area.

A summary of the results of this study is shown in Table 1.

It can be seen that throughout the entire sample of children, in all kinds of crashes, dedicated child restraints generally performed the best, followed by adult lap/shoulder belts and then by lap-only belts. As would be expected, children without restraints fared badly. Although this was not a random sample of crashes, the difference in injury risk between restraint and no restraint is of the same order of magnitude as shown in studies based on comprehensive statistical data.

Some of the results of the New South Wales field study in relation to dedicated child restraints have been reported previously (Henderson *et al*, 1994). The present paper focuses on the use of adult belts by children in the study. It describes the case histories of the most severely-injured children and also those who were not injured in severe crashes. The paper further adds data from a comparative series of laboratory sled tests using new-model child anthropomorphic dummies in adult lap/shoulder and lap-only seat belts. The dummies were made by First Technology Safety Systems. They represented children aged 18 months (CRABI dummy), three years and six years of age (Hybrid III).

THE FIELD STUDY: FACTORS RELATED TO INJURY SEVERITY

Belt Types in Use

It will be seen from Table 1 that in the sample of children aged 14 years or under entering into the Australian study, easily the commonest single type of restraint used was the lap/shoulder seat belt, without any kind of booster seat or cushion. This is not surprising, because the age range covered by this kind of restraint is much wider than that for child seats and infant capsules. There were 121 children in the study wearing lap/shoulder belts.

Thirty-five children were using lap-only belts. Since January 1971 all outboard seating positions in passenger cars sold in Australia have been required to be equipped with lap/shoulder seat belts. Thus, the only lap-only belts in the present sample were worn by children in centre-rear (23) and centre-front (4) positions, plus eight children lap-belted in third-row seats in multi-passenger vehicles.

* The study was performed by Michael Henderson Research and Roads and Traffic Authority personnel, in association with the Child Accident Prevention Foundation of Australia (CAPFA).

Table 2 summarises the maximum AIS (MAIS) score for children in the sample. It shows a lower proportion of MAIS 3-6 injuries among children using lap/shoulder belts rather than lap-only belts, but the difference is not statistically significant. The average MAIS for children in lap/shoulder belts was 1.405 (SD 1.262) and in lap belts 1.571 (SD 1.614).

Table 2.
Maximum AIS by type of seat belt

MAIS	0-2		3-6		Total
	N	%	N	%	N
Lap/shoulder belt	107	88.4	14	11.6	121
Lap belt	29	82.9	6	17.1	35
Total	136		20		156

Age and Injury Severity

Table 3 shows that six (5.0%) of the children using lap/shoulder belts were killed (MAIS 6), 21 (17.4%) suffered injuries with a maximum AIS of 2-4, and the majority (94, 77.7%) had injuries of AIS 1 or were uninjured.

Table 3.
Lap/shoulder Belts, Maximum AIS by Age of Child

Age (years)	MAIS						
	0	1	2	3	4/5	6	Total
< 3	1	5	0	0	0	1	7
4 - 6	1	15	2	1	0	1	20
7 - 9	6	21	4	4	0	1	36
10-14	3	42	7	2	1	3	58
Total	11	83	13	7	1	6	121

The ages of the 121 children using adult lap/shoulder belts ranged from one year to 14 (the sample maximum), with a mean age of nine. Table 3 indicates no relationship between age and injury as represented by maximum AIS. This is confirmed by correlation analysis (Pearson correlation r=0.003). This lack of correlation remains if the analysis is restricted to generally-frontal crashes with a principal direction of force between 10:00 and 2:00, and also if only crashes with a delta-V of over 45 km/h are analysed.

For 45 frontal crashes with known delta-V, there was also no correlation between age and the delta-V (r=-0.079). In other words, there was no suggestion that the younger the child, the lower the impact speed at which injury occurred.

Of the 121 children in lap/shoulder belts, 27 (22.3%) were aged six years or less, and would probably have been better served by a child restraint or a booster seat in combination with the adult belt. With such appropriate restraint, they might well have received no injuries at all. However, for this sample at least, they appear to have received as much benefit from the adult belts as older children.

The ages of the 35 children wearing lap-only belts ranged from two years to 14, with a mean of between eight and nine (see Table 4). Thirteen were aged two to six years, indicating that they were very small to have been restrained in any kind of adult belt. Relating maximum AIS to age, two of the 11 children (18%) aged five or under received MAIS 2+ injuries, and seven of the 24 (29%) aged six and over. The cell sizes are too small to read any significance into these figures.

Table 4.
Lap Belts, Maximum AIS by Age of Child

Age (years)	MAIS						
	0	1	2	3	4/5	6	Total
< 3	1	2	1	0	0	0	4
4 - 6	2	5	1	0	0	1	9
7 - 9	1	4	0	0	0	1	6
10-14	1	10	1	2	1	1	16
Total	5	21	3	2	1	3	35

Injury Severity by Body Region

Table 5 shows injuries by severity and body region for lap/shoulder belts, and Table 6 the same for lap belts. Many children sustained more than one injury, but only the two most severe injuries for each case have been included. For each kind of seat belt, the percentage of all children who sustained an injury to each body region is shown.

Thus, Table 5 shows that 16.5% of children wearing lap/shoulder belts sustained a head injury and Table 6 that 22.9% of those using lap-only belts did so, but that the majority of injuries were minor. There was a higher incidence of AIS 1 thoracic and neck injuries among lap/shoulder belt users, almost all being bruising from belt loads. However, shoulder belt loads did not result in any more than trivial injuries.

Table 5.
Two Most Severe Injuries by Body Region, Lap/shoulder Belts

AIS	1	2	3	4/5	6	Total	% in cases
Head	13	2	3		2	20	16.5
Face	23	3				26	21.5
Neck	12					13	10.7
Thorax	11		1	1	1	14	11.6
Abdomen	9	3	1			13	10.7
Spine	1	1			1	3	2.5
Extremities	19	12	1			32	26.4
External	31	1	1		3	36	29.7
Total injuries						156	
Total cases						121	

Table 6.
Two Most Severe Injuries by Body Region, Lap Belts

AIS	1	2	3	4/5	6	Total	% in cases
Head	5	1	1		1	8	22.9
Face	6		1			7	20.0
Thorax	1				1	2	5.7
Abdomen	7	2				9	25.7
Spine	1		1		1	3	8.6
Extremities	5					5	14.3
External	5	1		1	1	8	22.9
Total injuries						42	
Total cases						35	

There was a higher incidence of spinal and abdominal injuries among wearers of lap belts, although the numbers are too small to draw firm conclusions.

Crash Severity

In the case of lap/shoulder-belted children, for generally-frontal crashes with a principal direction of force between 10:00 and 2:00, the delta-V* ranged from 14 to 89 km/h, mean 44.5 km/h, SD 19.8 km/h. For these crashes, the delta-V was positively and significantly related to the MAIS for children in lap/shoulder belts ($r=0.438$, $p=0.003$).

For frontal crashes involving lap-belted children, the delta-V ranged from 11 to 77 km/h, with a mean of 44.8 km/h, SD 21.1 km/h. There was also a relationship between delta-V and MAIS, but it was weaker ($r=0.207$) and non-significant.

Seating Position

Those wearing lap/shoulder belts were evenly distributed through front passenger and the two rear outboard seating positions. For the whole sample, there was no significant relationship between MAIS and whether the child was seated in the front left position or in either of the two rear outboard positions.

Four children of the 35 wearing lap-only belts were in centre front seats, 23 in the centre rear, and eight children were in the third row of multi-passenger vehicles (six of these in outboard positions).

As would be expected, the risk of injury in side impacts is strongly related to the seating position. There were 14 children in lap/shoulder belts in side impacts who sustained injuries of MAIS 2 or more. Eleven of these children were sitting on the side of the impact, and only three on the other side. This difference is statistically significant ($p<0.05$).

Contact Points

Contact points (where identified) for the two principal injuries among children restrained by lap/shoulder belts are shown in Table 7 and for lap belts

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* The delta-V was calculated following measurements of vehicle crush and included scene data when available. Calculations were performed with the aid of the EDVAP vehicle analysis package (Engineering Dynamics Corporation, 1989).

in Table 8. Again, because of the rather small numbers of lap belted children in the sample, comparisons should be made with caution.

Table 7.
Contact Points for Two Most Severe Injuries, Lap/shoulder Belts

Body region	Point of contact						
	Seat belt	Wind-screen or pillar	Dash	Door or win-dow	Car seat	Glass	External to car
Head		3	2	4	2	1	1
Face		2	5	9	1	3	
Neck	5	1		1			
Thorax	10		1		1		
Abdomen	10			2			
Spine		1					
Extrem's	2		2	9	8	3	2
Totals	27	7	10	25	12	7	3

Table 8.
Contact Points for Two Most Severe Injuries, Lap Belts

Body region	Point of contact						
	Seat belt	Con-sole	Dash	Door or win-dow	Car seat	Roof	External to car
Head		1			4	1	1
Face		1		1	3		
Neck							
Thorax	1			1			
Abdomen	9						
Spine		1			1		1
Extrem's		2	1	1			
Totals	10	5	1	3	8	1	2

However, 20% of the lap-belted children (seven out of 35) sustained head contacts as opposed to about 11% (13 out of 121) of the lap/shoulder-belted children. Also, there was a higher proportion of belt-induced abdominal injuries among those using lap belts (nine out of 35, 26%) rather than lap/shoulder belts (12 out of 121, 10%).

CASE HISTORIES

Fatalities in Lap/shoulder Belts

The youngest child to be killed when wearing a lap/shoulder seat belt was riding in the front seat of a 1982 Toyota Cressida that ran heavily into the side of an oncoming out-of-control Chrysler Sigma on a country road, and after the crash ended up on its side. The Sigma caught fire as a result of the crash, and the fire spread in part to the Cressida. The child was a boy aged three years and eleven months. The delta-V was some 65 to 70 km/h. The child suffered AIS 6 internal thoracic and abdominal injuries, plus a fractured cervical spine at C1/C2. The female driver of the car was also fatally injured, with a fractured skull and internal abdominal injuries.

There was considerable distortion rearwards in the region of the A pillar on the passenger side. The child's head probably hit the windscreen, which had a bloodstained contact point. There were also contact marks on the lid of the glovebox. The seat belt showed evidence of heavy loading, unusual with a light child, and it is likely that the internal injuries were inflicted by the belt, possibly as he was partly ejected out of it. The crash was survivable in the absence of contact with internal surfaces, as shown by the fact that a five-year-old girl restrained by a lap/shoulder belt in the rear left seat suffered only minor concussion and belt bruising, and a nine-year-old girl similarly restrained in the right rear seat received only belt bruises.

This crash was the only one in which a child was killed in a frontal crash while wearing an adult three-point belt.

Four of the six crashes in which lap/shoulder-belted children were killed were side impacts associated with intrusion on the side the child was sitting, and the other was a rollover. In two of the side-impact crashes, the intrusion was very extensive and the crash probably unsurvivable in the child's seating position.

In the first of these two, an eleven-year-old girl was in the left rear seat of a 1981 Toyota Landcruiser. The car drifted off the left side of a country highway, came abruptly back on to the road surface and spun into the path of an oncoming van which hit at about 60 km/h. A

70-year-old female sitting next to her in the centre rear position was also killed, as was the adult male in the front passenger seat. A nine-year-old girl in the right rear seat survived with internal injuries. In the other case involving gross intrusion, an out-of-control utility truck impacted the left side of an oncoming Toyota Corolla at over 60 km/h. In the left rear seat was a 13-year-old boy who was killed immediately as a result of multiple skull fractures and brain tissue disruption.

Another death resulting from intrusion, following a side-swipe collision with a tree, was that of a 13-year-old boy who was sitting in the right rear seat of a 1989 Holden Commodore. Although the intrusion was not severe, the collision was at high speed and the impact sufficient to cause fatal chest injuries. Rather similar damage was caused to a 1971 Volkswagen 1500 Fastback sedan in a side-swipe collision with an oncoming panel van. A girl aged seven was seated in the right rear position, adjacent to the maximum point of intrusion, and she died from very severe head injuries. In this case there was conflicting evidence about belt wearing, as the car was carrying six people plus the driver, and the age of the vehicle made any loading marks on the dirt-impregnated seat belts impossible to detect. In any event, the configuration of the crash made that seating position probably unsurvivable, whether a seat belt was worn or not.

The only other death among children restrained by lap/shoulder belts occurred to a five-year-old boy who was ejected from the lap/shoulder belt in the right rear seat of a 1991 Toyota Landcruiser. Sadly, the child had shortly beforehand been using a booster seat in association with the restraint, but the booster was taken away to allow him to lie down on the rear seat, with effectively only the lap part of the restraint holding him in place. This was insufficient when the Landcruiser rolled after hitting a roadside rock face on a country highway, and he was ejected through the rear window of the vehicle. Two adults in the car, plus an eighteen-month-old girl in a child seat, all survived. The roof of the vehicle was distorted to some extent, but survival space was generally sufficient for all occupants.

Children Aged One to Four Years in High-speed Impacts

Although they would have been more appropriately seated in dedicated child restraints, some very small children using lap/shoulder belts in high-speed crashes nevertheless received only minor injuries.

The youngest was a one-year-old boy in the left rear position of a 1981 Ford Cortina that rolled in a single-vehicle crash on an open country road. There was extensive external damage to the car, and some distortion of the roof. However, both the one-year-old boy and his three-year-old sister, who was restrained in the right rear seat also with a lap/shoulder belt, escaped with minor bruising. A female adult sitting between them, restrained by a lap-only belt, died as a result of fracture dislocation of the cervical spine and disruption of the spinal cord, most probably as result of contact with the roof of the rolling car.

A girl aged two and a half years was in the left rear seat of a 1990 Daihatsu Charade that crashed head-on with a Nissan Patrol four-wheel drive. The delta-V was about 55 km/h. She suffered soft tissue neck injury that required admission for exclusion of cord injury, plus belt bruising on the left shoulder and both hips, but no more serious injuries. The restrained female driver sustained lacerations to the head and left knee, and a small child in a forward-facing child restraint was unhurt.

A slightly older child, a girl aged four survived a high-speed head-on crash in a Mitsubishi Sigma, with a delta-V of about 65 km/h, while seated in the front passenger seat. She received belt bruising only. The female adult driver suffered fractured facial and leg bones.

Children Aged Four to 14 Years in High-speed Impacts

Some older children also survived very destructive crashes in lap/shoulder belts. For example, there were two 10-year-old girls riding in a Mitsubishi Colt hatchback that came in to head-on collision on a country road with an oncoming Mazda RX7.

The delta-V was 65 to 70 km/h, and the driver of the Colt died from unsurvivable (AIS 6) chest and brain injuries. The child in the front passenger seat suffered no more than belt bruises, leaving loading marks on the webbing. The child in the rear seat did suffer abdominal injuries, but was discharged from hospital within three weeks.

A Toyota Tarago (Previa) multi-passenger vehicle was involved in a head-on collision with a truck at a delta-V of at least 60 km/h together with very extensive damage. In the third row of seats were riding, in the outboard positions, an eight-year-old girl and a ten-year-old girl. Both were wearing the available lap/shoulder

restraints. Also in the vehicle were three adults and a three-year-old boy in a child seat with harness. All three adults were killed, and all three children survived.

An older-style 1985 model Toyota Tarago drifted across to the wrong side of a country highway and hit a tree in the dead centre of the front of the vehicle. The delta-V was in the order of 60 km/h. The male driver suffered head injuries and fractured limbs, and the female front-seat passenger also received lower leg fractures. The vehicle was filled with eight children, in addition to the two adults in the front seats. Some of these children were unrestrained and lying on the floor, but four were wearing lap/shoulder seat belts. All suffered bruising from belt loading, and loading marks were apparent on the webbing. In addition, three of the children sitting in the outboard positions in the second and third row of seats - a male aged 13, another male aged 13, and a female aged 13 - received fractures to the limbs adjacent to the interior.

In addition, a female aged 13 sitting in the left outboard seat in the third row suffered a traumatic amputation of her left arm. The mechanism of this injury was not clear. The occupants in this crash survived the high deceleration loads but were injured by contact with the generally unyielding interior of this particular vehicle.

In yet another high-speed crash involving a carload full of children, a 1989 Toyota Landcruiser carrying two adults and five children slid off a dirt road and hit a tree at an angle that drove it into the left side of the car from the front left towards the vehicle's centre. The male adult in the front passenger seat was fatally injured, receiving chest and other critical injuries from the intruding tree. The female driver was injured by contact with the steering wheel and surrounding components. A 12-year-old female wearing a lap/shoulder belt was seated behind the front-seat passenger, and her pelvis was fractured from contact with the vehicle interior. A 16-year-old wearing a lap/shoulder belt in the right seat behind the driver was not significantly injured, with abrasions only. The remaining children were wearing lap-only belts, and will be described in the next section of this paper.

The only lap/shoulder belt-induced injury more than minor (AIS 1) was an AIS 2 haematoma of the liver received by an eleven-year-old male in the left rear seat of a 1972 Holden Torana. This ageing compact car did not have a locking retractor reel for the seat belt, and it is likely that the heavy belt loadings the boy received were as a result of wearing the belt rather loosely. The impact was dead centre front into a telegraph pole, with a delta-V in the order of 45 km/h.

As already noted, significant injury in the sample as a whole was more likely to be associated with side impacts than other configurations of crash. However, children wearing lap/shoulder belts survived some serious side impacts when seated away from the impacted side. Having gone through a red light, a 1990 Ford Falcon was hit heavily on the driver's side (right) door by a bus at a crossroad, and the driver was killed. The delta-V for the Falcon was around 50 km/h. A 14-year-old boy and a 10-year-old girl were in the front and rear left seats respectively, and suffered minor injuries only.

On the other hand, sitting adjacent to the impacted side in a pure side-impact collision was far more likely to result in injury. There were 14 seat-belted children injured (maximum AIS 2 or more, including fatals) in side impact crashes; eleven of the 14 were seated on the side of the main impact.

Lap-only Seat Belts

There were three fatalities among lap-belted children.

One of the children killed was a girl aged five and a half restrained in the centre rear seating position of a 1986 Toyota Cressida. Coming off a suburban medium-speed highway, the car hit a telegraph pole in the centre of the front of the car, with a resulting delta-V of about 45 km/h. Vehicle examination showed the lap belt to have been adjusted so that it would have been very loose for this child. Examination also showed the console between the two front seats to have been extensively damaged. In the frontal impact, the child received a pattern of injuries that is typical of lap-belt restraint in a frontal impact at more than a slow speed. She suffered minor facial injuries and some external leg injuries, probably from contact with the console. On the front and right and left sides of her hip were bruises and abrasions typical of lap-belt loading, and she had some associated internal haemorrhage between the bladder and the pubic symphysis. She died almost immediately from a fracture-dislocation of the second and third cervical vertebrae with associated cord damage, and the detail of the injury showed that this injury was caused by distraction of the spinal column.

In brief, this child was allowed to move forwards to an excessive extent by the loose lap belt, thus allowing head and face contact with the console in front of her.

She flexed violently over the lap belt, causing the bruising in the hip region and intra-abdominal injury. In the flexed position, her head was stretching the spinal cord as a result of the forces of deceleration, and this fact - in association, probably, with the relatively insignificant head contact - caused the distraction fracture-dislocation of the neck that was the fatal injury.

This was a survivable crash, giving rise only to moderate deceleration from the change of velocity. The driver suffered some lacerations to his face as he hit the windscreen, and a 13-year-old girl in the left outboard seat, in a lap-sash belt, suffered cracked ribs and bruising from belt loads.

Another death was an eight-year-old female who was seated in the outboard left seat of the third row of a light passenger-carrying van (a 1983 Holden Shuttle). The vehicle left a country road and rolled down a six-metre embankment. The damage to the vehicle indicated that during the roll the vehicle hit heavily on its left side towards the rear, causing some intrusion directly adjacent to the deceased child's seat. The girl died from severe pulmonary contusion affecting all parts of both lungs, probably in association with the vehicle damage in the region. Another child in the same vehicle, an 11-year old male in the outboard right seat in the third row, also wearing a lap belt, also suffered chest injuries that were not fatal.

In a crash that was essentially unsurvivable in the child's seating position, a 1975 Toyota Corona left an outer suburban road at high speed and half-rolled into a telegraph pole so that the pole deeply intruded into the roof of the car. A 13-year-old boy in the centre rear position died of multiple skull and facial fractures with associated brain damage.

Among those non-fatally injured in frontal crashes, in a very severe crash a girl aged 12 years was seated in the centre rear position of a 1983 Holden Statesman. The car drifted over to the wrong side of a country highway and collided head-on with an oncoming semi-trailer. The delta-V was in the order of 75 km/h, but with relatively low deceleration as the car under-rode the truck. Both adult front seat passengers were killed. The girl was wearing a lap-only belt, and received several facial fractures from contact with the console structure in front of her, and internal abdominal injuries from the lap belt. Her 18-year-old brother, in a lap/shoulder belt in the left rear position beside her, sustained minor chest and abdominal injuries from belt loading.

In the 1989 Landcruiser that hit a tree, to which reference has already been made in the section above, there were three children restrained by lap-only belts. A male aged 14 was in the centre seat of the bench immediately behind the front seats. He suffered moderate head and spinal injuries. In the third row of seats, another bench, were seated a 12-year-old boy on the left and a 13-year-old boy on the right. The first, seated adjacent to the intruding tree, suffered fractures to the skull and cervical spine. The other, seated away from the intrusion, received only left-side abrasions.

A 1989 Nissan Skyline collided with a cliff face at the side of the road. Three children were on the back seat, all restrained in available belts. The driver and the two children seated in the outboard rear positions (one a one-year-old in a child seat) received minor belt bruising only; the six-year-old boy in the centre rear position, however, was admitted to hospital with injuries to the bowel. The belt was apparently correctly adjusted.

A 14-year-old male was seated in the front centre passenger seat of a Toyota Landcruiser that was struck on its left side by an oncoming van, causing severe intrusion damage. He suffered internal abdominal injuries. Two adults (left front and centre rear) and a child (left rear) died in this crash.

SLED TESTING

In order to more clearly identify any differences between three-point lap/shoulder (lap/sash) and lap-only belts in their capacity to protect children in frontal impacts, a series of comparative sled tests was undertaken. These were all conducted on an MTS Monterey "Impac" rebound sled at a nominal delta-V of 48 to 49 km/h (30 miles/hr).* The configuration of this sled gives rise to a short-duration, near-sinusoidal pulse, with a rapid rise of acceleration. For the given delta-V, therefore, these tests represent a violent and rather "stiff" crash. The peak sled acceleration for all runs was within the range 26.8 g to 27.5 g, typically at 40 msec.

Three anthropomorphic dummies were employed, representing for the desired age ranges the most biofidelic examples currently available. All were manufactured by First Technology Safety Systems Inc, of Plymouth, Michigan. They were as follows.

* The original protocol required runs at 56 km/h, but calibration tests revealed the probability of damage to the dummies in the lap-belted configuration at this delta-V.

- CRABI ("Child Restraint Airbag Interaction") Eighteen-month Old Infant Dummy (Version 1).
- Hybrid III Three-year-old Dummy (prototype status, in verification testing stage, especially made available for this research by First Technology Safety Systems).
- Hybrid III Six-year-old Dummy (Model 127-0000).

Their basic dimensions are shown in Table 9.

Table 9.
Basic Dimensions, Child Dummies

Dummy	Weight		Erect sitting height	
	kg	pounds	mm	inches
CRABI 18-month Old	11.2	24.7	505	19.9
Hybrid III Three-year-old	14.5	32.0	546	21.5
Hybrid III Six-year-old	22.8	50.2	640	25.2

Each of the three dummies was tested with a lap/shoulder belt and a lap-only belt, with two sled runs for each configuration. The belt was replaced by a new one after each run. The acceleration/time characteristics of each run were measured by accelerometers mounted on the sled.

The lap/shoulder belt in each case was of running-loop configuration, with a dual inertia-locking and webbing-sensitive emergency-locking retractor (as required in Australian cars) mounted at the upper end of the shoulder belt. The positioning of the belt anchor points was in accordance with the requirements of Australian Standard 3629.1-1991, *Methods of testing child restraints; Part 1: Dynamic testing* (Standards Australia, 1991). This positioning is consistent with the Australian Design Rules for motor vehicle safety.

The seat used for the tests was a stylised generic rear passenger-vehicle seat, also in accordance with the requirements of Australian Standard 3629.1-1991. The base of this seat is a polyurethane slab, density 28-29 kg/m^3, 156 mm thick, on a rectangular frame. The seat back is 70 mm thick.

All three dummies were instrumented as follows:

- head acceleration: 3-axis accelerometers;
- upper neck forces and moments: 6-axis transducers;
- chest acceleration: 3-axis accelerometer;
- pelvis acceleration: 3-axis accelerometer.

In addition, the lumbar region of the 18-month CRABI carried a 6-axis transducer for forces and moments. Belt force transducers were mounted on the webbing straps and buckle mounts.

Sign conventions, head acceleration coordinates and data filter classes were as specified in SAE J211 (Society of Automotive Engineers, 1988). The condition of the dummies was monitored after each test by visual inspection and instrument checks. Faces were painted to detect contact points.

All runs were filmed by a stationary high-speed camera positioned to the side of the sled. The cameras were operated at 1000 frames per second.

Results of sled testing

The data on accelerations and loads are summarised in Table 10. Figures given there relate to those values suggested as being of primary importance to injury risk, and show each of the two runs for each configuration. The purpose at this stage of the research was simply to provide some base data comparing performance in lap/shoulder and lap-only belts.*

The *CRABI Eighteen-month-old* dummy was restrained by the lap/shoulder adult belt surprisingly well, although as might be expected the kinematics were far from satisfactory. The dummy still had considerable forwards rotation despite the upper torso remaining constrained by the shoulder belt.

When restrained by a lap belt, the dummy rotated much further forwards, so that the belt moved down on to the upper surface of the thighs. This allowed considerable excursion, and the dummy's head impacted the front of the seat, including the wooden frame supporting the 156 mm deep cushion. The result was a

* Fully detailed data from this series of sled runs will be published in a separate comprehensive technical report.

high resultant head acceleration and HIC value for both the lap-belt runs.

Table 10.
Summary of Principal Results, Lap/shoulder (L/S) and Lap-only Belts: Two Runs for Each Case (Figures Rounded to Nearest Whole Number)

	18-month-old CRABI		Three-year-old Hybrid III		Six-year-old Hybrid III	
	L/S	Lap	L/S	Lap	L/S	Lap
Head						
GRes (g)	87 88	135 391	72 79	184 189	140 84	339 474
HIC	1004 1056	865 2567	822 868	2196 2159	1488 1163	2753 3605
Neck						
Forwards shear +Fx (N)	53 87	1310 1310	44 85	906 1139	66 46	1001 1201
Rearwards shear -Fx (N)	-931 -951	-763 -790	-678 -790	-418 -548	-1430 -1290	-560 -685
Axial tension +Fz (N)	2168 2287	1816 2154	1665 1757	2128 2255	3090 2622	2496 3912
Forwards moment +My (Nm)	26 22	67 93	53 56	23 41	75 60	20 33
Chest						
-Gx (g)	-53 -51	-55 -76	-50 -55	-64 -63	-59 -53	-37 -54
Belts						
Lap (N)	1038 1069	1945 1910	2109 2025	3890 4017	3780 3117	6220 5918
Buckle (N)	3370 3333	2067 2048	4350 4349	3215 3261	710 1885	5176 5222
Shoulder (N)	2676 2754		2571 2760		4481 4366	

Lap belt loads were much higher in the lap-only configuration, as would be expected. Adding a shoulder belt about halved the loads on the lap belt.

Peak neck shear loads (+Fx and -Fx) were +1310 N for the lap-belted configuration and -951 N for the lap/shoulder belt. Axial tensile loads (+Fz) were slightly higher with the lap/shoulder belt, but forward neck bending moment (+My) lower with the lap/shoulder belt.

The *Hybrid III Three-year-old* was much better restrained by the adult belt than the smaller dummy. There was submarining to the extent that the lap portion of the belt rode over the rudimentary pelvic structure, but otherwise the dummy's motion was driven by its high centre of gravity consistent with a child of an equivalent age. The top mounting of the shoulder belt was high (as it is in passenger cars) in relation to the sitting height of the dummy, and the shoulder belt allowed considerable downwards motion of the dummy's torso as it moved forwards within it. However, the net excursion of the dummy head was within acceptable levels, and did not extend beyond the front of the seat base (410 mm from its angle with the seat back).

The Hybrid III three-year-old flexed sharply over the lap-only belt. In the first of the two runs in this configuration, the lap belt ruptured the dummy's vinyl "skin" on the abdominal region, between the pelvic and rib structures. In both the lap-belt runs the head of the dummy impacted the forward side of the seat and its base.

Lap belt loads were much higher with the lap-only belt than with the shoulder belt added.

Just as for the 18-month-old CRABI, head accelerations and +Fx neck shear loads were lower with the lap/shoulder belt, but -Fx neck loads were higher. The peak neck shear load was +1139 N for the lap-belt configuration.

Axial tensile (+Fz) neck loading was higher with the lap belt alone than with the lap/shoulder belt. The two lap/shoulder runs gave figures of 1665 N and 1757 N, and with the lap-only belt, the figures were 2128 N and 2254 N. The +My moment, however, was higher (at 53 and 56 Nm) with the lap/shoulder belt than the lap belt (23 and 41 Nm).

The *Hybrid III Six-year-old* was well restrained by the adult lap/shoulder belt, with acceptable excursion and kinematics generally. The rotation forward seen in the smaller dummies, with their relatively high centres of gravity, was not apparent.

With the lap-only belt, as with the other dummies,

there was sharp flexion and excessive head excursion. The dummy head struck the forward face of the rigid base of the seat with high resultant head accelerations and HIC values.

As with the other dummies, loads in the lap belt were nearly twice as high without a shoulder belt. In one run the lap belt became wedged between the ribs and the abdominal insert.

Head accelerations and HIC were higher with the lap belt, because of head strike. Neck +Fx shear was higher with the lap belt, and -Fx shear higher with the lap/shoulder belt. Axial loads were slightly higher with the lap/shoulder belt, contrary to the values for the three-year-old dummy.

In summary, head accelerations and HIC were higher with the lap belt, as were lap belt loads. Neck +Fx shear forces were all higher with the lap belt, but -Fx shear forces all lower. Results for +Fz axial tensile forces were mixed, none varying drastically from others. Results for forwards bending moment were also mixed, being higher with the lap/shoulder belt for the two larger dummies and lower with the smaller CRABI dummy.

DISCUSSION

Field and Statistical Studies

It is now well accepted that any child riding in a passenger vehicle should be restrained in dedicated restraint equipment of a type appropriate to the child's size and age. Surveys indicate that until the child weighs more than 36 kg, or has a sitting height of about 760 mm (roughly equivalent to an age of 11 or 12 years), the seat belt will not fit in an ideal manner (Klinich *et al*, 1994). However, the fact is that countless children worldwide, much smaller than this, commonly do ride in motor vehicles while restrained only by adult seat belts. It is a reasonable expectation that from time to time vehicles with children thus restrained will crash. It would be a matter of great concern if this mismatching led to a commensurate increase in risk of injury to the restrained child. As it happens, available epidemiological data do not point to restrained children of at least ten years or so being at especial risk (Evans, 1988). However, studies of the effects of adult belts on child injury reduction and injury patterns are rare, and predictions of injury risk (especially for smaller children) are based on a narrow knowledge base. This paper reports field and laboratory data that are intended to build on existing knowledge.

In the field study reported in part in this paper, the sample of children using adult lap/shoulder belts totalled 121. There were also 35 children in the study who were restrained by lap-only seat belts.

The prime cause of injury among children restrained by adult lap/shoulder belts was contact with the interior surfaces of the car, often in association with side impacts and related intrusion. The incidence of injury to the head and face was much the same among lap-belted and lap-sash belted children, but children using lap/shoulder belts in outboard positions received most of their head injuries by contact with the adjacent doors and window structures. Those wearing lap belts were mostly using centre seats, and sustained head and face injuries from the consoles and seat backs in front of them.

The incidence of injury to the heads and faces of lap-belted and lap/shoulder-belted children was comparable to that found by Khaewpong *et al* (1995) in a very similar field study in Washington D.C. Tingvall (1987), in Sweden, also found no difference in injury rate between children restrained by lap belts in the "safer" centre seat than in outboard seats with three-point belts. Further, using police-reported data in Canada, Chipman and Hu (1995) found that injury risk was similar in front seats (where shoulder belts are more common) and rear seats (where lap belts persist in that country).

However, several studies, including a recent one by Huelke and Compton (1994), have shown that rear seats represent a safer environment than front seats. Thus, if the injury-protective effect of lap/shoulder and lap belts was similar, rear-seat occupants should consistently be at lower risk of injury. This does not appear to be the case. In both the Australian and Swedish studies, because those wearing lap belts were using centre seats, many of the observed head injuries should have been preventable because upper torso restraint would have minimised the forward excursion that allowed contact with structures in front, such as consoles and front seats. Simply put, the net effect of the lap belt in terms of head-injury prevention appears to be that it nullifies the benefit of riding in the rear of a passenger vehicle.

The field study reported here, earlier Australian studies (Henderson *et al*, 1976), and recent studies of fatalities in the United Kingdom (Rattenbury and Gloyns, 1993) have all confirmed the overwhelming importance of head injury in determining the outcome for a restrained child in a crash. While protection of the

neck of the child is important, it is more important to limit the excursion of the head and upper torso. Where there is conflict between ways to bring about these aims, the protection of the head should take priority.

For an adult belt to be effective, of course, the child must be properly held within it. The field study did not find significant performance degradation from suboptimal repositioning of the seat belts by restless children. This is in contrast to suggestions by, for example, Agran and Winn (1988) and Meissner *et al* (1994). To the extent that repositioning occurs, it did not appear to affect protection to a significant extent; indeed, it should not, because an adequate restraint should be tolerant of minor "misuse".

The field study did disclose, however, deliberate degradation of the system by some adults. One fatality resulted from a child being removed by his adult carers from a booster seat and then being placed in only the lap portion of a lap/shoulder belt, from which he was ejected. Further, while as already noted the number of cars with manually-adjustable seat belts is these days very small, we did find one case of belt-induced abdominal injury in a child restrained in a manually-adjustable lap/shoulder belt that was being worn too loosely. A substantial benefit of the emergency-locking retractor reel is that it keeps the webbing in reasonable proximity even to the restless child.

Although the use of lap-only belts by children in our sample prevented many of them from more serious injury, the evidence of this study is that the lap belt is an incomplete restraint, to be used only when no better system is available. We found a significantly greater incidence of belt-induced abdominal injury among lap-belt wearers than lap/shoulder belt users, which supports the conclusion of Lane (1992) that the child in the centre seat (with a lap belt) is at significantly greater risk of seat-belt induced injury.

In addition, there is the additional factor that in Australian cars (unlike the typical American car, where lap belts are much more common and lap belts have retractors) the lap belt is almost always manually adjustable only. This compounds the problem of misuse by too easily allowing the belt to be worn loosely and thus increasing the risk not only of abdominal injury but also head injury through excessive excursion of the torso.

There has been a recent movement of some manufacturers, including major Australian ones in the mass market for family cars, away from the use of centre-seat lap belts and towards lap/shoulder belts. This provides more effective restraint for the very positions that children are most likely to use them, and thus maximises the benefit to any child of riding in the rear.

The Risk of Cervical Spine Injury

The alternative fitment of a lap/shoulder seat belt in the centre rear seat would provide better protection overall. However, some critics have suggested that to restrain the upper torso, especially that of a child, places the neck at greater risk than if the torso is allowed to swing unrestrained. Anatomical considerations (Burdi *et al*, 1969; Huelke *et al*, 1992), coupled with case reports of cervical spine injury to forward-facing children (Fuchs *et al*, 1989; Langwieder and Hummel, 1989; Huelke *et al*, 1992) have caused considerable international attention to be drawn to the issue of cervical and high thoracic spinal cord injury to infants and young children in forward-facing restraint systems.

However, data searches in Australia have failed to show that the lap/shoulder seat belt poses a significant threat to a child's spine. In any event, serious spinal injury is rare. In the United States, after reviewing about 60,000 crashes for 1980 to 1989 in the National Accident Survey Study (NASS) files, Huelke *et al* (1992) found only nine children aged 10 years or less who had a cervical spine injury of AIS 3 or greater. None were in a child restraint, three were wearing lap belts in the rear seat, and the others were unrestrained.

On the other hand, over the years Australian case histories have included a high proportion of well documented crashes, at much higher changes of velocity than the 48 km/h barrier equivalent, that did not result in more than minor cervical spine injury to children restrained facing forwards in adult belts or child restraints.

In the USA, Kelleher-Walsh *et al* (1993) also found no injuries to the cervical spine in their retrospective case review of 198 children injured in forward-facing child restraints. Other studies have indicated that although the use of some kinds of restraint can increase the overall risk of neck injury, such injuries are generally minor while there is a decreased risk of injury overall for both children (Agran and Winn, 1987; Norin *et al*, 1984) and adults (Bourbeau *et al* 1993). In particular, torso restraint of any kind appears to increase the risk of minor (AIS 1) injuries to the cervical spine as

a trade-off for improved protection from more severe injury (Yoganandan *et al* 1989).

Reporting a series of 66 deaths among children in the UK using adult lap/shoulder belts, Rattenbury and Gloyns (1993) found (while conceding the small number of cases) "little evidence of a major risk of life-threatening injuries being caused by the diagonal section of the adult belt, except perhaps for very young children . . . The authors' view is that direct belt induced neck injury for children in adult belts (with or without booster cushions) is not as great a problem as some people have feared".

The field study reported in the present paper has confirmed earlier findings from Australia and elsewhere that children - even very small ones - do well in severe crashes when using lap/shoulder seat belts, and that concerns about vulnerability based on purely anatomical considerations may be misplaced. This was also the case for child restraints (Henderson *et al* 1994).

In the present study, neck injury in children using adult lap/shoulder belts was not found to exceed very minor degrees of severity even when belt loadings had caused significant bruising of the soft tissues of the thorax and nearby neck. Although the field study did not on its own establish an upper limit of tolerance for cervical spine injury in restrained children facing forwards, it indicated that the limit may be higher than might be deduced from clinical studies of injured children. The present field study included children who were not significantly injured despite the severity of the crash, and who would not therefore have been included in the typical trauma system databases. To study only those children who are injured can obscure the beneficial effect of safety equipment and give a false impression of vulnerability.

There appears to be a difference between the incidence of cervical spine injury (without head contact) among children in child restraints in the United States and Europe on the one hand, and Australia (and perhaps the United Kingdom) on the other. A key difference is that most Australian child restraints have a high top tether. Without such a tether, as in most US and European child seats, the seat and child together can rotate forwards and subject the cervical spine to the axial tensile +Fz forces that result in the type of distraction injuries reported in most of their cases by Langwieder and Hummel (1989) and Huelke *et al* (1992). Brown *et al* (1995) recently described a series of tests with a six-month-old CRABI dummy, with and without high and low mounted top tether straps for a child restraint. They found that axial Fz forces were reduced 30-40% (as well as resultant neck forces) in the presence of a top tether that held the restraint and the child upright.

These findings initially appear to be contrary to those of Weber *et al* (1993) and Janssen *et al* (1993) that changing the parameters for child restraint mounting do not much affect values for neck forces. However, Australian child restraints have top tethers as an integral requirement, and the tethers for most restraints have (by good fortune) become high mounted. The seats cannot perform properly without them. In contrast, the comparisons of top tethers conducted by Weber and others used seats with *low mounted* top tethers. These seats were also capable of being restrained *without* top tethers.

The point of the findings of Brown *et al* (1995) is that more vertical restraint of a child's upper torso seems to result in reduced axial neck forces. However, the rigidity in fixation of a child restraint is probably an order of magnitude greater than an adult seat belt.

After analysing a selection of cases of real-world spinal cord injuries in children, Stalnaker (1993) concluded that as long as the injuries are not caused by external forces applied to the head, spinal column tension is by far the most important parameter for limiting distraction injuries for children of the age group he analysed, up to five years. Trosseille and Tarriere (1993) correctly complicate the issue by pointing out that different forces in different crashes involving children of different ages produce different injuries and thus lead to the definition of different tolerances. Nevertheless, although the relative importance of shear, compression and tensile forces in bringing about injuries to children's necks is yet to be fully elucidated, much contemporary work stresses the importance of axial tensile forces.

Unfortunately, the neck of the Hybrid III dummy - having been designed very much with flexion and extension as priorities (Deng, 1989) - is poorly biofidelic in regard to axial forces (Pintar *et al*, 1990). Essentially, it is too stiff. That could be one explanation for the rather similar and non-discriminatory values for +Fx tensile forces for all the sled tests for all three dummies reported in the present paper.

Sled test data for three dummies

To support and build upon the field data reported in this paper, the first objective of our related sled study was to assess the effects of using three-point lap/shoulder seat belts for the restraint of a selection of child anthropomorphic test dummies, in comparison with the effects under the same test conditions but using lap-only seat belts. (Later analysis in a technical report will discuss further the matter of injury tolerance.) Particular attention was paid to neck forces and seat-belt loads. This appears to be the first time that such direct comparisons have been undertaken in a systematic manner.

Until recently there have not been available sufficiently biofidelic child dummies to attempt crash simulation studies. However, an 18-month-old CRABI dummy is now available, as is an early model of the new Hybrid III six-year-old dummy. Further, the prototype Hybrid III three-year-old dummy became available in Australia for a limited period in early 1996 thanks to First Technology Safety Systems Inc, and was used for this research.

The sled test data for the three dummies showed mixed results for neck shear, axial tension and forward bending moment. Head accelerations and lap belt loads were consistently higher with the lap belt alone, with the shoulder belt sharing loads when used. In summary, accepting some inconsistencies in the results from dummy to dummy, the results are in accord with the field data: broadly, that in return for a greatly reduced risk of head and abdominal injury, a lap/shoulder belt may present a slightly higher risk of minor inertial neck injury, equivalent to AIS 1 or 2. However, there is nothing in this set of sled test results to indicate that adding a shoulder belt to a lap belt places a child at a higher risk of serious neck injury.

There have of course been several previous studies of neck loads on impact, intended at least in the early stages to develop neck tolerances for adults. The work with adult volunteers and cadavers by Mertz and Patrick (1971) indicated a risk of injury with a bending moment in flexion of 189 Nm, with a possibility of muscular injury at lower levels. For tensile loading these authors suggested a tolerance of 1160 N during postero-anterior acceleration of the torso, in rough accordance with the conclusions of Sances *et al* (1982). Shea *et al* (1991) reported a tensile load to failure of about 500 N in the absence of muscle tone. Mertz has summarised tolerance levels for several neck values in order to evaluate the responses of the Hybrid III (adult) dummy (Mertz, 1984).

Turning to children in child restraints (as opposed to adult belts), Weber *et al* (1993) used a six-month-old CRABI dummy (7.8 kg) in reproducing a crash of 50 km/h delta-V in which a six-month-old child had sustained a spinal cord contusion at T2. The child seat had been used without an effective top tether. They recorded a resultant force in the upper neck of 1260 N and in the lower neck 1159 N. The resultant moments were -6 Nm in the upper neck and 45 Nm in the lower neck.

Planath *et al* (1992) reported data following reconstruction on sled runs of crashes involving two children sustaining fatal head/neck injuries in forwards-facing child seats. The forwards-facing sled tests were performed with a Type P572C (Hybrid II) three-year-old dummy with a replacement neck that could be instrumented at the craniocervical junction (upper neck). Runs were at 40 km/h and 50 km/h, but sled g levels were not reported. The 50 km/h runs reproduced a crash with a 15-month-old child in a forwards-facing child seat. The child sustained fatal brain contusion without skull fracture, and no neck injury. The average figures for the tests were for HIC 809, shear (Fx) 280 N, tension (Fz) 2570 N, and flexion (My) 33 Nm.

Planath *et al* also brought together data from sled tests with rearwards-facing seats, plus data from scaling down data for adults. In addition, they noted the work on child/airbag interactions of Prasad and Daniel (1984) and Mertz and Weber (1982) with matched sets of tests with a three-year-old "airbag dummy" and piglet child surrogates.

The synthesis of all these data led them to conclude that the following values could be used as guidelines for neck protection criteria for assessment of the risk of neck injury for a child of about four years of age: tensile axial force, 1000 N; shear force, 300 N; forward bending moment, 30 Nm.

Janssen *et al* (1993) used similar reconstruction and scaling techniques, and employed a TNO 3/4 (9-month-old, 9 kg) dummy for their series of sled runs. The neck of the standard TNO dummy cannot be instrumented, and it was modified for this research. The restraint system was a four-point child harness in a child seat in all cases. They proposed maximum shear and tension forces for guidelines for protection criteria for children

through all age ranges. For a three-year-old, the suggested maxima for neck tension and shear would be about 1000 N, and for bending moment about 30 Nm.

Trosseille and Tarriere (1993), again using crash reconstruction techniques (four crashes, including one also used by Weber in her work), found for six-month-old children no injury under Fx 950 N and My 41 Nm, but injury over Fz 1200 N. They note the importance of obtaining data from *uninjured* children, which we also stress. They agree with Planath's (1992) suggestion of a limit of Fx of 300 N for three-year-old children, but note the substantial and rapidly-changing influence of age: there were children of 4.5 years who sustained no injury with Fx of 750 N. They also found no injury at Fz of 2500 N for this age group, and suggest further work to explain this.

Planath *et al* (1992) cautiously suggest that their figures might be unduly conservative. Further, Janssen *et al* point to the fact that measures taken to lower neck forces might increase excursion of the restraint and the child and thus the risk of head injury.

All the research groups noted above stress the dangers in comparing results from different dummies, and variations in design could explain some of the differences between dummies that we found. There is also the matter of time dependency. There is general agreement in the literature that there will be a higher tolerance to forces of very short duration, usually published as "peak" forces, whereas forces applied over 30 msec or more would have a better association with injury tolerance. We support all the above cautions.

Relating Field and Laboratory Data

Generally, the values for force and bending moment in our sled test series were high in comparison with other research. However, in our field data there were 19 children aged two years to 14 who were restrained in lap/shoulder belts in generally frontal crashes at a calculated delta-V of 45 km/h or over (see Table 11). More than two-thirds of these children (13) were in frontal crashes of 65 km/h or over, which gives some allowance for errors in delta-V calculations. It is probable, therefore, that all these children were exposed to forces of the same order of magnitude that we found in our series of sled runs, generally above the tolerance criteria suggested for guidance by Planath *et al* (1992) and other workers.

Yet, among these children there was only one neck injury of AIS 3 or more. This AIS 6 (fatal) injury in a three-year-old directly resulted from a heavy head contact with the windshield, and was described in this paper among the case histories. The other neck injuries were all AIS 1 or 2, being soft tissue injuries commonly associated with bruising and abrasions from belt loading.

In their crash reconstructions, both Planath *et al* (1992) and Trosseille and Tarriere (1993) recorded neck tensile (Fz) forces of over 2.5 kN when no neck injuries had been sustained in the real crashes. Although we did not make direct comparisons of individual crashes with individual sled runs for the purpose of this paper, these relationships are in accordance with our observations.

Table 11.
Lap/shoulder belts, frontal crashes with delta-V of 45 km/h or more

Age (years)	Maximum AIS 0 - 2	Maximum AIS 3 - 6	Total
< 3	1	1	2
4 - 6	2	0	2
7 - 9	4	1	5
10 - 14	8	2	10
Total	15	4	19

This is not, of course, to suggest that children's necks are immune from inertial injury in high-speed frontal impacts. This is manifestly not the case. Much larger studies, including *uninjured* children, are required properly to assess the degree of risk. But it may well be the case that some of the crash reconstruction studies in the literature, being based on children whose spines were known to have been severely injured, are consequently based on outlier cases involving crash-related or child-related factors not typically representative.

The spine and the head together make up an exceedingly complex system, and spinal injury mechanisms are sensitive to countless variations in the way that potentially injurious loads are applied. There is a very great deal of work yet to be done before tolerance levels for the cervical spine can be firmly established, and in respect to children this work is at a very early stage. Children, by definition, are growing up quickly and tolerances may be expected to change year by year for each child, yet vary from child to child at a given

age. The problems are compounded by the difficulties in performing cadaver experimentation with children, and there have only recently been improvements in the biofidelity of test dummies. Animal models are generally inappropriate, and now rarely used. Thus, field and epidemiological research has a particularly important part to play.

There are many more head than neck injuries in the data from field studies. Lap-belt-induced injury of the abdominal organs and lumbar spine are also far more common than inertial injuries to the cervical spine. In the development of design or performance criteria, for the minimisation of the risk of cervical spine injury it is important not to unreasonably raise the risk of other serious injuries.

SUMMARY

To obtain maximum protection, children should be restrained in dedicated child seats, or adult belts supplemented by booster seats, until they are of a size appropriate to the use of adult belts.

However, field data from investigating crashes involving 121 children aged one to 14 years in adult lap/shoulder belts show that they were generally well protected even in severe frontal crashes, and none sustained belt-induced inertial neck injury. Change of velocity was related to injury risk, but age was not.

Lap-belted children sustained a higher proportion of abdominal injuries and a similar proportion of head injuries despite almost all being seated in centre positions away from the side of the car.

A series of sled runs with 18-month, three-year-old and six-year-old new-generation dummies showed generally slightly higher values for neck shear forces and moments among those using lap/shoulder belts, but much lower values for abdominal belt loads and head accelerations. These data were consistent with the conclusion that adding torso restraint slightly increases the risk of minor (AIS 1 or 2) neck injury, but has the major benefit of reducing the risk of serious head and abdominal injuries.

The analysis of field data based on uninjured as well as injured children should lead to the derivation of realistic tolerance criteria, whereas the use only of injured children can lead to over-conservative estimates.

Present data indicate that adult lap/shoulder belts do not present a significant risk of severe injury to young children.

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REFERENCES

Agran P F and Winn D G , Injuries Among 4 to 9 Year Old Restrained Motor Vehicle Occupants by Seat Location and Crash Impact Site, in *Proceedings, 32nd Annual Conference, Association for the Advancement of Automotive Medicine*, Seattle, AAAM, 1988.

Agran P F , and Winn D , Traumatic Injuries Among Children using Lap Belts and Lap/shoulder Belts in Motor Vehicle Collisions, in *Proceedings, 31st Annual Conference, American Association for Automotive Medicine*, New Orleans, AAAM, 1987.

Bourbeau R, Desjardins D, Magg U and Laberge-Nadeau C, Neck injuries among belted and unbelted occupants of the front seat of cars, *The Journal of Trauma*, 35(5):794-799, 1993.

Brown J, Kelly P, Griffiths M, Tong S, Pak R and Gibson T, The Performance of Tethered and Untethered Forward Facing Child Restraints, in *Proceedings, 1995 International IRCOBI Conference on the Biomechanics of Impact*, IRCOBI, September 1995.

Burdi A R, Huelke D F, Snyder R G and Lowrey G H, Infants and children in the adult world of automobile safety design: paediatric and anatomical considerations for design of child restraints, *Biomechanics*, 2: 267-280, 1969.

Chipman M L and Lu X, The Effectiveness of Safety Belts in Preventing Fatalities and Major Injuries Among School-aged Children, in *39th Annual Procceedings, Association for the Advancement of Automotive Medicine*, AAAM 1995.

Corben C W and Herbert D C, *Children Wearing*

Approved Restraints and Adults' Belts in Crashes, Traffic Accident Research Unit, Report 1/81, Department of Motor Transport, NSW, 1981.

Deng Y-C, Anthropomorphic dummy neck modelling and injury considerations, *Accident Analysis and Prevention*, 21(1): 85-100, 1989.

Evans L, Risk of fatality from physical trauma versus sex and age, *Journal of Trauma*, 28: 368-378, 1988.

Fuchs S, Cervical spine fractures sustained by young children in forward-facing car seats, *Paediatrics*, 84(2), 1989.

Henderson J M, Herbert D C, Vazey B A and Stott J D, Performance of Child Restraints in Crashes and in Laboratory Tests, in *Proceedings, Seat Belt Seminar*, Melbourne 1976, Commonwealth Department of Transport, Canberra, 1976.

Henderson M, Brown J and Paine M, Injuries to Restrained Children, in *38th Annual Proceedings, Association for the Advancement of Automotive Medicine*, Lyon, AAAM 1994.

Huelke D F, Mackay G M, Morris A, and Bradford M, Car Crashes and Non-Head Impact Cervical Spine Injuries in Infants and Children, SAE 920562, in *Proceedings, SAE International Congress*, Detroit, Society of Automotive Engineers, Warrendale PA, 1992.

Huelke D F and Compton C P, The Effects of Seat Belts on Injury Severity of Front and Rear Seat Occupants in the Same Frontal Crash, in *38th Annual Proceedings, Association for the Advancement of Automotive Medicine*, Lyon, AAAM 1994.

Janssen E G, Huijskens C G, Verschut R and Twisk D, Cervical Spine Loads Induced in Restrained Child Dummies II, SAE paper 933102, in *Child Occupant Protection*, SAE SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Kelleher-Walsh B, Walsh M J, States J D and Duffy L C, Trauma to Children in Forward-Facing Car Seats, SAE paper 933095, in *Child Occupant Protection*, SAE SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Klinich K DeS, Pritz H B, Beebe M S and Welty K E, Survey of Older Children in Automotive Restraints, SAE 942222, in *Proceedings, 38th Stapp Car Crash Conference*, Society of Automotive Engineers, Warrendale PA, 1994.

Khaewpong N, Nguyen T T, Bents F D, Eichelberger M R, Gotschall C S and Morrissey R, Injury Severity in Restrained Children in Motor Vehicle Crashes, SAE 952711, in *Proceedings, 39th Stapp Car Crash Conference*, Society of Automotive Engineers, Warrendale PA, 1995.

Lane J C, *The Child in the Centre Seat*, Monash University Accident Research Centre, for the Federal Office of Road Safety, Report CR 107, Department of Transport and Communications, Canberra, 1992.

Langwieder K, and Hummel T, Neck Injuries to Restrained Children, in *Proceedings, Annual Conference of the International Research Committee for the Biokinetics of Impact: Workshop on the Future of Child Restraints*, 1989.

Meissner U, Stephens G and Alfredson L, Children in Restraints, in *38th Annual Proceedings, Association for the Advancement of Automotive Medicine*, Lyon, AAAM 1994.

Mertz H J and Patrick L M, Strength and Response of the Human Neck, SAE 710855, in *Proceedings, 15th Stapp Car Crash Conference*, Society of Automotive Engineers, Warrendale PA, 1971.

Mertz H J, *Injury Assessment Values Used to Evaluate Hybrid III Response Measurements*, General Motors Corporation, 1984.

Mertz H J and Weber D A, Interpretations of the Impact Responses of a 3-year-ol Child Dummy Relative to Child Injury Potential, *Proceedings, 9th International Technical Conference on Experimental Safety Vehicles*, Kyoto, 1982.

Norin H, Carlsson G and Korner J, Seat Belt Usage in Sweden and its Injury Reducing Effect, in *Advances in Belt Restraint Systems Design Performance and Usage*, P-141, Society of Automotive Engineers, Warrendale PA, 1984.

Pintar F A, Sances A, Yoganandan N et al, Biodynamics of the Total Human Cadaveric Cervical Spine, SAE 902309, *Proceedings, 34th Stapp Car Crash Conference*, Society of Automotive Engineers, Warrendale PA, 1990.

Planath I, Synthesis of Data Towards Neck Protection Criteria for Children, in *Proceedings, 1992 International IRCOBI Conference on the Biomechanics of Impact*, IRCOBI, September 1992.

Prasad P and Daniel R P, A Biomechanical Analysis of Head, Neck and Torso Injuries to Child Surrogates Due to Sudden Torso Acceleration, SAE 841656, *Proceedings, 28th Stapp Car Crash Conference*, Society of Automotive Engineers, Warrendale PA, 1984.

Rattenbury S J and Gloyns P F, A Population Study of UK Car Accidents in Which Restrained Children Were Killed, in *Child Occupant Protection*, SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Sances A Jr *et al*, *Head and Spine Injuries*, AGARD Conference on Injury Mechanism, Prevention and Cost, Koln Germany, 1982; cited in McElhaney J H and Myers B S, *Biomechanical Aspects of Cervical Trauma*, in *Accidental Injury: Biomechanics and Prevention*, Nahum and Melvin (Editors), Springer-Verlag, 1993.

Shea M, Edwards W T, White A A and Hayes WC, Variations of stiffness and strength along the human cervical spine, *Journal of Biomechanics*, 24(2):95-107, 1991.

Snyder R G and O'Neill B, Are 1974/1975 automotive belt systems hazardous to children?, *American Journal of Diseases of Children*, 129: 946., 1975.

Society of Automotive Engineers, *SAE J211, Instrumentation for Impact Tests*, SAE 1988

Stalnaker R L, Spinal Cord Injuries to Children in Real World Accidents, SAE paper 933100, in *Child Occupant Protection*, SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Standards Australia, *Methods of testing child restraints; Part 1: Dynamic testing, Australian Standard 3629.1-1991*, Standards Australia and Standards Association of New Zealand, North Sydney, NSW, Australia, and Wellington NZ, 1991.

Tingvall C, Children in Cars, Some Aspects of the Safety of Children as Car Passengers in Road Traffic Accidents, *Acta Paediatr. Scand., Suppl.*, 339: 1-35, 1987.

Trossielle X and Tarriere C, Neck Injury Criteria for Children from Real Crash Reconstructions, SAE paper 933103, in *Child Occupant Protection*, SAE SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Vazey B, *Child Restraint Field Study*, Traffic Accident Research Unit Report 7/77, NSW Department of Motor Transport, 1977.

Weber K, Dalmotas D and Hendrick B, Investigation of Dummy Response and Restraint Configuration Factors Associated with Upper Spinal Cord Injury in a Forward-Facing Child Restraint, SAE paper 933101, in *Child Occupant Protection*, SP-986, Society of Automotive Engineers, Warrendale PA, 1993.

Yoganandan N, Haffner M, Maiman D J et al, Epidemiology and Injury Biomechanics of Motor Vehicle Related Trauma to the Human Spine, in *Proceedings, 33rd Stapp Car Crash Conference*, Society of Automotive Engineers, 1989.

EFFECT OF HARNESS MOUNTING LOCATION ON CHILD RESTRAINT PERFORMANCE

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ABSTRACT

This paper details an experimental investigation into the effect of harness mounting height, relative to the occupant's shoulders, on the performance of forward facing child restraints in frontal impacts. Child restraints typically feature a range of mounting slots for locating the restraint harness in the seat back. There had been speculation that, in frontal crashes, excessively low harness mountings could lead to an increased risk of spinal injuries.

The experiments conducted for this project showed that, when compared to results for harness slot positions at shoulder level, lumbar compressive forces were significantly larger for harness slot heights below the dummy's shoulders. However, these lower mounting positions produced lower head and neck loads. In all cases, higher mounting positions better limited the dummy's head excursion. All tests were performed twice, and repeatability between identical tests was better than that typically quoted for such experiments.

This project establishes a link between the restraint harness mounting height and the level of protection offered to the occupant's spine, head and neck. It recommends that a mounting height at the level of the child's shoulders offers the best overall protection in a frontal impact. It also recommends that the Australian Standard AS 1754-1991 should be amended, to increase the minimum height of mounting slots. These recommendations may need to be modified in the future as a result of further research in child biomechanics.

INTRODUCTION AND OBJECTIVES

Forward-facing child restraint systems are used in motor vehicles around the world for child passengers aged from six months to approximately four years. The devices aim to restrain children securely and comfortably during journeys, and to provide protection in impacts. Individual countries have developed their own design and performance requirements for the systems, based on dynamic testing. However, because of a lack of research, no country has a comprehensive set of performance-based child restraint design requirements, detailing allowable sizes and configurations of restraint components.

The design of most child restraints incorporates a capacity to adjust the mounting height of the shoulder belts of the harness, by threading the belts through one of a number of available slots. This is to allow the restraint to accommodate children as they grow. However, it is unclear which harness mounting location, in relation to the child's shoulders, provides the greatest protection in the event of an impact. Child restraints demonstrate varying philosophies as to restraint harness mounting position. Some restraints feature particularly high mounting slot locations, while others locate their slots low down in the seat back. However, slot locations have traditionally been a result of marketing demands rather than the requirements of child safety.

There has been speculation that the geometry of the child restraint harness has an important determining effect on the injuries suffered by children in motor vehicle crashes. In particular, it is suspected that very low harness mounting locations can cause excessively high compressive forces in an occupant's shoulders, torso and lumbar spine. The effect of the harness mounting height on protection to other areas, such as the head and neck, is unknown. No specific research had been conducted to establish whether or not there is a connection between harness geometry and specific child injuries.

This paper describes a testing and analysis programme to investigate the effects of child restraint harness mounting height relative to shoulder height on the level of protection provided to child occupants in frontal impacts. This programme seeks to establish a link between harness mounting height relative to shoulder height and the severity of lower spinal, head and neck loads experienced by dummies in frontal impacts. This information should lead to a recommendation on a suggested optimum mounting position for child restraint shoulder straps, to maximise overall child protection.

BACKGROUND

Child Restraint Design

The absence of firm guidelines for child restraint design means that available restraints display diverse design philosophies.

Standards and Rules - Child restraints in Australia must conform to the Australian Standard AS 1754-1991. As well as outlining the dynamic tests a restraint must pass before it can be offered for sale, the Standard also sets out a range of maximum and minimum sizes for some child restraint components (See Figure 1).

The rules regulating the height of the harness mounting slots are of particular interest to this project. AS 1754-1991 states that the lowest harness slot must be located at least 250 mm up the seat back, while the highest harness slot must be at least 365 mm up the seat back.

Differences in Child Restraint Design - Because of different regulations in force in different countries, child restraint designs vary significantly around the world. Table 1 lists some important design parameters that affect the performance of child restraint systems.

Table 1. Design factors affecting child restraint performance

- Attachment of top tether strap
- Recline angle of seat back
- Harness mounting location
- Method of attachment to vehicle

The top tether strap is a child restraint feature that is mandatory only in Australia and Canada. The mounting positions of the top tether strap vary among restraints, from midway up the restraint back to the very top of the restraint. Likewise, the angle of recline of the seat back varies considerably among designs. Some restraints feature a near-vertical seat back, while others recline considerably. Available harness mounting positions on child restraints also span a broad range. Some manufacturers set the harness mounting slots high up the seat back, while others use a lower range of slots. These design parameters all potentially influence the protection afforded by child restraints to children in impacts.

Recent studies have investigated the effect of the use of the top tether strap and of different rigid and flexible restraint mountings on child restraint performance. Research into the effects of these different designs on occupant protection will help legislators and manufacturers understand how to design child restraints that optimise the protection provided for children in crashes.

Injuries Suffered by Restrained Children

In Australia, most children properly restrained in child restraints avoid serious injuries in crashes. The most common injuries are bruises, abrasions and lacerations. A study by Henderson* showed that, in 1993, five children in Australia were seriously injured in forward-facing child restraints. However, in each of these cases, gross misuse of the child restraint was a major contributing factor. More significantly, a number of children restrained in forward-facing child restraints were able to survive severe frontal crashes in which other occupants, both adults and children restrained by adult seat belts, were killed. This demonstrates the significant level of protection offered to Australian children by properly used child restraints, and the superior level of ride-down provided by child restraints compared to adult seat belts. The study found that none of the properly restrained children suffered neck injuries

* Henderson, 1993

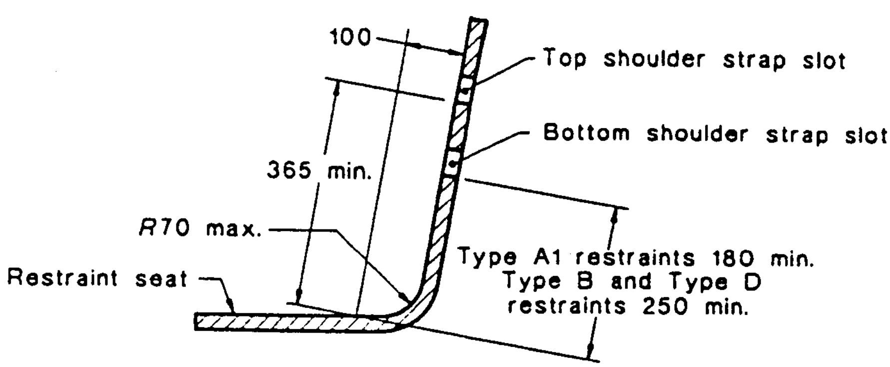


Figure 1. Dimensional restrictions on the design of Australian child restraints, as required by AS 1754-1991

in the accidents. Statistics on child accident deaths since the early 1980's* showed that fatalities are caused almost exclusively by intrusion into the occupant space or head strikes to the vehicle interior. The only injuries caused purely by deceleration in Australia were bruising and abrasions from the restraint harness. These findings suggest that a restraint that effectively limits a child's head excursion in a crash protects the child significantly from life-threatening injury.

Outside Australia, head injuries account for the majority of serious injuries**. The injuries range from bruising and lacerations to severe brain damage and skull fractures. A study in Germany by Langweider showed that head injuries are predominantly caused by intrusion into the occupant space, by the occupant's head striking the vehicle interior, and by flying debris. Unrestrained children also typically suffered a range of injuries to the extremities. There have however also been a number of cases of properly restrained forward-facing children suffering cervical spine injuries. The majority of these neck injuries are minor, but there have been several cases in which restrained children have suffered serious neck injuries.

Clearly, child restraints that effectively limit head excursion without imposing excessive loads on the head and neck offer significant protection in accidents.

METHOD

This investigation into the effect of harness mounting location on child restraint performance took the form of a series of experiments on the crash testing sled at the Crashlab research facility in Sydney, Australia. Sled testing was preferred to full scale testing because of its greater repeatability and its lower cost structure.

Testing Impact - The testing program investigated the response of dummy and child restraint systems to a regulated frontal impact. The chosen impact featured a velocity change of around 48 km/h, and a half-sine acceleration profile with a peak of approximately 28 G. Such an impact represents a relatively heavy frontal accident, and is the same as used in previous child restraint research projects at Crashlab. This allows comparison between results from this and other projects. This impact is also the testing pulse specified by the Australian Standard for child restraint testing.

Test Dummy Selection - CRABI six-month and eighteen-month anthropomorphic test dummies were used to simulate the occupant behaviour in the experiments. CRABI dummies offer facilities for comprehensive instrumentation, and child restraint users in the six to eighteen month age range are most relevant for research. Moreover, the use of two dummies in this investigation allows more general conclusions and recommendations than would otherwise be possible. Accelerometers and load cells measured accelerations in the head, chest and pelvis of the dummies, as well as forces and moments in the neck and lumbar spine regions. High-speed cameras were mounted on the sled to capture details of dummy motion.

Child Restraint Selection - The restraints used in the testing programme were the Australian Safe'n'Sound Series III device by Britax, and the Securé CS4 unit from Renolux in France. Both offer a choice of two different slot heights for locating the restraint harness. The Safe'n'Sound slots are particularly high up the seat back: the *lower* slots on this device are at shoulder height for a typical eighteen-month-old child. Conversely, the Securé's slots are particularly low: the *upper* slots being at the shoulder height of a typical six-month-old child. Figure 2 illustrates the differences in slot heights for the Safe'n'Sound device.

Together, these two child restraints offer a comprehensive selection of possible shoulder strap mounting locations. Furthermore, the use of two restraints and two dummies provides a wide range of harness mounting locations relative to dummy shoulder heights. The lower slots of the Securé restraints are well below the shoulder height of the eighteen-month dummy, while the upper slots of the Safe'n'Sound restraints are well above the shoulder height of the six-month dummy.

Test Programme - The testing programme was comprised of sixteen runs. Each of the four dummy-restraint combinations was tested with the harness mounted in both the upper and lower slot positions. Furthermore, each test was performed twice to ensure repeatability.

Table 2. Test programme

Test Numbers	CRABI Dummy	Child Restraint	Harness Position
1,2	6-month	Securé	Lower
3,4	6-month	Securé	Upper
5,6	6-month	Safe'n'Sound	Lower
7,8	6-month	Safe'n'Sound	Upper
9,10	18-month	Securé	Lower
11,12	18-month	Securé	Upper
13,14	18-month	Safe'n'Sound	Lower
15,16	18-month	Safe'n'Sound	Upper

* Henderson, 1993
** Langweider, 1989

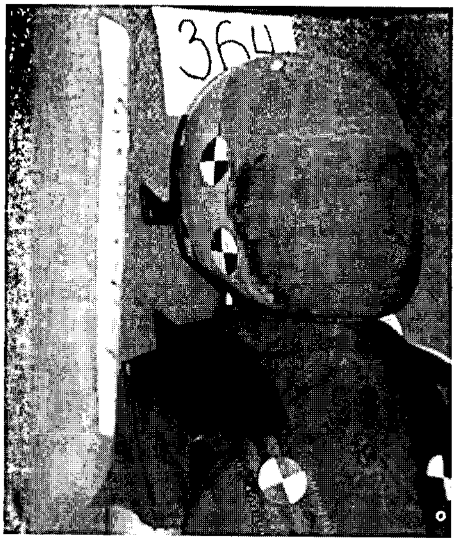
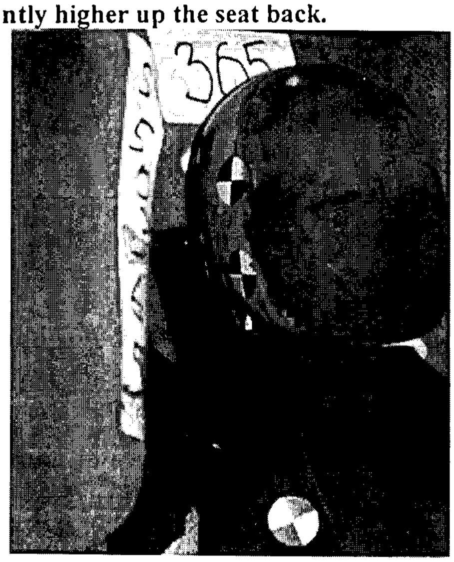


Figure 2. The lower harness slots on the Safe'n'Sound Series III child restraint (see above) are located level with the shoulders of an average eighteen-month-old child. The upper harness slots (see below) are significantly higher up the seat back.



RESULTS

The tests revealed a correlation between child restraint harness mounting height and loads experienced by the head, neck and lower spine of dummies. The peak values for the following parameters:

- lumbar spine compression force
- head resultant acceleration
- upper neck tensile force

are summarised in Tables 3(a) and 3(b). The peak values for lumbar spine compression force are also shown graphically in Figures 3(a) and 3(b).

The tests also demonstrated a correlation between harness mounting position and maximum head excursion. Both Australian and overseas crash studies have revealed that the head is the most frequently injured area in serious crashes involving restrained children, so restraint configurations that limit head excursion go some way towards offering good protection to children in frontal impacts. For all dummy-restraint configurations, head excursions were found to be better limited by the use of the upper harness mounting slots (See Figure 4). The variations in maximum head excursion between the different harness configurations were of the order of 30 to 70 mm.

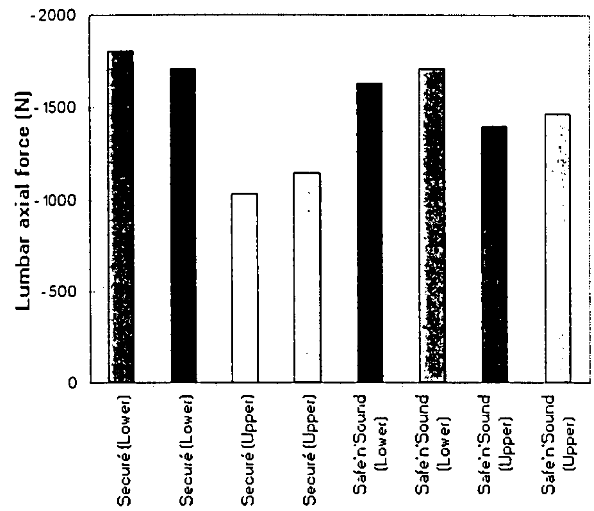


Figure 3(a). Peak lumbar compression forces for tests involving the six-month dummy

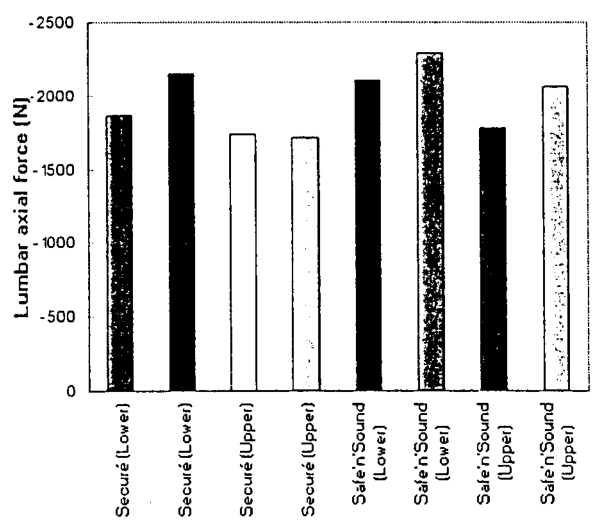


Figure 3(b). Peak lumbar compression forces for tests involving the eighteen-month dummy

Table 3(a). Peak values for tests involving the six-month dummy

Test		1	2	3	4
Restraint		Securé	Securé	Securé	Securé
Harness position		Lower	Lower	Upper	Upper
Lumbar FZ	Peak (N)	-1805	-1711	-1032	-1142
Head GRes	Peak (G)	57.0	54.4	69.5	68.5
Upper Neck FZ	Peak (N)	1156.4	1105.7	1667.1	1639.3

Test		5	6	7	8
Restraint		Safe'n'Sound	Safe'n'Sound	Safe'n'Sound	Safe'n'Sound
Harness position		Lower	Lower	Upper	Upper
Lumbar FZ	Peak (N)	-1631	-1712	-1395	-1464
Head GRes	Peak (G)	63.0	65.1	63.6	64.9
Upper Neck FZ	Peak (N)	1387.8	1493.3	1459.7	1515.5

Table 3(b). Peak values for tests involving the eighteen-month dummy

Test		9	10	11	12
Restraint		Securé	Securé	Securé	Securé
Harness position		Lower	Lower	Upper	Upper
Lumbar FZ	Peak (N)	-1863	-2151	-1739	-1714
Head GRes	Peak (G)	54.7	56.9	63.5	66.3
Upper Neck FZ	Peak (N)	1378.9	1487.0	1585.3	1683.4

Test		13	14	15	16
Restraint		Safe'n'Sound	Safe'n'Sound	Safe'n'Sound	Safe'n'Sound
Harness position		Lower	Lower	Upper	Upper
Lumbar FZ	Peak (N)	-2108	-2297	-1780	-2065
Head GRes	Peak (G)	62.1	59.3	59.7	57.7
Upper Neck FZ	Peak (N)	1606.3	1451.3	1519.7	1493.7

DISCUSSION

Dummy Loads

While this testing programme used two different child restraints and two different child dummies, several general trends were apparent in the relationship between the mounting position of the child restraint harness belts relative to the dummy's shoulder height and the loads on dummy components recorded by the electronic data systems.

Lumbar force trends were consistent for all tests. The most significant finding was that harness mounting locations below shoulder height caused a significant amplification in lumbar compressive force when compared with harness mountings at shoulder height. Harness mountings above shoulder height provided only small reductions in peak spinal compression loads.

Trends in peak head acceleration and upper neck tensile force were also consistent. When compared with harness slot locations at shoulder height, slots below shoulder height provided modest reductions in peak resultant accelerations and forces experienced by the head and neck respectively. Tests using slots significantly above shoulder height displayed small increases in peak head accelerations and neck forces.

Modest reductions in lower neck loads were observed for harness mountings below shoulder height. Trends in peak chest and pelvic acceleration readings did not appear to correlate with harness mounting heights. Similarly, top tether forces were shown to not to be dependent on the harness configuration. Results from webbing transducers on the child restraint harness lap and sash belts displayed relatively poor repeatability.

Dummy Motion

Although dummy motion in all tests showed common features, changes in harness configuration caused subtle variations that gave rise to different loads.

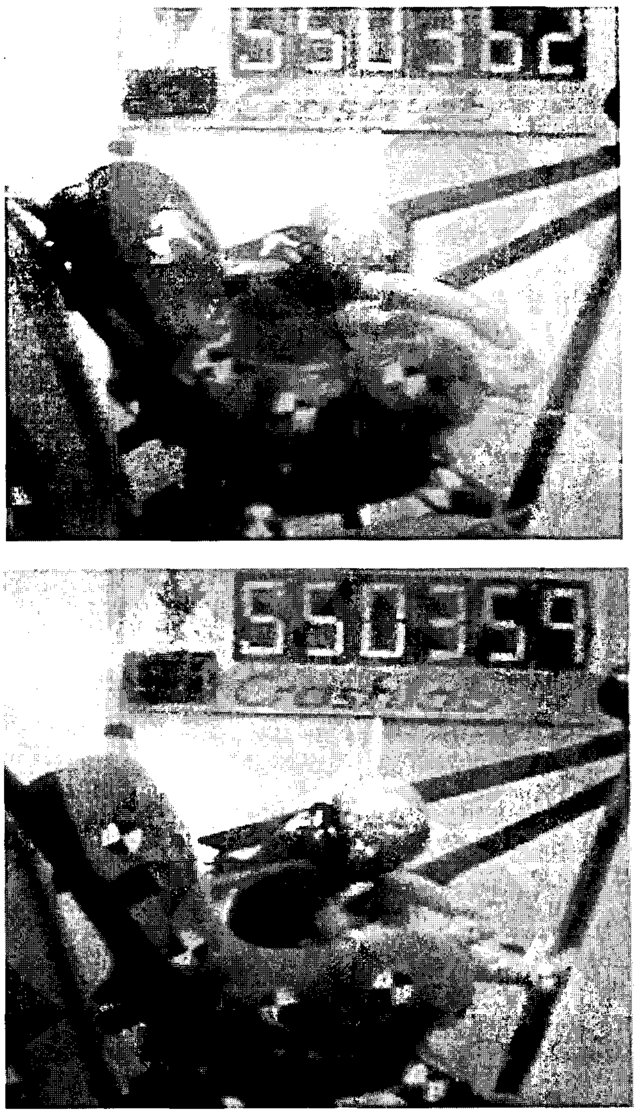


Figure 4. The use of the upper harness slots (top) better limited the head excursion of the dummies than the use of the lower harness slots (bottom), such as in these tests using the eighteen-month CRABI dummy and the Securé CS4 child restraint.

The maximum excursion of the head in an impact is of interest when assessing the effectiveness of a child restraint system. On-board footage from the side-mounted camera showed that, in all cases, the use of the higher slots for restraint harness mounting led to smaller maximum horizontal head excursions. Furthermore, the higher slots appeared to also better limit the dummies' vertical motion as well. This is important, as many serious injuries to restrained children have been linked to large head excursions resulting in heavy head strikes or an increased likelihood of neck injuries.

Also of interest was the angle of the shoulder straps at maximum excursion. The use of the lower slots always resulted in a steeper harness angle than that which occurred with the use of the upper slots. Moreover, the Securé restraints' large angle of seat back recline meant that harness angles at peak excursion were larger than for the Safe'n'Sound.

Head impacts were present on all tests, with the head usually hitting the chest, legs or the restraint buckle.

Repeatability of Results

Calibration tests were conducted on the dummy head and neck components before, during and after the testing programme to ensure their consistent performance throughout. Furthermore, each test was run twice, to monitor the repeatability of the experiments.

Repeatability for tests using Safe'n'Sound restraints, as well as those using the CRABI 6-month dummy and the Securé restraints, was excellent. However, results for tests using the Securé restraint with the 18-month CRABI dummy were generally less consistent. Film analysis showed that the motion of the 18-month dummy in the Securé restraint was somewhat erratic, and was more sensitive to initial conditions than other combinations. This was due to the fact that the installation of the 18-month CRABI dummy in the Securé restraint is less stable than other dummy-restraint combinations.

Electronic data results for most tests were generally repeatable to around ±7% of peak values. This variability was mainly due to inconsistencies in the responses of dummy components, particularly neck units. However, the differences in head accelerations and neck and lumbar spine forces and moments for different test configurations were often greater that 15%. This indicates that the different dummy responses were due to differences in experimental setup, and it is therefore valid to say that the harness mounting height has an influence on the head, neck and spinal loads experienced by dummies in frontal impacts. On occasions when results from different tests showed differences of less that 7%, it was not possible to attribute variations in results to different experimental setups, since these variations were less significant than the lack of repeatability of the experiments.

Factors contributing to differences in dummy loads

Lumbar compressive forces were typically highest in tests where there was a large angle between the restraint sash harness belts and the horizontal plane tangential to the dummy's shoulders. The seat backs of both brands of

restraint were reclined, since the test seat tilted back at an angle, and the restraint seats also reclined with respect to the test seat. The harness sash must absorb the energy of the impact by applying a restraining force to the dummy's shoulders. The belts can only act in tension along the line between the slots and the shoulders. Since the horizontal component of belt force is determined by the energy of the impact (which was the same for all tests), the vertical component of belt force (which gives rise to lumbar spine compression) is determined by the angle of the harness belt. The greater the angle between the sash and the horizontal, the greater the vertical component of load in the sash, and the greater the compressive force felt by the dummy's spine.

The relationship between sash belt force and the angle of recline of the sash also helped to explain other observations from the electronics results. In an accident, a great deal of energy is dissipated by plastic deformation of the harness belts. (It is because of this significant deformation that restraints and seat belts may only be used for a single test.) Like other elastic-plastic materials, seat belts have a two-stage response to tensile loads. The higher stresses generated by low-mounted harness configurations mean that the harness material plastically deforms to a greater extent. This plastic deformation produces a gentler ride down effect for the child occupant due to the reduced effective belt stiffness, resulting generally in lower neck forces and head accelerations. However, the gentler ride down comes at the expense of greater head and torso peak excursions. These effects could be expected to be significant in child restraints with particularly low harness mounting slots and significantly reclined seat backs.

Effects of harness mounting height

This project established a link between child restraint harness mounting height and loads experienced by the test dummies. Harness mounting heights significantly below shoulder level gave rise to substantially higher spinal compressive forces than mounting locations level with or above shoulder height.

The project also established a link between restraint harness mounting height and head accelerations and neck loads. Mounting positions below shoulder height offered modest reductions in peak dummy head accelerations and neck forces when compared to mounting points at or above shoulder height.

These trends were more pronounced for the Securé restraint than for the Safe'n'Sound device. It is thought that the significant angle of recline of the Securé seat back accentuated the effects of variations in the harness mounting height. The angle between the upper portion of the sash harness and the horizontal determines the component of compressive force transmitted to the shoulders and lower spine. Thus, the lower the mounting height of the harness with respect to the shoulders, and the greater the angle of recline of the seat back, the greater the compressive force applied to the lower spine. However, this increased sash belt force may cause the belt to deform over a greater distance (hence the greater head excursion), albeit in a less severe manner (causing the lower head and neck loads).

There is still insufficient information on the effects of the recline angle of the restraint seat back on the levels of protection offered to occupants. This parameter appeared to significantly influence this project's results, but its effects in isolation have not yet been studied. The Roads and Traffic Authority in Sydney will conduct a project to investigate this issue in the near future.

Optimum harness mounting location

The lack of information on child injury tolerance levels makes it difficult to draw precise conclusions as to the optimum mounting height for child restraint harnesses. Taking into account current biomechanical data, and in particular the uncertainty surrounding young children's tolerance to lumbar spine crushing forces, child restraint harnesses should be mounted in slots level with the child's shoulders. If there are no harness mounting slots located at shoulder height, then the use of higher slots is preferable to the use of lower slots. This positioning avoids the excessive spinal compression loads associated with harness mounting positions below shoulder height, and also limits head excursion and the probability of head strikes, the major cause of death and serious injury to properly restrained children in Australia. Although this positioning does not minimise the neck forces and head accelerations experienced by restrained children, it is currently the best compromise, providing restrained children with the best overall level of protection in a frontal accident. As more information on injury tolerance levels, particularly those for lumbar spine compression, becomes available, this recommendation should be reviewed.

Recommended changes to the Australian Standard

It has been shown that the use of child restraint harness mounting locations significantly below shoulder height can cause appreciable magnifications in compressive loads in the lumbar spine, when compared with mounting locations at or above shoulder level. The current Australian Standard AS 1754-1991 requires the

lower and upper shoulder strap slots to be at least 250 mm and 365 mm respectively up the seat back. However, these slot heights are insufficient for children over two years of age. The Securé CS4 restraint used in this testing programme is accredited under AS 1754-1991, but its uppermost harness mounting slots are level with the shoulders of an average eighteen-month-old child. Clearly, the shoulders of a four-year-old restrained in a Securé restraint will be significantly above the harness mounting locations. In light of the findings of this research, this could lead to significant compressive forces in the lower spine in the event of a heavy frontal impact.

The restrictions on the mounting locations of child restraint sash harnesses in the current Australian Standard AS 1754-1991 should be modified. The current regulations allow manufacturers to provide an inadequate range of mounting slots. Current anthropometric data shows that the minimum height specified for the uppermost slots is too low for children aged two and over. The Standard should require that the uppermost mounting slots on a child restraint system be at least as high as the average shoulder height of the oldest children for which the restraint is designed.

CONCLUSIONS AND RECOMMENDATIONS

- There is a link between the mounting location of child restraint harnesses and the loads experienced by restrained test dummies in frontal impacts.
- Harness mounting height is a compromise: mountings level with or above shoulder height give significantly lower spinal loads and head excursions, but higher head and neck loads than mounting heights below shoulder level.
- The results suggest that the optimum mounting height for a child restraint harness is level with the child's shoulders. However, if there are no mounting slots positioned at shoulder height, then the use of a higher mounting location is preferable to the use of a lower location. This recommended height gives the occupant good overall protection.
- The restrictions on the mounting locations of child restraint sash harnesses in the current Australian Standard AS 1754-1991 should be modified. The Standard should require that the uppermost harness mounting slots on a child restraint are at least as high as the average shoulder height of the oldest users for which the restraint is intended.
- The recommendations of this project should be reviewed as information on child injury tolerance levels increases.

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REFERENCES

Beusenberg, M.C. et al "Status of Injury Mechanics for the Development of Child Dummies", Paper 933104, Child Occupant Protection SP-986, Society of Automotive Engineers, USA. 1993.

Brown, J. et al "The Performance of Tethered and Untethered Forward Facing Child Restraints", IRCOBI Proceedings, Brunnen, Switzerland. 1995.

Henderson, M. et al "Injuries to Restrained Children", Child Accident Prevention Foundation of Australia. 1994.

Langweider, K. et al "Neck Injuries to Restrained Children", IRCOBI Proceedings, Stockholm, Sweden. 1989.

Sampson, D.J.M. "Effect of Harness Mounting Location on Child Restraint Performance", Bachelor of Engineering Thesis, Department of Mechanical Engineering, University of Sydney, Australia. 1995.

Stalnaker, R.L. "Spinal Cord Injuries to Children in Real World Accidents", Paper 933100, Child Occupant Protection SP-986, Society of Automotive Engineers, USA. 1993.

Standards Australia, "AS 1754-1991: Child Restraint Systems for Use in Motor Vehicles", Australia. 1991.

Tong, S. "Performance of Forward Facing Child Restraints With and Without the Top Tether Strap", Bachelor of Engineering Thesis, Department of Mechanical Engineering, University of Sydney, Australia. 1994.

THE VALIDITY OF THE PROPOSED EUROPEAN PEDESTRIAN PROTECTION PROCEDURE AND ITS EXPECTED BENEFITS

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ABSTRACT

EEVC has developed a subsystem test procedure for pedestrian assessment. This procedure is the basis of a draft proposal for a European Parliament and Council directive relating to the protection of pedestrians and other road users in the event of a collision with a motor vehicle and amending directive 70/156/EEC.
This procedure proposes to use three independant subsystem tests to assess the protection against leg and head injuries.
The proposal is discussed taking into account the experience gained in the validation programme. This analysis shows that before the integration of this work into a directive it is necessary to perform additional work.
This concerns especially the leg form test for which the design of deformable elements should be optimized, and the reduction to 35 km/h of the impact speed should be considered.
The bonnet leading edge test is more questionnable, and the potential benefits of such a test are not demonstrated. This test should be at least validated through a specific programme, and the possibility of cancelling this test should be considered.
Cost benefit studies give very different results, but three out of the four indicate a high benefit of the procedure.

INTRODUCTION

Currently applicable type approval car safety regulations concern mainly the protection of car occupants. However the protection of vulnerable road users can be considered as a priority for most European countries, as pedestrians account for 11 to 33 % of traffic accident fatalities.
EEVC has developed a set of subsystem tests to assess the protection of pedestrian in accidents (EEVC/CEVE 1994)

The EEVC test procedure includes three subsystem tests which are the legform to bumper test, the bonnet leading edge test, and the headform to bonnet top test.

EEVC SUB SYSTEM TESTS

The legform to bumper test was developed by INRETS in France. For this test a biofidelic instrumented mechanical leg is propelled against the front of a car at 40 km/h in a free flight. The anthropometry and anthropomorphy of the leg form represent an adult 50th percentile human leg : the mass of the femur and of the tibia are respectively 8.6 and 4.8 kg, and the total length of the mechanical leg is 926 mm. The knee joint is designed to be biofidelic compared to the behaviour of a human leg hit on its external side; the deformation of the knee is controlled by two deformable elements providing the relevant force/deformation characteristics in bending and in shearing. Two angular displacement transducers measure the relative displacement beetween a knee link bar and respectively the upper and the lower leg. In addition the lower leg is fitted with a uniaxial accelerometer fixed at its top, just below the knee.

The leg form is probably the most complicated of the three sub system test tools. The INRETS legform exists as a prototype, and validation tests conducted by several laboratories have shown that this mechanical leg is sensitive to the variation of bumper stiffness and initial impact point height on the leg, which are the two parameters the best correlated with the occurence of leg injuries in pedestrian impacts. Some minor problems which might be solved when the legform will be manufactured under industrial process were found. They concern mainly the response in shearing, (the mechanical leg is too stiff) and the durability of angular transducers.

The response of the mechanical leg knee in bending and shearing is based on biomechanical tests made with human legs under these two loading process; these tests allowed to draw force/time histories, but it is very difficult to determine human knee deformations characteristics, especially in shearing.

Three protection criteria are proposed for the mechanical leg as indicated in table 1. The two first protection criteria are especially aimed to protect against knee injuries in bending and shearing.The limit of lower leg acceleration has for objective to avoid impacts against too stiff structures which may cause tibia or fibula fractures.

Loading	Proposed limit
Bending	15°
Shearing	6mm
Tibia Acceleration	150g

Table 1 - Leg to bumper test requirements

Recently TRL has developed an alternative legform in which the force/ deformation behaviour is controlled by springs. Results with this mechanical leg have not

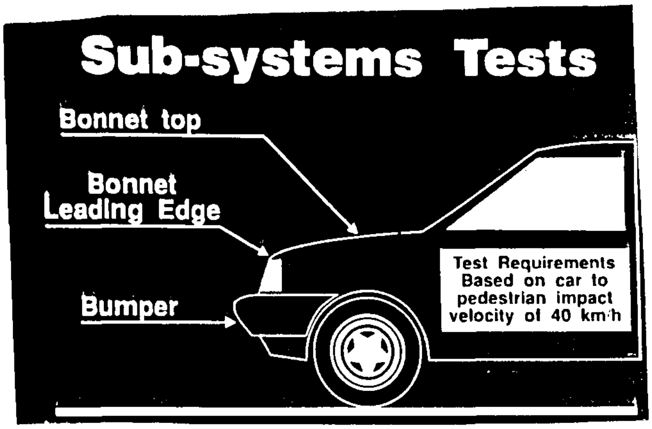

Fig. 1 The three sub-system tests of EEVC proposal.

yet been published and then this mechanical leg cannot be considered as validated. The use of a spring to control the deformation makes that the mechanical leg unlike human leg recovers during the impact and then has no permanent deformation.

The bonnet leading edge test uses a guided upper leg representing an adult femur. The test conditions (angle, impact speed, impactor mass) are determined taking into account the profile geometry of the car front. The proposed criteria are a limit of 4 kN for the impact peak force and 220 Nm for the bending moment of the front arm covered with a compliant foam and which hits directly the bonnet leading edge.

The bonnet leading edge is aimed to protect adult pedestrian against femur fracture and child pedestrian against pelvic/abdominal injuries. However the adult femur tolerance seems clearly higher than the proposed value, and the child pelvic/abdominal tolerance is not established. The upper legform has been refined by TRL after a limited number of validation tests and is commercially available, but has been yet used by a very small number of users.

The protection of the head is assessed by a subsystem headform to bonnet top test developed by BAST. Two headforms are specified : a child headform for tests performed on the bonnet area limited by a line located between 1 and 1.5 m wrap around distance, and an adult headform for the rearer part of the bonnet. The mass of the adult and the child headforms are respectively 2.5 and 4.8 kg.The two headforms are fitted with a triaxial accelerometer, and a HIC limit of 1000 is the proposed protection criterion for all the tests. The impact speed is 40 km/h but the impact angle is lower for the child headform test (50°) than for the adult one (65°). The headforms are commercially available and were used in validation tests against a large number of present cars and offroad vehicles fitted with bullbars.

DISCUSSION

Pedestrian protection assessment tests which are the basis of the procedure were developed separetely by three laboratories and even if an EEVC working group coordinated the tasks, the proposed procedure seems not homogeneous.

Firstly, the impacted speed is the same for legform to bumper and for headform to bonnet tests; however all the car to pedestrian biomechanical tests show that the head to bonnet impact speed is at least 15% higher than the car to leg impact speed. Taking into account the above data either the headform test speed should be increased to around 46 km/h or the legform test speed should be decreased to 35 km/h. Cadaver tests performed with mass production cars indicate that knee injuries can be found for impact speed as low as 20 to 25 km/h. Then choosing 35 km/h as legform impact speed would correspond to a real improvement of pedestrian protection against leg injuries. To make the proposal more homogeneous it seems advisable to reduce the impact speed of the legform test to 35 km/h.

Secondly the effect of the bonnet leading edge test requirement on the assessment is not demonstrated; especially accident studies indicate that femur fracture is an uncommon pedestrian injury compared to other leg injuries; In pedestrian accidents involving modern cars, only 4.2%.of adults and 10.6% of children suffer femur fracture (Otte 1989), the latter being related to bumper (and not bonnet leading edge) impact. Tests performed with present cars show that almost none of them fulfill the proposed requirement. These findings make the bonnet leading edge test questionnable, especially it seems that if in accidents present cars do not produce injuries to be assessed by this test, they would normally pass easily the proposed criteria. As validation tests show the opposite it seems that the requirements concerning the bonnet leading edge test would be reconsidered.

Third the headform test can reproduce only injury mechanisms related to linear acceleration and then does not take into account the effect of head rotational acceleration which is considered as a relevant head injury mechanisms in pedestrian accident situations; then the proposed procedure for head injury assessment seems mainly a procedure to limit the

stiffness of the bonnet and not a procedure to optimize the protection of pedestrian against head injuries.

Validation tests seem to indicate that it is more difficult to pass head protection requirements with the child headform than with the adult one (Zellmer 1994). On the opposite accident studies seems to show that for the same impact speed head injuries are less frequent for children than for adults (Otte 1989). A possible reason for this apparent inconstancy is that the same protection criteria value (HIC 1000) is proposed for adult and child tests, whereas the tolerance of children to head injuries is unknown, and if we consider that in general the tolerance of children is higher than the adult one, the limit HIC value of 1000 can be considered as too conservative.

CONSEQUENCES FOR CAR DESIGN

Tests done with the legform against the bumper shows that the procedure is sensitive to the variation of parameters the most related to the risk of leg injuries (Cesari 1994). Two directions should then be explorated to comply with the requirements : on one hand, the front face would be designed in such a way that the initial impact point on the leg is lowered, and on the other hand the compliance of the car front components in contact with the mechanical leg would be sufficient.

To pass head impact protection tests it is necessary to provide to the bonnet a deformation characteristic as much homogeneous as possible on all its surface. Especially this means that the bonnet stiffening frame should be designed for that purpose, and that it is necessary to allow the bonnet to deform enough which means that any rigid component in the engine compartment close to the bonnet should be avoided. If that seems feasible for engine components, this is much more difficult for the suspension tops which are normally located as high as possible, and then very close to the bonnet.

COST BENEFIT ANALYSIS

When the EEVC procedure was established several institutions in Europe conducted cost benefit studies concerning the implementation of the procedure. The published cost benefit studies were performed by ACEA (ACEA 1992), BAST (Bamberg 1994), SWOV (Van Kampen 1994) and TRL (Lawrence 1993).

The main results of these studies are indicated in table 2. This table shows clearly that the three research institutes conclude with similar results showing that the proposed procedure cost less in terms of car modification than the amount of money it saves by decreasing the number of serious and fatal injuries, but the industry study concludes in a cost 57 times higher than the expected benefits.

Study	Cost (Ecus)	Benefits (Ecus)	Cost/benefit ratio
TRL	11 to 19		1:4.3 to 1:7.5
BAST		25 to 34	
SWOV		49.6	
ACEA	270	4.7	57:1

Table 2 - Cost benefit of the EEVC pedestrian impact requirements

The TRL study considers only fatally and seriously injured pedestrians involved in accident occuring at impact speed below 40 km/h and for injuries related to the car areas concerned with the procedure. The effect on accidents occuring at impact speed above 40 km/h is not taken into account in the study, and this would minimize the expected benefits.

BAST and SWOV studies do not propose a cost benefit ratio but only the benefits expected with the implementation of the pedestrian procedure. Both are based on national figures, and the higher expected benefits proposed by the SWOV study can be related to the fact that the latter takes into account the effect on pedestrians and cyclists. The expected benefits as proposed by these two studies are slightly lower than the value proposed by the TRL study, but nevertheless these figures indicate that the implementation of the procedure would be benefitial.

The differences are first related to the value chosen for the cost of the modifications. TRL uses the value determined by an independant consultant, and takes into account the cost of research and development and the cost of modifications necessary to fulfill the requirements. ACEA cost should include the same items and then even if the determination of the cost is a difficult task, the difference between the two evaluations is to high (in the ratio of 1 to 20). The ACEA evaluation seems more in the order of magnitude of modification of existing cars, whereas the inclusion of these requirements in the specifications of a new car model during the development stage would probably cost much less.
Another explenation for the difference between studies is the determination of the number of pedestrian accidents for the years after 2000. All studies use the trends of last years and project this variation in the

future. It is clear that there is a decrease of pedestrian accident number between 1980 and 1992; however the decreasing is much less important for the last years than for the first ones (United Nations 1995). For example the 26 OECD countries for which accident statistics are available show a small increase of accident fatalities from 1992 to 1993, and looking in details to the variation for each country allows to find that if for some countries the number of pedestrian accidents continues to decrease it is growing in some central Europe countries for example.

Figure 2 shows the the difference of pedestrian accident fatalities in relation to the country population (Fontaine 1995); this risk varies in a ratio of 1 to 5 for different developed countries. Specificities in traffic conditions can partly explain these differences and for exanple in Nederland, which is lowest risk country, there is 70 % more cyclists than pedestrians killed,

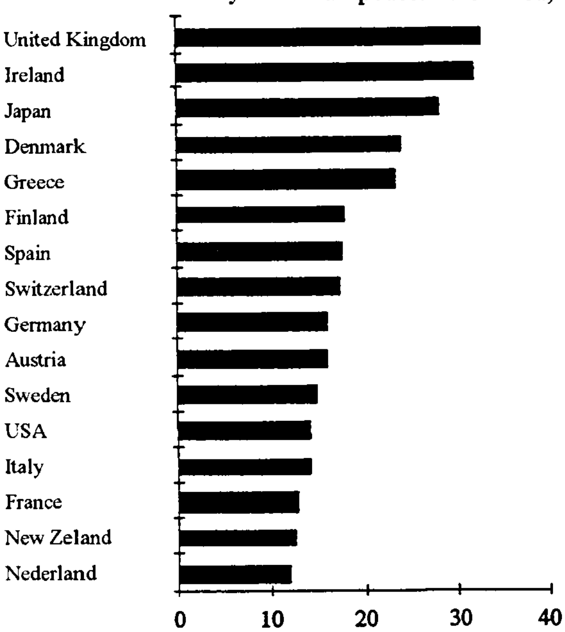

Fig. 2 Killed pedestrian for 100 fatalities in traffic acc

whereas in most of the other countries there is much less cyclists than pedestrians involved in fatal accidents.

CONCLUSIONS

The work done by EEVC to propose subsystem tests for pedestrian protection assessment is very promising, however at its present stage of development it seems that additional work to validate the method and possibly to amend it.

There is a need for improvement of the design of deformable elements of the mechanical leg, and this should be followed by a validation programme. To give more homogeneity to the set of the three subsystems it seems necessary to lower the impact speed of the bumper/leg test to 35 km/h. Adult headform test is validated through a large number of tests, which showed that present cars give generally results clearly above the requirements, and child headform test seems require more car modifications, unlikely the accident results would let to expect.

The bonnet leading edge test is more questionable, as its benefits in term of injury assessment are not clear, and its application may require car modifications not linked with the improvement of pedestrian protection.

Two cost benefit studies performed by TRL and ACEA gave very different results in the ratio of more than 1

Killed pedestrian per Million of inhabitants

to 240. Differences in the prediction of pedestrian accidents, the percentage of those concerned by the proposed procedure, and of the cost of modifications necessary to comply with the requirements explain the scatter of these results; however two other studies performed by SWOV and BAST conclude in a figure of the same order of magnitude as the one proposed by TRL for the expected benefits of the proposed method.

REFERENCES

ACEA. Pedestrian accidents in Europe : Developments and challenges. European Automobile Manufacturers Association. Brussels eptember 1992.

Bamberg R., H. Zellmer, Nutzen durch fahrzeugseitigen Fussgängerschutz. Berichte der BASt, Fahrzeugtechnik Heft F5, Bergisch Gladbach, April 1994

Cesari D. , F. Bermond, Optimization of pedestrian leg injury protection using a biofidelic mechanical leg. 1994 International Conference on the Biomechanics of Impact, Lyon September 1994.

EEVC/CEVE, Proposals for methods to evaluate pedestrian protection for passenger cars. EEVC Working Group 10 Report. November 1994

Fontaine H., Y. Gourlet, A. Ziani, Les Accidents de Piétons. Rapport INRETS n° 201, Arcueil france, Mai 1995.

Lawrence G.J.L., B.J. Hardy, R.W. Lowne, Costs and benefits of the EEVC pedestrian impact requirements. Crowthorne, U.K. Transport Research Laboratory. Project Report 19, S220C/VF. 1993.

Otte D., Influence of vehicle front geometry on the injury situation of injured pedestrians. Medical University of Hanover, April 1989.

United Nations Statistics of Road Traffic Accidents in Europe and North America. New York and Geneva 1995

Van Kampen L.T.B., Cost-benefit study concerning car front impact requirements to increase the crash-safety of pedestrians and cyclists. SWOV Report R-94-31, Leidschendam 1994.

Zellmer H., K.P. Glaeser, The EEVC-WG 10 Head Impact Test Procedure in Practical Use. Proceedings of the Fourteenth International Technical Conference on Experimental Safety Vehicles, Munich May 1994.

Motorcycle Impact Performance: Further Results

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ABSTRACT

This paper describes the results of 101 full scale motorcycle/car impact tests to evaluate the effects of various engine guard treatments and impact configurations, and also the effects of a passenger and vehicle speed combinations on impact performance and kinematic injury potential (KIP) for various motorcycle models. Included were seven different impact configurations, two moving/moving speed combinations, tests with and without passengers, three different add-on engine guards and three different motorcycle types. The impact dummies used were a partially instrumented fiftieth percentile male Hybrid II (operator dummy) and fifth percentile female (passenger dummy). Data included dummy and vehicle trajectory information from high speed films and electronically measured accelerations. Changes in kinematic injury potential due to the addition of add-on engine guards, passengers, and speed variations were analyzed. Conclusions and recommendations based on statistical analysis of the data are presented.

INTRODUCTION

Previously reported results [1] described 63 full scale crash tests analyzing the effects of add-on engine guards on rider injury potential. These results were based on three motorcycle types, three different add-on engine guards, five impact configurations, a single motorcycle operator dummy, and one impact speed combination. This paper describes the results of combining the original 63 tests with 27 additional full scale crash tests involving additional test pairs and additional impact configurations. Also described are the results of 11 full scale crash tests with operator and passenger dummies performed using different vehicle speed combinations.

Specifically, the previous examination of the effects of add-on engine guards on injury potential has been broadened to include additional impact configurations and additional test pairs. Also, one impact configuration (offset frontal) was done both with and without passenger in order to examine the effect of a passenger on operator injury potential and to allow the comparison of passenger and operator injury potential. The offset frontal condition with passenger was also tested with different impact speed combinations in order to study the effects of vehicle speeds on passenger and operator injury potential.

Background

<u>Crash Bar Research</u> - The previous work [1] provided an historical overview of past crash bar research, and examined the results of 63 full scale crash tests in order to analyze the changes in rider injury potential due to the addition of three different types of add-on engine guards. Statistical analysis of the data from the 63 tests indicated that the addition of a conventional accessory engine guard produced no statistically significant change in kinematic injury potential. However, both types of non-standard heavy duty engine guards tested produced statistically significant increases in kinematic injury potential for the motorcycles and impact configurations examined.

<u>Operator/Passenger Accident Data</u> - Hurt, et al [2] performed detailed on-scene, in depth investigations of 900 motorcycle accidents in the greater Los Angeles area, including 154 accidents (17%) involving both an operator and a passenger. Similarities were observed between the passenger and rider injury data, and this is attributed to similar exposures to injury causing surfaces. Some differences were observed between passenger and operator injuries, with passengers suffering less frequent lacerations and urogenital injuries but more abrasions. Hurt, et al also observed that in frontal impact configurations the passenger was somewhat protected by the rider, as the rider precedes the passenger into the collision area.

<u>Impact Speed Accident Data</u> - With respect to impact crash speeds, Hurt (et al, 1981) observed a mean motorcycle crash speed of 21.5 miles per hour (34.6 kilometers per hour). Accident investigation results indicated that crash speed was a critical factor related to injury severity. Only 10% of riders involved in motorcycle 11 to 20 mph (18 to 32 km/h) crashes suffered serious or worse injuries. Speeds of 21 to 30 mph (34 to 48 km/h) and 31 to 40 mph (50 to 64 km/h) increased the percentage of riders suffering serious or worse injuries to 27% and 47% respectively.

Accident databases - The distribution of impact configurations in the Los Angeles accident database [2] and Hannover accident database [3] [4] were combined by Pedder, et al [5]. As described, the two databases contain over 500 motorcycle accidents involving passenger cars, upright motorcycles, and single, seated operators. Each accident was described using five impact variables. These variables comprised car and motorcycle contact points, the relative heading angle between the car and motorcycle, and the car and motorcycle impact speeds. The accidents were categorized into different geometries (combinations of contact points and relative heading angle). When combined with vehicle speed variations, the various impact geometries resulted in several hundred "impact configurations" which were required to categorize all the accidents. The data indicate that no single impact configuration represents more than a few percent of the accidents. The data, which are for one category of motorcycle accident, indicate the wide diversity of accident types that occur in the real world. This suggests that a broad range of impact configurations should be considered in motorcycle impact research.

Objectives

The objectives of the current research were:

- to reassess the effects of add-on engines guards on kinematic injury potential (KIP) across a range of engine guards and motorcycle types, using a broader range of impact configurations; and
- to assess the effects of passengers on operator KIP, and differences between passenger and operator KIP; and
- to assess the effects of speed variation on KIP, for one impact configuration.

EXPERIMENTAL PROCEDURES

Test Vehicles

Motorcycles - All motorcycles used in this study were in the large category in comparison to the average range of motorcycles in use. In their class the test motorcycles were one of three types:

- Light weight (Sport type), approximately 500 lbs (227 kg)
- Medium weight (Cruiser type), approximately 600 lbs (273 kg)
- Heavy weight (Touring type), approximately 750 lbs (341 kg)

Within each type there were some minor variations in features and in frame details, which were considered to be small relative to the differences among the three main types of motorcycles used.

Add-on Engine Guards - Three different add-on U-shaped engine guards were used as listed in Table 1.

Table 1
Specifications of Add-On Engine Guards

Engine guard	Outside diameter, inches (mm)	Wall thickness, inches (mm)	Section modulus inches^3 (cm^3)
Accessory engine guard (baseline for Touring motorcycle)	1 1/4 (31.8)	3/32 (2.4)	0.091 (1.5)
Spec A engine guard	1 1/2 (38.1)	1/8 (3.2)	0.171 (2.8)
Spec B engine guard	2 (50.8)	3/32 (2.4)	0.256 (4.2)

The Spec A and B engine guards were two types of non-standard, non-available heavy duty engine guards having approximately 2 and 3 times the section modulus of the baseline accessory engine guard, respectively. Note that the baseline touring motorcycle had as standard equipment an engine guard similar to the add-on accessory engine guards and therefore was not tested in a "no engine guard" condition.

Opposing vehicle - The opposing vehicle for all tests was a 1985 to 1987 Chevrolet Celebrity 4-door sedan. This was selected because it was the highest sales volume model and the highest sales volume size category (ie, intermediate) in the United States during the above time period. The weight of the opposing vehicle was 2750 lbs (1250 kg).

Test Facility

The test facility used for all tests was Failure Analysis Associates, Inc. in Phoenix, Arizona. Specialized equipment and procedures utilized for motorcycle crash tests were described previously [1].

Impact Configurations

Seven impact configurations were used as described in Table 2 and Figure 1 to evaluate engine guards: the five previously used [1] and a broadside impact (Configuration 6) and angled car front impact (Configuration 7). To study passenger and speed effects, testing of Configuration 5 was expanded to include operator with passenger (two-up) impacts with both vehicles traveling at 20 mph (32 km/h) (referred to as a 20/20 mph impact), and operator with passenger impacts involving a 30 mph (48 km/h) motorcycle and a 10 mph (16 km/h) opposing vehicle (a 30/10 mph impact).

Table 2
Impact Configuration Description

Impact Configuration	Opposing Vehicle Contact Point	Motor-cycle Contact Point	Relative Heading Angle, deg	Motor-cycle Speed mi/h (km/h)	Opposing Vehicle speed mi/h (km/h)
1	Front-corner	Side	90	20 (32)	20 (32)
2	Side-front*	Front	120	20 (32)	20 (32)
3	Side-front*	Front	135	20 (32)	20 (32)
4	Side-front*	Front	150	20 (32)	20 (32)
5	Front-corner	Front-corner	180	20 (32) 30 (48)	20 (32) 10 (16)
6	Front	Side	90	20 (32)	20 (32)
7	Front	Front-corner	135	20 (32)	20 (32)

*At base of car A pillar

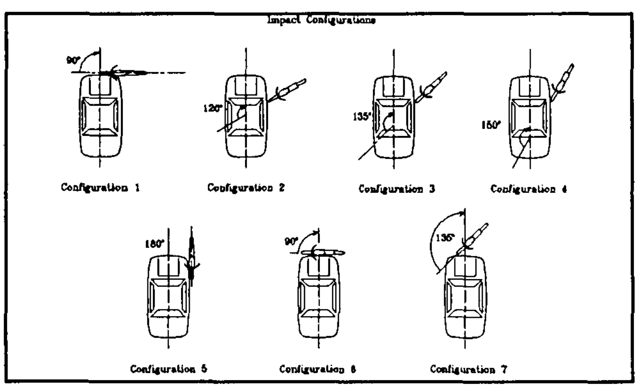

Figure 1. Impact Configurations

Crash Dummies

The operator dummy used for all tests was a 50th percentile male Hybrid II dummy with sit/stand pelvis, mounted on the test motorcycle in a nominally upright seated position. For those tests involving a passenger, a 5th percentile female (model H3X-5F) dummy, also with a sit/stand pelvis, was seated in the passenger position on the motorcycle. Both dummies were fitted with thermal knit underwear, shoes, and full face-type helmets.

A review of test films showed several broken cast-brass hip ball studs during the two-up tests. The broken castings primarily occurred with the 5th percentile female dummy. Table 3 describes the geometrical differences between the 50th percentile and 5th percentile brass casting design. It can be seen that the section modulus of the 50th percentile casting is about 3.4 times greater than that of the 5th percentile casting, which would account for the increased number of failures in the 5th percentile dummy. These parts, which are standard components of the dummies, are not designed as frangible components and it is inappropriate to use these component breaks as an indicator of injury potential. However, the electronic and photo-optic data for these tests were used in the analysis.

Table 3
Specifications of Cast-Brass Hip Ball Designs

	50% Male	5% Female
Femur Ball Dia in (mm)	1.75 (44.4)	1.25 (31.7)
Femur Shaft Dia in (mm)	0.75 (19.0)	0.50 (12.7)
Section Modulus in^3 (cm^3)	0.041 (0.67)	0.012 (0.20)

Measurements

<u>Electronic</u> - Limited sets of electronic sensors were mounted in the dummies, in order to minimize the number of external cables which could potentially distort dummy motion. Triaxial accelerometers were located in the dummy heads and pelvises, and on that rigid component on the motorcycle which was nearest to the center of gravity. The electronic data was filtered according to SAE J211 [6] requirements.

<u>Photo-optic</u> - For all tests several high speed 16mm cameras were used to photograph dummy and

motorcycle motions during the crash sequence. The film from the motorcycle top and side view cameras (typically at 1000 frames per second) was digitized using a NAC 160F film digitizer, in order to quantify the motions of various dummy and motorcycle parts. This included the dummy helmet centroid (center of a circle circumscribed about the helmet), the shoulder target, hip target, and motorcycle frame target.

For impact Configuration 6, the film from the motorcycle front view camera was also digitized in order to quantify the lateral pitch rate of the dummy, based on movements of the centerline of the pelvis and the centerline of the upper chest.

The photo-optic measurements were made over the primary impact interval (0 to 500 ms), or until the dummy left the field of view, whichever occurred sooner. Dummy motions later than this tended to involve motions toward or away from the cameras and the measurement method could not readily account for such motions. The reader is directed to the previous paper [1] for additional descriptions of the frame analysis intervals and filtering procedures.

Kinematic Injury Potential Indices

As previously reported [1], a set of 12 primary kinematic injury potential (KIP) indices were generated for each test based on the electronic and photo-optic measurements. These were:

- Head maximum resultant acceleration (HAR)
- Head injury criteria (HIC)
- Pelvis maximum resultant acceleration (PAR)
- Pelvis maximum integral acceleration (IPAR)
- Head maximum vertical velocity (HVZ)
- Pelvis maximum height (PH)
- Pelvis change in velocity (PVX)
- Pelvis whole body acceleration (PWBAX)
- Torso pitch rate (TPR)
- Motorcycle change in velocity (MVX)
- Motorcycle whole body acceleration (MWBAX)
- Head increase in resultant velocity (HVR)

The first four indices were calculated using the electronic measurements; and the remaining eight indices were calculated using the photo-optic measurements. A more complete description and discussion of the 12 KIP indices may be found in the previous work [1].

As noted, for impact Configuration 6 the lateral torso pitch rate was determined using the motorcycle front view camera and was used as the KIP index indicating torso pitch rate. This is because in this case the car is impacting from the side of the dummy and therefore the primary motion related to injury potential is in the dummy lateral direction. For all other impact configurations forward torso pitch was used as the kinematic injury potential index describing torso pitch rate. In these cases the car is generally in front of the dummy therefore the primary motion related to torso pitch injury potential is in the forward direction.

Analysis Methods

<u>Paired comparisons</u> - The test data were analyzed using the method of paired comparison, wherein each test to examine the effect of one test variable was compared to a corresponding baseline test. For example, to evaluate the effect of a Spec A add-on engine guard, a test was performed with the engine guard and the results compared to a baseline test involving the same motorcycle, impact configuration, and speed but without the engine guard. Therefore, nominally, only one test variable was different within each pair.

The 101 full scale crash tests provided a total of 88 paired comparisons. Table 4 describes the test variables, baseline tests, and the number of test pairs.

Table 4

Test Variables and Baseline Tests

Variable	Baseline	Number of Test Pairs
Engine Guard	No Engine Guard or Accessory Guard	63
Operator with Passenger	Operator without Passenger	4
Operator and Passenger at 30 mph	Operator and Passenger at 20 mph	5 Operator 5 Passenger
Passenger	Operator	11

<u>Percentage change</u> - The KIP indices described above have different physical units (eg, feet/second, g, degree/second, etc) associated with them. In order to facilitate analysis, and in particular, to assess trends across indices which have different units and magnitudes, the test results for each paired comparison were expressed as a percentage change as follows:

$$\text{Percentage Change}_i = \frac{KIP_{i,T} - KIP_{i,B}}{KIP_{i,max}} \times 100$$

where

> i is the ith KIP index
>
> $KIP_{i,T}$ is the index value for a given test
>
> $KIP_{i,B}$ is the index value for the baseline test
>
> $KIP_{i,max}$ is the maximum index value across a group of related full scale tests

This particular form was used because it expresses the change due to a particular test variable, relative to the "worst case" value for a particular index across a group of related tests.

A positive percentage change in KIP indicates that the variable increased the average KIP values.

<u>Significance tests</u> - The test data involved a large number of paired comparisons. For each of these comparisons, a given variable could increase, decrease, or have no effect on a particular KIP index. In general, the results across hundreds of comparisons tend to be quite "mixed". However, the main goal was to assess the overall trends across the database, in terms of the effects of a given test variable on various groups of results, ie, for the groups of:

- 12 KIP variables;
- 3 motorcycle types; and
- 7 impact configurations.

Two overall indices were used to quantify these trends, namely,

- The average percentage change, for a group of results, and
- the 95% confidence interval of the average percentage change, which indicates the statistical significance[1)] of the average percentage change.

The average percentage change for each group was calculated in a straight forward manner, based on the "percentage change" values in the group.

The 95% confidence interval of the observed average percentage change was assessed in accordance with standard statistical methods. This takes into account the possibility that the observed differences may be due in part to random experimental variation.

In some instances repeat tests were performed which increased the number of statistical degrees of freedom for a given group. In these cases, in order to analyze the results using the paired comparison method, the repeat tests were paired chronologically, with the first treatment test being paired with the first baseline test, and the second treatment test being paired with the second baseline test, etc. When repeat tests were performed, equal numbers of variable and baseline tests were used.

TEST RESULTS

Maximum value of KIPs

<u>Add-on engine guard study</u> - As discussed above, the difference between KIP indices within a test pair was normalized using a maximum KIP value to produce a percentage change in the KIP index. The previous add-on engine guard work [1] involved 63 tests which were the basis for the maximum KIP values used in the calculation of the percentage change. For the current engine guard study, 90 tests (63 previous tests and 27 additional tests) were used to determine a set of maximum KIP values. Table 5 describes for each KIP the prior maximum value (based on 63 tests), the maximum value of the additional tests (27 tests) and the overall maximum based on 90 tests. Eight of the 12 maximum KIP values were increased due to the addition of the 27 tests, with 7 of the 8 new KIP maximum values being the result of impact Configuration 7. The overall maximum KIP values shown in Table 5 were used to normalize all add-on engine guard tests, in order to determine the percentage change in individual KIP values.

<u>Two-up and speed effects study</u> - Eleven new impact Configuration 5 two-up tests and four rider-only tests (the latter were also used as baseline tests in the add-on engine guard study) were used to assess the effects of passengers and speed variation on passenger and operator KIP. Table 6 shows the maximum operator or passenger KIP values from these 15 tests used to normalize the average percentage change in KIP indices for the two-up and speed effects study.

<u>Effects of maximum KIPs</u> - Reduced maximum KIP values have the effect of increasing the calculated percentage change of KIPs and the 95% confidence intervals. In general, the fewer the tests in a group,

---

1) A statistically significant result is reported when the average percentage change is greater than the 95% confidence interval. Note that results are shown rounded to the nearest percent

the smaller the maximum KIP is likely to be, and the larger the percentage changes and confidence interval. Therefore the results from the two-up and speed effects study (which have smaller maximum KIP values) will tend to result in larger averages and confidence intervals, all other factors being equal. However, since both the average and confidence intervals are "scaled" equally, changing maximum KIP values does not affect the statistical significance of the results.

Table 5
Maximum KIP Values for the Engine Guard Study

KIP	Max of Prior Tests (63 Tests)	Max of Additional Tests (27 Tests)	Overall Max (90 Tests)
HAR(g)	228	181	228
HIC(-)	1047	938	1047
PAR(g)	242	155	242
IPAR(g^2s)	98	57	98
HVZ(ft/s)	26.2	29.1 (7)	29.1
PH(ft)	2.6	3.7 (7)	3.7
PVX(ft/s)	-43.3	-45.4 (5)	-45.4
PWBAX(g)	-24.5	-39.0 (7)	-39.0
TPR(deg/s)	981	1296 (7)	1296
MVX(ft/s)	-42.3	-60.9 (7)	-60.9
MWBAX(g)	-19.9	-30.2 (7)	-30.2
HVR(ft/s)	5.3	10.7 (7)	10.7

( ) denotes impact configuration
Dark boxes denote the overall Max KIP

Engine Guard Results

Sixty-three test pairs were involved in the evaluation of the add-on engine guards. Each test pair consisted of an engine guard equipped motorcycle compared to a baseline motorcycle. The baseline cases for the Sport and Cruiser motorcycle had no engine guard installed. The baseline Touring motorcycle had as standard equipment a engine guard similar to the add-on accessory engine guard, and therefore it was not tested in a "no engine guard" condition.

Table 6
Maximum KIP Values for the Two-up and Speed Effects Study

KIP	Max Value
HAR(g)	134
HIC(-)	627
PAR(g)	155
IPAR(g^2s)	57
HVZ(ft/s)	20.2
PH(ft)	1.9
PVX(ft/s)	-28.6
PWBAX(g)	-20.8
TPR(deg/s)	1066
MVX(ft/s)	-27.3
MWBAX(g)	-12.5
HVR(ft/s)	8.6

When grouped by individual guard type, motorcycle type and impact configuration, the 63 test pairs populated 49 separate groups. The number of groups is less than the number of tests pairs due to repeat testing. Table 7 shows the "test matrix" indicating the number of test pairs found in each of the 49 separate groups.

Table 7
Engine Guard Test Matrix

Engine Guard	Motor-cycle Type	Impact Configurations								No. of groups
		1	2	3	4	5	6	7		
Accessory	Sport	1*	1	1	1	1	1	1		7
	Cruiser	1	1	1	2	6	1	1		7
Spec A	Sport	1	1	1	1	1	1	1		7
	Cruiser	1	1	1	2	2		1		6
	Touring	1	1	1	1	1	1	1		7
Spec B	Sport	1	1	1	1	1				5
	Cruiser	1	1	1	2	6				5
	Touring	1	1	1	1	1				5
										49
Number of Test Pairs		8	8	8	11	19	4	5	63	

* Number of Test Pairs

The average percentage change in KIP indices and the 95% confidence interval for each group is shown in Table 8. Nine groups (designated by boxes with thickened outlines) show statistically significant results.

The significant trends are:

- Three of the nine groups indicated that the average KIP decreased with the addition of an engine guard
    - the Accessory, Spec A, and Spec B engine guards each decreased the average KIP for 1 group
- Six of the nine groups indicated that the average KIP increased with the addition of an engine guard
    - the Accessory guard increased KIP in 1 group
    - the Spec A guard increased KIP in 3 groups
    - the Spec B guard increased KIP in 2 groups

Table 8

Summary of Average Percentage Change in KIP Indices Resulting from Add-on Engine Guards

Engine Guard Treatment	Motor-cycle Type	Impact Configuration						
		1	2	3	4	5	6	7
Accessory	Light	-11(9)	nd	-4(5)	-2(10)	10(10)	-5(16)	0(12)
	Medium	-5(17)	-2(8)	0(5)	-3(8)	3(3)	-3(14)	2(8)
Spec A	Light	4(8)	-3(11)	7(7)	27(23)	4(7)	-13(12)	0(9)
	Medium	2(28)	-5(6)	-1(6)	1(9)	14(10)	na	-1(17)
	Heavy	22(25)	2(5)	2(4)	5(7)	5(12)	3(7)	6(15)
Spec B	Light	-4(8)	-8(13)	-5(7)	16(18)	6(11)	na	na
	Medium	-1(17)	-5(6)	0(5)	1(5)	13(6)	na	na
	Heavy	-9(8)	4(4)	6(9)	-3(15)	13(10)	na	na

( ) denotes the 95 percent confidence interval on the average percentage change
"na" denotes test not performed
"nd" denotes no data because of data acquisition failure

When grouped by engine guard type and motorcycle type (ie, combining all impact configurations), the 63 test pairs were separated into 8 groups. Statistical analysis of these 8 groups (results shown in Table 9) indicated statistically significant differences in 2 of the 8 groups. The Spec A guard increased the average KIP for the heavy motorcycle, and the Spec B guard increased the average KIP for the medium motorcycle.

Table 9

Effect of Motorcycle Type on Average Percentage Change in KIP Indices Resulting From Add-On Engine Guard (across all impact configurations)

Engine Guard Treatment	Motorcycle Type	Average Percentage Change in KIP	Significant at 0.05 Level
Accessory	Light	-2(4)	no
	Medium	0(3)	no
Spec A	Light	4(5)	no
	Medium	3(5)	no
	Heavy	5(3)	yes
Spec B	Light	1(5)	no
	Medium	7(4)	yes
	Heavy	2(4)	no

When grouped by guard type and impact configuration (ie, combining all motorcycle types) 19 groups were formed (results are found in Table 10). Four of the 19 groups indicated statistically significant differences. The Accessory guard increased the average KIP for impact Configuration 5. The Spec A guard increased the average KIP for both impact Configurations 4 and 5, and the Spec B engine guard increased the average KIP for impact Configuration 5.

The engine guards appeared to have disadvantages for the 150 degree and 180 degree impacts (ie, where the motorcycle and car are moving in more opposing directions). The disadvantages for the Spec A guard (8% and 10% increases in KIP) and the Spec B guard (12% increase in KIP) are significantly higher than the 4% disadvantage observed with the Accessory guard in Configuration 5.

When each engine guard type is evaluated across all motorcycles and all impact configurations, the results are as shown in Table 11. The statistically significant differences are:

- The Spec A engine guard increased the averaged KIP value (ie, had a harmful effect) by 4% ± 3%,
- The Spec B engine guard increased the averaged KIP value (ie, had a harmful effect) by 4% ± 2%

Note that the results for the Accessory engine guard suggests a slight reduction (1%) in average KIP value but this is not statistically significant at the 0.05 level.

Table 10
Effect of Impact Configuration on Average Percentage Change in KIP Indices Resulting From Add-On Engine Guard (across all motorcycle types)

Engine Guard Treatment	Impact Configuration	Average Percentage Change in KIP	Significant at 0.05 Level
Accessory	1	-8(9)	no
	2	-2(8)	no
	3	-2(3)	no
	4	-3(6)	no
	5	4(3)	yes
	6	-4(10)	no
	7	1(7)	no
Spec A	1	6(12)	no
	2	-2(4)	no
	3	3(3)	no
	4	8(7)	yes
	5	10(6)	yes
	6	-5(7)	no
	7	2(7)	no
Spec B	1	-5(6)	no
	2	-2(4)	no
	3	0(4)	no
	4	4(6)	no
	5	12(5)	yes
	6		
	7		

A comparison of the above results to those previously published [1] indicates some small changes due to the additional tests pairs, impact configurations, and new maximum KIPs. However, the overall trends remain the same. Overall, the addition of two impact configurations, and 27 additional tests did not change the previously reported results, which indicated that the Spec A and Spec B engine guards increased overall average KIP values.

Table 11
Effect of Engine Guards on Average Percentage Change in KIP Indices Resulting From Add-On Engine Guard
(across all motorcycle and impact configurations)

Engine Guard Treatment	Average Percentage Change in KIP	Significant at 0.05 Level
Accessory	-1(2)	no
Spec A	4(3)	yes
Spec B	4(2)	yes

The Effect of a Passenger on Operator KIP

Four test pairs were assembled to study the effect of a passenger on operator kinematic injury potential. Each test pair involved the same motorcycle type, speed and impact configuration (all four test pairs involved Configuration 5). The four test pairs involved one Sport pair, two Cruiser pairs, and one Touring pair. For each test pair, an operator with passenger was compared to an operator without passenger (baseline). The results are shown in Table 12.

Table 12
Average Percentage Change in Operator KIP Resulting from the Addition of a Passenger

Motorcycle Type	Average Percentage Change in KIP	Significant at 0.05 Level
Light	-8(19)	no
Medium	6(12)	no
Heavy	15(17)	no
All MC Combined	5(9)	no

When grouped by motorcycle type, analysis indicated no statistically significant differences in operator KIP due to the presence of a passenger. When all motorcycle types are combined into a single group analysis also indicated no statistically significant differences in KIP. Therefore for these four test pairs there is no information indicating that a passenger

significantly changes the average operator kinematic injury potential.

Examination of the 12 individual KIPs for all 4 pairs (ie, the average percentage change of 4 HAR, HIC, etc) indicates that 11 of the 12 KIPs show no statistically significant change. However the presence of a passenger did lower the pelvic height (PH) of the operator 34% ± 28% for this speed and impact configuration, which is a beneficial effect for the operator.

The Effect of Vehicle Speed on Operator and Passenger Average KIP

Ten two-up tests were analyzed to evaluate the effect of vehicle speeds on operator and passenger average KIPs. Five 20/20 mph tests (one Sport motorcycle and four Cruiser motorcycles) were done in the offset frontal Configuration 5. Five matching 30/10 mph tests were also performed. The average percentage change of KIP indices and the corresponding confidence intervals are shown in Table 13.

Table 13
Average Percentage Change in KIP
Resulting from Changing Impact Speeds
from 20/20 mph to 30/10 mph

Rider	Motor-cycle Type	Average Percentage Change in KIP	Significant at 0.05 Level
Operator	Light Medium	-5(21) 6(10)	no no
Passenger	Light Medium	-3(24) -2(8)	no no
Operator	All MC	4(9)	no
Passenger	All MC	-2(7)	no
Combined Operator and Passenger	All MC	1(6)	no

When grouped by motorcycle type, analysis indicated no statistically significant changes in KIP due to speed for either the operator or passenger for either the light or medium motorcycle types. In addition when all motorcycle types were grouped together neither the operator nor passenger KIPs indicated a statistically significant change. Finally when the results for all motorcycle types and both the operator and passenger are grouped together, there were no statistically significant changes in KIPs. Therefore, for impact Configuration 5 there is no statistical information indicating that changing impact speeds from 20/20 mph to 30/10 mph changes the average KIP.

Several factors could contribute to this apparent lack of speed sensitivity for this particular change in test speeds. First, the KIPs are primarily related to head and upper body injury potential. The combined LA and Hannover accident databases [5] show that the offset front impact Configuration 5 does not generally have a high frequency of head injuries.

Second, the initial motorcycle to OV impact forces for the 20/20 and 30/10 mph impacts are essentially the same, since both speed combinations result in a 40 mph (64 km/h) relative closing speed between vehicles. Although the relative speeds of the operator and passenger with respect to the opposing vehicle are the same in both speed combinations, the operator and passenger speeds in the 30/10 mph tests are greater with respect to the ground. Therefore the 30/10 mph tests could potentially result in more severe passenger and operator impacts with the ground. However, 8 of the 12 KIPs analyzed are based on photo optic data, which due to the two dimensional limitations of the analysis procedure, are limited to the initial phases (500 ms or less) of the impact sequence which generally does not include ground contact. Therefore, ground impacts are not heavily weighted when calculating the average percentage change in kinematic injury potential; and this may contribute to the lack of speed sensitivity noted above.

In order to further address this issue, the 4 electronic KIPs (HAR, HIC, PAR, and IPAR) which are measured over the entire impact sequence were analyzed to determine if there was a statistical difference between ground impacts for the 30/10 and for the 20/20 mph tests. This analysis was performed by creating test pairs comparing both the operator and passenger ground impacts for the 30 mph motorcycle with those for the 20 mph motorcycle (baseline) case. The average percentage change of KIP and confidence intervals were calculated using the procedures described previously, except that this analysis was limited to the 4 electronic data measures. The results (Table 14) indicate that changing the speed from 20/20 to 30/10 mph produced a statistically significant increase (22% ± 19%) in the operator ground impact (electronic) KIPs.

Table 14
Average Percentage Change in Ground Impact KIP Resulting from Changing Test Speeds from 20/20 mph to 30/10 mph

Rider	Average Percentage Change in KIP	Significant at 0.05 Level
Operator	22(19)	yes
Passenger	-10(20)	no
Combined Operator and Passenger	8(14)	no

Passenger KIPs Compared to Operator KIPs

For this case, 11 pairs were created by comparing the passenger average KIP from a given test to the operator (baseline) average KIP for the same test. All 11 tests involved impact Configuration 5 and either a 20/20 or 30/10 mph impact. The change in average percentage KIP and the confidence intervals calculated for this analysis are shown in Table 15.

Table 15
Average Percentage Change in KIP Indices when Comparing a Passenger to an Operator

Motorcycle Type	Test Speeds (MC/OV mph)	Average Percentage Change in KIP	Significant at 0.05 Level
Light	20/20	5(24)	no
	30/10	2(19)	no
Medium	20/20	-2(8)	no
	30/10	-10(8)	yes
Heavy	20/20	-15(15)	no
Light	All speeds	3(13)	no
Medium	All speeds	-6(6)	yes
All types	All speeds	-5(5)	yes

When grouped by motorcycle type and speed, 1 of 5 groups indicated a statistically significant change. The passenger average KIP was found to be lower than the operator average KIP for the 30/10 mph Cruiser motorcycle impacts. When both speed combinations were combined and the tests were grouped by motorcycle type, the average passenger KIP for the Cruiser was found to be lower than the average operator KIP. When all motorcycle types and speeds are combined, the passenger KIP is 5% ± 5% lower than the average operator KIP.

A review of the test films from the 11 impact Configuration 5 (180 degree off-set frontal impact) two-up tests showed initial contact between the front of the passenger dummy and the back of the operator dummy. in general, this contact tends to create forces acting downward on the operator and upward on the passenger. In addition when the 12 individual KIPs for all 11 pairs were analyzed (ie, average change of 11 HAR's, HIC's, etc) 10 of the 12 individual KIPs indicated no statistically significant difference. However 2 KIPs indicated a statistically significant difference between the passenger and operator. The passenger pelvic height (PH) is 28% ± 16% greater than that of the operator; and the passenger change in head resultant velocity (HVR) is 18% ± 17% less than that of the operator. Therefore, for this speed and impact configuration, dummy to dummy contact appears to result in a higher pelvic height for the passenger and a lower resultant head velocity for the passenger.

It is possible that changes in operator or passenger vertical head positions may occur, due to presence of the passenger, but to date this has not been analyzed.

Although limited to 2 speeds and 1 impact configuration, these test results, which show an overall decrease in passenger KIPs, do not appear to be in conflict with accident data [2].

SUMMARY AND CONCLUSIONS

Summary

A series of 101 full scale crash tests were performed to assess the effects of add-on engine guards, passengers, and impact speeds on motorcycle/car impact performance. The test program involved a relatively broad range of variables including

- 3 engine guards
- 3 motorcycle types
- 7 impact configurations
- 2 speed variations
- tests with and without passengers

Dynamic measurements for all tests included

electronic data collected from both the operator and passenger dummies as well as photo-optic data resulting from digitizing high speed films. The electronic and photo-optic data was used to calculate a set of 12 kinematic injury potential (KIP) indices for each test and each dummy.

Data analysis involved defining 88 paired comparisons between individual tests. Each paired comparison was between a specific baseline test and a test in which a specific test variable was changed. Therefore, nominally, the test variable was the only difference between the two tests in a test pair. Test variables included in this study were:

- the presence or absence of a add-on engine guard;
- the effect of a passenger on operator injury potential;
- the effect of changing motorcycle/car impact speeds from a 20/20 mph speed combination to a 30/10 mph vehicle speed combination; and
- passenger injury potential versus operator injury potential.

For each variable and each paired comparison, the percentage change in each KIP index, due to the variable, was determined. Trends across groups comprising: all KIP indices; all motorcycle types; all impact configurations; and all motorcycle types and impact configurations, were determined. For each group and for each variable a statistical analysis was performed to assess the effects of the test variable, on kinematic injury potential.

Conclusions and Recommendations

Previously published results [1] had shown that when the data for all motorcycle types and all impact configurations were combined, both of the Spec A and Spec B non-standard heavy duty engine guards produced statistically significant increases in kinematic injury potential. The Accessory engine guard produced no statistically significant change in kinematic injury potential. The current research, which is an expansion of this earlier work to include additional test pairs and impact configurations, confirmed the previous conclusion that, since the Spec A and B engine guards increased kinematic injury potential for the motorcycle and impact configurations examined, heavy duty engine guards cannot be recommended for general application to motorcycles.

Tests utilizing impact Configuration 5 (an offset frontal impact) with both an operator and passenger indicated that, overall, the presence of a passenger resulted in no statistically significant change in operator kinematic injury potential. The presence of a passenger did however result in a statistically significant reduction in the operator pelvic height, which can be considered to be a beneficial effect.

Tests with impact Configuration 5 (offset frontal impact) using 2 different vehicle speed combinations indicated no statistical indication that changing the impact speeds (from a 20 mph motorcycle with 20 mph opposing vehicle, to a 30 mph motorcycle with 10 mph opposing vehicle) changes the average KIP. This result is influenced by the fact that the majority of KIP indices used are related to the primary impact between the motorcycle, dummies and opposing vehicle. For both speed combinations tested, the vehicles had the same relative closing speed and therefore similar primary impact forces. The operator ground impact KIPs for the 30 mph (48 km/h) motorcycle were found to be greater than the operator ground impact KIPs for the 20 mph (32 km/h) motorcycle impact.

When comparing passenger KIP to operator KIP for Configuration 5 impacts, the results show a statistically significant difference between passenger KIPs and operator KIPs, with the passenger KIPs being about 5% lower than the operator KIPs. These results however are based on a single impact configuration (a frontal offset impact) where the operator precedes the passenger into the impact zone.

The results described represent the largest group of tests to date to evaluate the effect of engine guards on motorcycle impact performance, and the only known statistical analysis of the effect of passengers on motorcycle impact performance. However, the passenger and speed effect tests were limited to one impact configuration and two different speed combinations. Testing involving passengers at different impact configurations and speed combinations could provide further insights into the effects of passengers on overall crash dynamics.

Refinements in current dummy designs should also be considered to either reduce failure of structural parts which are not intended to fracture, or to prevent the loss of body parts such as the legs, when failures of key structural components occur. The use of redundant load paths such as cables or light weight "flexible structural skin" should be considered to prevent frequent loss of large masses from the dummy, which is a rare event in real accidents and which in tests can affect subsequent dummy kinematic performance and motions.

Additional analysis of the existing database might also result in further insights into injury potential assessment. Such analysis might consider the development of new KIPs to assess the effect of ground impacts on head and neck injuries using the high speed films, and/or paired comparison head trajectory analysis. Future consideration of such aspects could provide further insights into motorcycle impact performance.

REFERENCES

[1] Schmeling, G., Archer, R., Wiley, K.D., and Zellner, J.W., "Motorcycle Impact Performance," Fourteenth International Technical Conference on Enhanced Safety of Vehicles, Munich, Paper No.94-S7-0-06, May 1994.

[2] Hurt, Jr., H.H., Ouellet, J.V., and Thom, D.R., Motorcycle Accident Cause Factors and Identification of Countermeasures, Final Report, DOT-HS-5-501160, University of Southern California, Jan 1981.

[3] Otte, D., A Review of Different Kinematic Forms in Two-wheeled accidents: Their Influence on Effectiveness of Protective Measures, SAE 801314, Society of Automotive Engineers, Inc., 1980.

[4] Otte, D., P. Kalbe, and E.G. Suren, Typical Injuries to the Soft Body Parts and Fractures of Motorized Two-wheelers, IRCOBI Conference, France, 1981.

[5] Pedder, J.B., Otte, P. and H.H. Hurt, Jr., Motorcycle Accident Impact Conditions as a basis for Motorcycle Crash Tests, Twelfth International Technical Conference on Experimental Safety Vehicles, Sweden, 1989.

[6] Anon., Instrumentation for Impact Test, SAE J211b, Society of Automotive Engineers, Inc., Dec 1974.

Application of ISO 13232 to Motorcyclist Protective Device Research

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ABSTRACT

International Standard 13232 has been developed and internationally approved for the purpose of providing common research methods for assessing the feasibility of protective devices which might be fitted to motorcycles and which are intended to reduce injuries to riders resulting from car impact. The Standard represents the current international consensus of relevant experts from 10 participating nations reached through the committee process. The Standard involves agreed methods for: description of a standardized motorcycle accident population; a specialized motorcyclist crash dummy; measurement methods; injury indices; full scale test procedures and conditions; and methods for calibrating and using computer simulations to predict performance across the population of accidents. The Standard provides a practical and specific means for evaluating the comparative effects of proposed protective devices. Results of applying the Standard to a full scale test evaluation of an example proposed UKDS motorcycle leg protector device are presented and discussed, along with suggestions for possible future refinements of the Standard.

INTRODUCTION

During the last 25 years, research on the feasibility of rider crash protection devices which might be fitted to motorcycles has occurred in Great Britain, Japan, Germany, and the United States. This research has involved various industry, government and private organizations; a variety of test methods, as reviewed by Sakamoto (1990); and different rider protection philosophies, for example, those described by Sporner, et al (1990).

One example of such research in the 1980's was the leg protector work of TRRL, the United Kingdom's Transport and Road Research Laboratory (now TRL), which led in 1987 to a proposed Draft Specification (UKDS) for motorcycle leg protectors.

Subsequently, several UKDS leg protector designs were evaluated in full scale tests by TRRL and by the motorcycle industry, with generally opposite results (TRRL, 1991; Rogers, 1991a, 1991b). In particular, one leg protector design was separately evaluated by TRRL and by the industry, using different test methods (Rogers, 1994), and this resulted in large differences in measurements and conclusions. Table 1 compares some of the different test procedures used during this period of research.

An International Leg Protector Seminar (IMMA, 1991) and the recommendation of experts in the crash protection field led to the conclusion that an internationally accepted motorcyclist crash dummy and research methodology were necessary first steps, before further objective and meaningful research could be pursued.

This paper reviews the development, content and status of a common research methodology which has been standardized in ISO 13232; and illustrates the application of the Standard to the full scale test evaluation of an example UKDS leg protector device.

BACKGROUND

Development of ISO 13232

Recognizing the need for common test and evaluation methods, the United Nations Group for General Road Vehicle Safety (UN/ECE/TRANS/WP29/GRSG) decided in March 1992, at the suggestion of the International Motorcycle Manufacturers Association (IMMA), to ask the International Organization for Standardization (ISO), to establish a common research methodology for motorcycle crash testing.

GRSG's parent committee, UN Working Party 29, approved the plan but asked that the standard be completed before the end of 1995, which meant that a complete draft would be needed by Spring 1994.

In September 1992, the motorcycle subcommittee of ISO (ISO/TC22/SC22) established a new working group, WG22, to deal with "motorcycle research impact test procedures".

Six working group meetings were held between November 1992 and April 1994 involving some 25 experts and observers from the United Kingdom, Germany, France, the Netherlands, Belgium, Italy, the United States of America, Japan, Canada, and China, with input from both the motorcycle industry worldwide and technical experts in the crash research field (Van Driessche, 1994). As official originator of the proposed ISO standard, IMMA provided to WG22 an initial working draft (WD), based on methods developed and used by the motorcycle industry in preceding years. In the process of preparing more detailed and complete drafts, WG22 based its work on the use of such existing technology, consensus procedures, and data indicating method feasibility. The Standard was therefore a codification of methods which, for the most part, were available and in use. In addition, throughout the drafting process, liaison was maintained with the corresponding ISO car subcommittees.

In Summer 1994, a committee draft (CD) was balloted and approved within SC22. This was followed by balloting of a Draft International Standard (DIS); and final approval of the DIS by the ISO National Member Bodies in March 1996. Publication of ISO 13232 is anticipated in Summer 1996.

Review of ISO 13232 provisions

ISO 13232 consists of 8 interacting and mutually dependent parts:

- Part 1: Definitions
- Part 2: Definition of impact conditions in relation to accident data
- Part 3: Motorcyclist dummy
- Part 4: Measurements
- Part 5: Injury indices and risk/benefit analysis
- Part 6: Full scale impact test procedures
- Part 7: Computer simulation procedures
- Part 8: Test and simulation documentation

Application of these 8 parts enables:

- Quantitative measurement of the effects of the device on injury indices, for each body region, and summed across all body regions;
- A full scale test evaluation of the effects of a proposed device, based on seven pairs of full scale impact tests (ie, each pair comprising a motorcycle with and without the device fitted); and
- An overall evaluation of the predicted effects of the proposed device, across a sample of the accident population, based on a calibrated computer simulation, and 200 pairs of simulated impacts (with and without the device fitted).

Table 2 summarizes some of the main provisions of the Standard. A more detailed description of the provisions and rationale is given by Van Driessche (1994). In addition, specific rationale for the provisions is included in the Standard.

Continued refinement of the Standard

It is anticipated that the Standard will be amended whenever necessary to take into account new research needs, technological progress, and practical experience.

Currently, WG22 technical work is continuing toward definition of a possible first revision of the Standard, taking into account practical experience and new technology.

EXAMPLE APPLICATION OF THE STANDARD

Objectives of this study

The objectives of the research reported herein were:

- To assess the practicality and feasibility of ISO 13232; and
- To apply ISO 13232 in a full scale test evaluation of an example proposed protective device.

The example device to be evaluated was a UKDS leg protector, designed and fitted by TRRL to a Kawasaki GPZ 500 motorcycle. This specific design has been the subject of previous reports, namely those of:

- Chinn (1990), using test methods (eg, TRRL in Table 1) quite different from those of ISO 13232;
- Rogers (1994), using test methods (eg, IMMA in Table 1) similar but not identical to those of ISO 13232.

***Vehicle Data**[1)]

*Motorcycle - The test motorcycle (MC) was a Kawasaki GPZ 500 with specifications given in Table 3. Photographs of the test motorcycle are given in Figs 1 and 2.

*Opposing Vehicle - The opposing vehicle was a production Toyota Corolla 4 door saloon, Japan domestic model, model year 1988 to 1990, inclusive, as specified in ISO 13232-6. Specifications are summarized in Table 4. Photographs of the opposing vehicle are given in Figs 3 and 4.

*Proposed Protective Device - Photographs of the UKDS leg protector as designed and fitted to the test motorcycle by TRRL are given in Figs 5 and 6. Table 5 describes the leg protector, and some laboratory test data for it are described by Rogers (1994).

Test Facility

The test facility used for the full scale impact tests was that of the Japan Automobile Research Institute (JARI). The facility consists of a main rail along which a motorcycle trolley is drawn by cable; and a series of side runways at various angles to the main rail, along which the opposing vehicle is drawn by cable. The vehicle speed ratio is determined by a system of pulleys. The motorcycle is guided to the point of impact by braces at the handlebar, wheels and main frame until its release just prior to impact. The motorcycle front and rear wheels roll along the ground during the entire delivery and impact sequence.

With regard to performance, the measurements indicate that, at the JARI facility, the relative and absolute tolerance requirements of ISO 13232-6 were achieved for all the tests reported herein, in terms of: relative heading angle, opposing vehicle and motorcycle impact speeds, motorcycle roll angle and opposing vehicle contact point.

***Impact Configurations**

*Nominal impact configurations - The impact configurations (IC's) for the full scale tests were the seven IC's required by ISO 13232 for a full scale test evaluation of a proposed device, and illustrated in Fig 7, namely:

- IC1 : broadside
- IC2 : angled car front
- IC3 : T-bone, moving/moving
- IC4 : angled car side, similar direction
- IC5 : angled car side, opposing direction
- IC6 : offset frontal
- IC7 : T-bone, stationary car

*Photographs before first MC/OV contact - Photographs from the high speed camera film for MC top and side views of the frame immediately preceding first MC/OV contact for each of the 14 tests are given in Annex 1.

*Measured conditions - The measured conditions for each test as determined from high speed camera film and still camera are presented in Table 6.

***Paired Comparison Information**

In all seven pairs of full scale tests, each test met the impact condition requirements of ISO 13232-6, 4.5; and all seven test pairs were complete pairs.

As indicated under "measured conditions", there were no out-of-tolerance tests, using the methods and measurement resolution associated with ISO 13232. There was, however, some uncertainty in whether the dummy position tolerances were met, and to a lesser extent, in the other impact conditions, due to the limited measurement resolution which is inherent in the methods used in the current Standard. It can be stated that within the resolutions associated with ISO 132323, all tests were within tolerance.

***Items not complied with**

Annex 2 lists and provides explanations for ISO 13232 items not complied with. The main item pertained to some uncertainty in meeting the dummy position tolerance, due to the limited resolution of the measurement method specified by the Standard.

***Impact Sequences**

The impact sequence information for each of the 14 full scale tests is listed in Annex 3.

[1)] * denotes items recommended by ISO 13232 to be included in any publications which cite the Standard

•Performance Data

Annex 4 lists the performance data for each of the 14 full scale tests, for the primary impact, and for the entire impact sequence, as specified in ISO 13232-8, A.8.4.

•Summary of Individual Paired Comparison Results

Within each of the seven test pairs, fitment of the LP resulted in mixed changes in injury indices. "Mixed" means that, within each test pair, some of the injury indices indicated increases in injuries, some indicated no change, and some indicated decreases in injuries, due to fitment of the protective device.

In other words, in none of the seven test pairs did all of the injury assessment variables, injury potential variables, and injury indices specified in Table 1 of ISO 13232-8, change in one direction (ie, either beneficial or harmful), as a result of fitment of the leg protector.

•Summary of comparisons across impact configurations

Across the seven impact configurations tested and during the entire impact sequence (except as noted), fitment of the leg protector resulted in the following changes:

* Head maximum GAMBIT:
  *increased in 5 out of 7 cases;
  *decreased in 2 out of 7 cases;

* Head HIC:
  *increased in 4 out of 7 cases;
  *decreased in 3 out of 7 cases;

* Head AIS:
  *increased in 3 out of 7 cases;
  *remained the same in 3 out of 7 cases;
  *decreased in 1 out of 7 cases;

* Risk of life threatening head injuries:
  *increased in 1 out of 7 cases;
  *remained the same in 4 out of 7 cases:
  *decreased in 2 out of 7 cases;

* Neck shear injury index:
  *increased in 4 out of 7 cases;
  *decreased in 3 out of 7 cases;

* Neck tension injury index:
  *increased in 4 out of 7 cases:
  *decreased in 3 out of 7 cases;

* Neck compression injury index:
  *increased in 5 out of 7 cases;
  *decreased in 2 out of 7 cases;

* Neck flexion injury index:
  *increased in 3 out of 7 cases;
  *decreased in 4 out of 7 cases;

* Neck extension injury index:
  *increased in 2 out of 7 cases;
  *decreased in 5 out of 7 cases;

* Neck torsion injury index:
  *increased in 4 out of 7 cases;
  *decreased in 3 out of 7 cases;

* Chest AIS was zero in all cases;

* Abdomen AIS was zero in all cases;

* Femur AIS=3 fractures:
  *increased in 1 out of 7 cases;
  *remained the same in 5 out of 7 cases;
  *decreased in 1 out of 7 cases;

* There were no knee AIS=2 or 3 dislocations in any of the tests;

* Tibia AIS=2 fractures:
  *remained the same in 5 out of 7 cases;
  *decreased in 2 out of 7 cases;

* There were no tibia AIS=3 fractures in any of the tests;

* Helmet maximum vertical difference in trajectory (compared to the baseline trajectory) during the primary impact period was:
  *lower in 6 out of 7 cases;
  *undefined in 1 out of 7 cases (as noted in Annex 2);

* Percentage change in helmet velocity, at first helmet/OV contact was:
  *positive in 1 case;
  *negative in 4 cases;
  *undefined in 2 cases (as noted in Annex 2);

* Percentage partial incapacity index:
  *increased in 1 out of 7 cases;
  *remained the same in 5 out of 7 cases;
  *decreased in 1 out of 7 cases;

* Probability of fatality:
  *increased in 4 out of 7 cases;
  *remained the same in 1 out of 7 cases;
  *decreased in 2 out of 7 cases;

Note that some of the indicated body region changes were at less than injurious levels and some were at injurious levels, and this important difference should be considered when evaluating these results. ISO 13232 takes this into account by requiring the "total normalized injury cost" to be evaluated. In this regard, the:

* Total normalized injury cost (TNIC):
  *increased in 4 out of 7 cases;
  *remained the same in 1 out of 7 cases;
  *decreased in 2 out of 7 cases.

In the case of the neck, ISO 13232 does not quantify probable injury severities (as it does for other body regions), and the neck is not included in the normalized probable injury cost. However, it was observed in the test data that, of the six neck injury indices, the neck compression injury index tended to have the largest values in these tests (ie, be the closest to the levels for potential serious injury indicated in the Standard). Fitment of the leg protector increased the neck compression injury index in 5 out of 7 cases.

Figure 8 summarizes the main injury indices for the seven test pairs. Also indicated is the frequency of occurrence of each of the seven impact configurations in the 501 Los Angeles/Hannover accidents described in ISO 13232-2, annex B.

The main leg protection benefit occurred in the offset frontal configuration (accident frequency = 1), due to elimination of lower leg fracture in this case; and in the moving-moving T-bone configuration (accident frequency = 4), due to decreased head injury (from AIS 2 to AIS 1) in this case.

The main leg protector harmful effects occurred in the stationary T-bone configuration (accident frequency = 5), due to greatly increased head injury (from AIS 0 to AIS 5); the angled car front configuration (accident frequency = 7) due to transfer of injury from the lower to the upper leg, and also due to an increased head injury (from AIS 0 to AIS 1); and the broadside configuration (accident frequency = 3), due to increased head injury (from AIS 0 to AIS 1).

With regard to frequency of occurrence, the most frequently occurring of the seven impact configurations (IC4, the angled car side, similar direction) indicated some leg protector harm (TNIC increase of 0,035 life unit[2]); and the second most frequent configuration (IC2, angled car front) indicated substantial leg protector harm (TNIC increase of 0,115 life unit).

Overall, the largest change due to fitment of the leg protectors, and the most injurious test overall, was the stationary T-bone impact configuration with leg protectors noted previously (with a normalized probable injury cost (TNIC) increase of 0,67 life unit). It is observed that this impact configuration has an above average frequency of occurrence among the seven full scale test configurations, and has twice the average frequency of occurrence of the 200 Los Angeles/Hannover configurations.

After taking into account the frequency of occurrence of each of the seven impact configurations, the overall total normalized injury cost for the seven impact configurations increased by 315%, as a result of fitment of the UKDS leg protectors.

Discussion of Cause/Effect Relationships

The high speed films, electronic data and helmet trajectory and velocity data were examined in order to identify the causes of the leg protector harmful effects in the stationary T-bone and angled car front configurations.

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[2] ISO 13232 quantifies total body injury in terms of total normalized injury cost (TNIC). The normalization is relative to the average cost of a fatality, based on bioeconomic data. A TNIC value of 1,0 corresponds to the cost of one fatality (or life); and therefore the TNIC units could also be called, in this limited sense, "life units".

Figures 9 and 10 are photographs from the high speed films of the stationary T-bone tests, indicating the position of the helmet at first contact with the car. With the baseline motorcycle, the helmet contacts the top of the roof of the car with a head acceleration of 112 g and AIS 0 head injury. With the leg protector motorcycle, the helmet impacted the edge of the roof, resulting in a head acceleration of 193 g, and an AIS 5 head injury. The helmet trajectory with leg protectors was found to be 123 mm (4.8 inches) lower than with the baseline motorcycle. This lower helmet trajectory was the result of the large leg protector restraint forces acting on the knees (4,9 kN (1 110 lb)), which caused the torso to pitch downward about the hips.

In the angled car front configuration, a similar lower helmet trajectory occurred with leg protectors (88 mm(3.5 inches) lower than with the baseline motorcycle); and the resultant head acceleration was increased (from 42 g for baseline to 75 g for leg protectors) during primary impact. The leg protector acted to prevent fracture of the lower leg by preventing initial car contact thereby reducing the bending moment on the tibia. However, as indicated in Figure 11, the leg protector increased the left femur compression force (from 4,33 kN (970 lb) to 5,97 kN (1 340 lb)). More importantly, the femur bending moment (My) (as sensed at the upper femur load cell) was more than doubled by the leg protector (from 199 Nm to 424 Nm) resulting in a bending fracture of the femur. Examination of the high speed films and electronic data indicated that this was the result of the knee being forced into the knee protection element, followed by upward movement of the hip during the impact, leading to very large forces and torques at the knee. This same knee "jamming" or "fixity" phenomenon was observed in previous research (eg, Rogers, 1991a), and appears to be a fundamental deficiency of systems which concentrate all the restraint forces on the knees, whilst the hip and upper body continue to move in other directions.

Overall evaluation (risk/benefit) analysis by computer simulation

In general, in order to do an overall evaluation of a proposed protective device, the performance across the sample of 501 motorcycle/car accidents (distributed among 200 impact configurations) should be evaluated, as required by ISO 13232. The Standard recommends this be done by means of a suitably calibrated computer simulation; and detailed requirements for the formulation, calibration and use of the simulation are defined.

Efforts to do such an overall evaluation of the UKDS leg protector device by computer simulation are continuing at the present time.

CONCLUSIONS AND RECOMMENDATIONS

ISO 13232

International Standard 13232 specifies methods for evaluating the feasibility of proposed rider protective devices which might be fitted to motorcycles, and represents an international consensus on test procedures and current evaluation technology.

In the research reported herein, the procedures and methods of ISO 13232 were found to be both practical and feasible, and the Standard appears to be a useful tool for research in the field of secondary safety devices on motorcycles.

In particular, the relative and absolute tolerance requirements of ISO 13232 were met, with regard to: relative heading angle, opposing vehicle and motorcycle impact speeds, motorcycle roll angle and opposing vehicle contact point.

Based on this research, and acknowledging the complexity and size (in excess of 400 pages) of the Standard, it is inevitable that some refinements to ISO 13232 might need to be considered, such as, for example:

- Dummy position tolerance criteria and/or measurements methods should be improved, as the current measurement resolution is too coarse;
- Revised motorcyclist neck and neck injury indices should be developed (for improved biofidelity and to provide a means for neck injury prediction in motorcycle crash tests);
- Additional, optional, specified dummy equipment should be permitted, including gloves and alloy shoulder (for better durability) and vest (to prevent arm separation due to shoulder failure);
- Revised height for overhead camera (current height is somewhat impractical);
- Revised procedure for digitizing helmet position in broadside impact (to account for large y motions);

and
- Other items.

UKDS leg protectors

The effects of UKDS leg protectors on rider injuries were assessed by means of seven pairs of full scale motorcycle/car impact tests, using motorcycles fitted and not fitted with TRRL designed UKDS leg protectors, according to ISO 13232. As in previous research, it was found that fitment of leg protectors resulted in a mixture of beneficial and harmful effects.

Upper and lower leg fractures were eliminated in the offset frontal impact configuration (which is the least frequently occurring accident among the seven standard impact configurations).

However, similar to the results of previous research, fitment of the UKDS leg protector resulted in increased head injury severities in 3 out of 7 impact configurations; increased probability of fatality and injury costs in 4 out of 7 impact configurations; and increased neck compression injury index in 5 out of 7 impact configurations. This was observed to be the result of forward and/or lateral torso pitch, caused by a robust restraint of the knee, as seen in Figs 9 and 10.

With regard to injury cost, fitment of leg protectors increased by more than 300% the overall total normalized injury cost of the seven full scale impact configurations specified by ISO 13232.

Other harmful effects resulting from leg protector fitment include transfer of leg injury -- from the lower leg to the upper leg -- in the angled car front impact (the second most frequently occurring of the seven standard impact configurations). This transfer of injury is a fundamental result of the way in which the knee is restrained, which applies large forces and torques sufficient to fracture the femur. Such femur fractures are more severe and costly (and in some cases life threatening) than the lower leg fractures which leg protectors are intended to reduce.

Such harmful effects are undesirable and unacceptable in any device intended to improve safety. Based on these results and the previous research, this type of device should not be fitted to production motorcycles. For the same reasons, there appears to be little merit in the further development of this protection concept.

Research into the feasibility of other rider protective devices and concepts, and refinement of research methods, should continue.

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REFERENCES

Anon., Motorcycles - Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles, ISO 13232, International Organization for Standardization, Geneva, 1996 (forthcoming).

Anon., "Leg Protectors: Do They Work", Proceedings of the International Seminar on Leg Protectors - Chantilly, France, International Motorcycle Manufacturers Association, Fresnes, France, November 1991.

Anon., "TRRL Review of Research on Motorcycle Leg Protection - 1991", Transport and Road Research Laboratory, Crowthorne, 1991.

Chinn, B.P., and Karimi, H., "Leg Protection for a Sports Motorcycle," Society of Automotive Engineers Paper 900748, February 1990.

Rogers, N.M., "Further Crash Tests of Motorcycle Leg Protectors as Proposed in the UK Draft Specification", 13th International Technical Conference on Experimental Safety Vehicles, Paris, November 1991a.

Rogers, N.M., "A Technical Evaluation of Motorcycle Leg Protectors", 13th International Technical Conference on Experimental Safety Vehicles, Paris, November 1991b.

Rogers, N.M., Evaluation of TRL Designed Leg Protectors for a Medium Sized Sport Motorcycle," 14th International Technical Conference on the

Enhanced Safety of Vehicles, Munich, May 1994.

Sakamoto, S., "Research History of Motorcycle Leg Protection", Society of Automotive Engineers Paper 900755, Feb 1990.

Van Driessche, H., "Development of an ISO Standard for Motorcycle Research Impact Test Procedures", 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, May 1994.

Sporner, A., Langwieder, K. and Polauke, J., "Passive Safety for Motorcyclists - From Leg Protector to the Airbag", Society of Automotive Engineers Paper 900756, 1990.

Table 1
Comparison of Some of the Past Test Methods used in Leg Protector Research

Test Element	TRRL	IMMA
Dummy	Modified OPAT	Modified Hybrid III
Injury indicating dummy legs	Aluminum honeycomb on metal plates	Breakable composite bones
Dummy knees	1 axis	3 axis
Data acquisition system	External, via cable	Internal to dummy (to avoid motion distortion due to cable)
Dummy hand position	Taped to fuel tank	Grippable hands on handlebars
Opposing vehicle	GM Vauxhaul Ford Sierra various others	Toyota Crown Toyota Celica
Relative angle between motorcycle and car	various, at 30° increments	various, at 45° increments
Motorcycle wheels prior to release from trolley	Stationary	Rolling (for increased stability, accuracy, realism)

Table 2.
Summary of Some Main Provisions of ISO 13232

Provision	Explanation/Reasons
Part 1: Definitions	
* Paired comparison	- Testing and comparing results of two crash tests where the only variable is the presence of a proposed protective device.
* Impact conditions	- The 5 variables which describe an impact: the MC and opposing vehicle (OV) speeds and contact points; and their relative heading angle.
* Injury index	- A measure of the probability of a specific injury and/or injury cost, based on measured values of the injury assessment variables and/or frangible component data.
* Frangible component	- Components of the dummy which are intended to mechanically at prescribed force/deflection values, in order to simulate human injury mechanisms, and to record predicted injuries.
* Injury costs	- The expected costs of an observed or simulated injury or set of injuries based on standardized bio-economic data, to allow comparisons across body regions and among crash tests.
Part 2: Impact conditions in relation to accident data	
* 7 impact configurations for full scale tests	- See Figure 7. Configurations which are feasible at some existing outdoor impact test facilities; and which are either frequently occurring or injurious in the accident data; or have been used in past research.
* 200 impact configurations for overall evaluations of a protective device, via calibrated computer simulation	- Based on Los Angeles and Hannover data, this provides a standard sample of the population of MC/car impacts.
Part 3: Motorcyclist dummy	
* Hybrid III 50th percentile male basis dummy, with sit/stand construction, compatible with 6 axis upper neck load cell	- Response biofidelity - Availability of supporting data - Motorcycle seat compatibility - Helmet compatibility
* Motorcyclist head skins	- More realistic interaction with prototype airbags
* Neck shroud	- Wider adjustment range for riding positions
* Modified lower neck mount	- Improved biofidelity in oblique head impacts
* Torsion element	- More realistic head orientation, and adjustment for riding position
* Replacement nodding blocks	
* Replacement thoracic spine	- To contain internal recorder
* Modified chest skin	- Enable static torso angle measurement
* Modified straight lumbar spine	- More realistic riding position - Improved biofidelity (decreased stiffness)
* Frangible abdominal insert	- To record abdominal penetration (frontal and oblique)

Table 2., Continued

Provision	Explanation/Reasons
* Modified pelvis (optional)	- To contain internal recorder
* Indexed elbow bushing	- For positioning, to prevent elbow locking during test
* Grippable hands	- To grip handle bars, stabilize dummy on motorcycle in realistic manner
* Frangible femur and tibia bones	- To monitor for fracture along length, around circumference of bones - Improved biofidelity (human-like stiffness) - More human-like motion after fracture
* Frangible knee	- To monitor for dislocation at the knee joint, in torsion and lateral bending
* Leg retaining cables	- To prevent separation of the leg after bone fracture (functions like human sinew)
* Frangible component conformity of production (initial and subsequent)	- For certification and quality control purposes
Part 4: Measurements	
* Electronically recorded variables	
- 29 required variables - 25 optional variables	- For head and leg protective device research
- chest and pelvis accelerations not recommended	- To avoid misinterpretation due to hard impacts to rigid dummy structures
* Mechanicable recorded variables - 9 required variables from frangible component damage	- To record distributed injuries
* Photographic targets to be digitized	- To record initial conditions just prior to impact; and to record helmet position time histories
* Internal data recording system - 32 channels, minimum - 8 bit resolution, minimum - special anti aliasing filters - same cg and mass as Part 572	- To prevent distortion of dummy motions, which can occur if external cables were used - To provide standardized recorder resolution, range, mass, mechanical, dimensional, etc. characteristics - To maintain basic mass, cg, and dimensions of Hybrid III components, and therefore response.
* High speed photography and procedures	- To provide common set of viewing angles, fields of new, resolution, analysis intervals, blur, etc.

Table 2., Continued

Provision	Explanation/Reasons
Part 5: Injury indices	
* Injury assessment variables (GAMBIT, HIC, neck maximum forces, chest compression and VC)	- To provide common measures of potentially injurious forces acting on upper body regions, which have some biomechanical basis
* Injury potential variables - helmet trajectory, velocity	- To provide indirect measures which could be related to potential for injury, if some object were to be impacted by the helmet
* Leg injury equivalent	- To relate frangible bone fracture to human AIS levels
* Injury severity probabilities	- To relate injury assessment values to probability of specified types and severities of injury
* Injury indices - probable AIS for each body region - total normalized injury cost	- To provide a common set of injury severity measures, to allow comparison across body regions and among tests
Part 6: Full scale test procedures	
* Opposing vehicle - Toyota Corolla 1988 - 1990 4 door saloon	- To provide a common, available, opposing vehicle with characteristics near 50th percentile on a worldwide basis
* MC and OV preparation	- To provide common initial conditions for variables which could influence the test results
* Dummy and instrumentation	
- calibration	- To provide for periodic mechanical calibration
- verification	- To provide a pretest check of electronic functioning
- joint tensions	- To provide for stable, reproducible dummy positioning
- clothing	- To provide some dummy protection and common photographic appearance
- position on MC	- To provide for realistic, reproducible positioning
- helmet	- To provide a common impact absorbing helmet
* Impact conditions - pre test measurements - post test measurements - vehicle speed control - relative and absolute tolerances - number of tests - ambient conditions	- To provide an accurate, repeatable and reproducible basis for paired comparison impact tests

Table 2., Continued

Provision	Explanation/Reasons
Part 7: Computer simulation procedures	
* Modelling procedures	- To require that simulations be based on the laws of physics; and that they describe the essential features of crash tests (eg, main components of the dummy, MC, car, and impact speeds, angles and contact points, etc)
* Parameter measurements	- To ensure that actual physical measurements be used as inputs to simulation
* Outputs	- To ensure the outputs are consistent with the required injury indices
* Post processing	- To ensure that graphic displays are based only on what is present in the mathematical model; and to ensure that injury analysis, and overall evaluations are done in a consistent manner, which does not exceed the calibration limits
* Calibration	- To compare and calibrate the simulation model against data from 31 laboratory tests and 14 full scale tests
Part 8: Documentation and reports	
* Documentation and forms for full scale tests, computer simulation and overall evaluations	- To facilitate data exchange and direct comparison of results between researchers - To provide consistency and completeness in documentation - To enable confirmation or reproduction of tests or analyses by others
* Recommendations regarding publication of results	- To promote inclusion of key information in publications, to present information objectively, and to allow others to understand the basic data and the validity of the tests

Table 3.
Specifications of Test Motorcycle

Size:	Medium
UKDS category:	3a
Manufacturer:	Kawasaki
Overall length:	2 125 mm
Overall width:	675 mm
Overall height:	1 165 mm
Weight - Motorcycle with LP:	189 kg (dry)

Table 4.
Specifications of Opposing Vehicle

Type:	Saloon
Manufacturer:	Toyota
Model:	Corolla
Model year:	1988 - 1990
Overall length:	4 200 mm
Overall width:	1 660 mm
Overall height:	1 340 mm
Weight:	1 100 kg ± 20 kg

Table 5.
Leg Protector Description

Element		Material
PIE	External	Sheet metal
	Internal	Polyurethane
RSE		Sheet metal + solid bar with notch
KPE		Aluminium honeycomb

Table 6.
Measured Impact Conditions

Measured Condition	IC1		IC2		IC3		IC4		IC5		IC6		IC7	
	Base	LP	Base	LP	Base	LP	Base	LP	Base	LP	Base	LP	Base	LP
Relative heading angle, deg	90,0	90,0	136,0	137,0	90,2	91,2	45,8	46,0	135,9	135,4	178,9	179,6	90,0	90,0
OV impact speed, m/s	9,9	9,8	6,9	6,8	6,9	6,9	6,8	6,8	6,8	6,8	0	0	0	0
MC impact speed, m/s	0	0	13,5	13,8	13,8	13,6	13,6	13,3	13,5	13,6	13,6	13,6	13,5	13,5
MC roll angle, deg	0,0	1,0	0,5	3,8	0,4	0,0	0	1,9	0,8	0,2	0,6	1,2	0,8	0,8
OV contact point, absolute, cm	1,5	1,8	5,8	1,5	5,8	6,3	4,9	1,0	-1,0	-0,4	-1,2	-2,5	-2,1	1,5
OV contact point, relative, cm	0,3		4,3		0,5		4		1,4		1,3		3,6	
Criterion, cm	5		10		15		15		15		3		5	

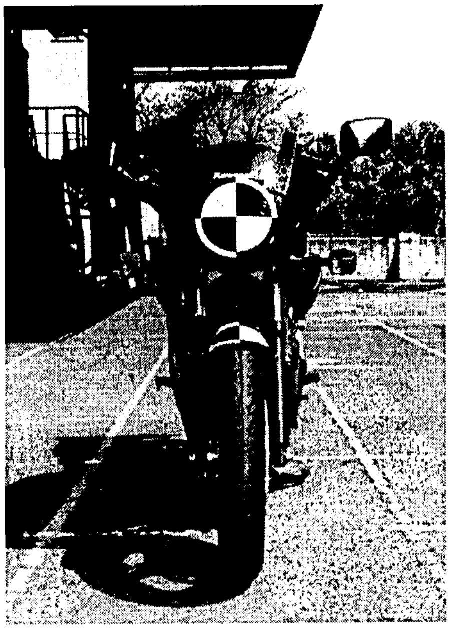


Figure 1. Front View of Test Motorcycle

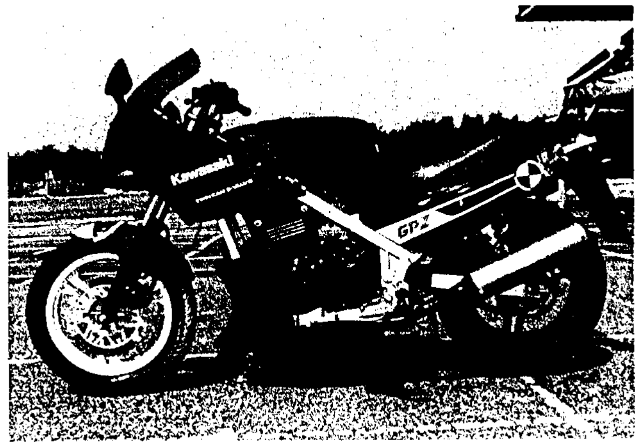


Figure 2. Side View of Test Motorcycle

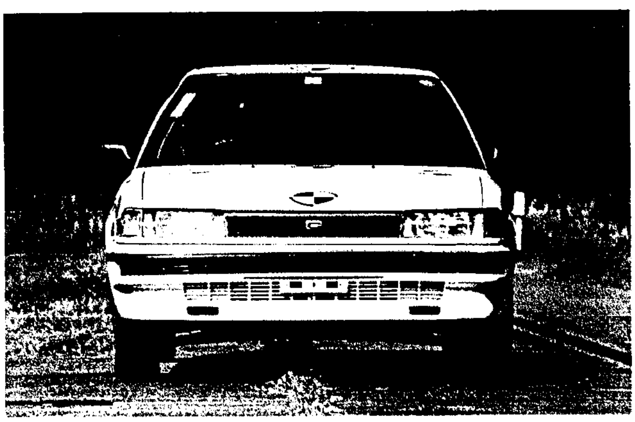


Figure 3. Front View of Opposing Vehicle

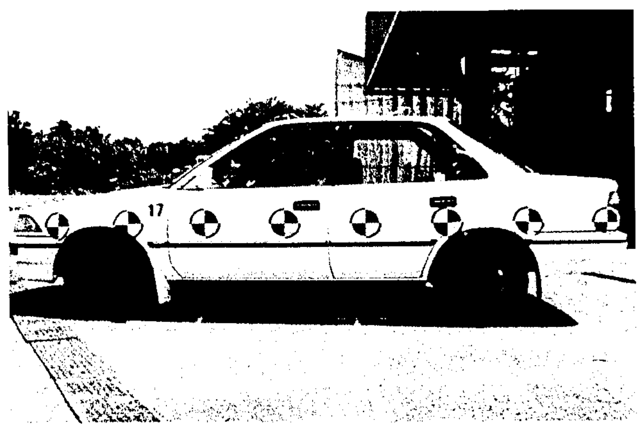


Figure 4. Side View of Opposing Vehicle

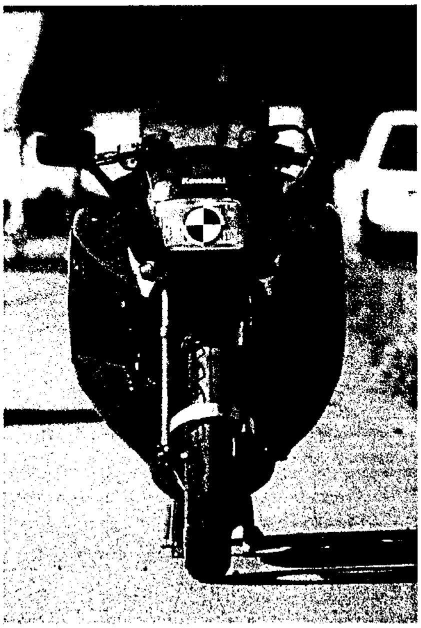


Figure 5. Front View of Leg Protector, Fitted to Test Motorcycle

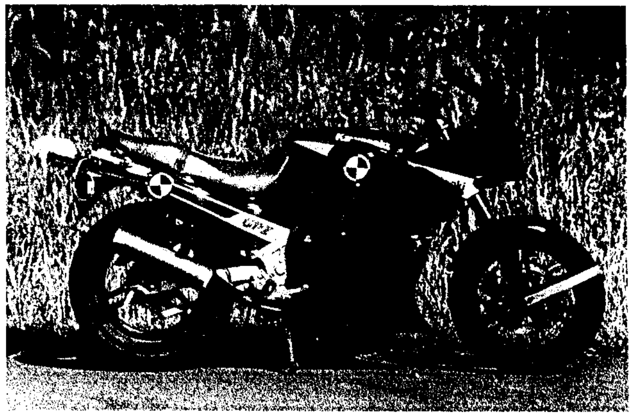


Figure 6. Side View of Leg Protector Fitted to Test Motorcycle

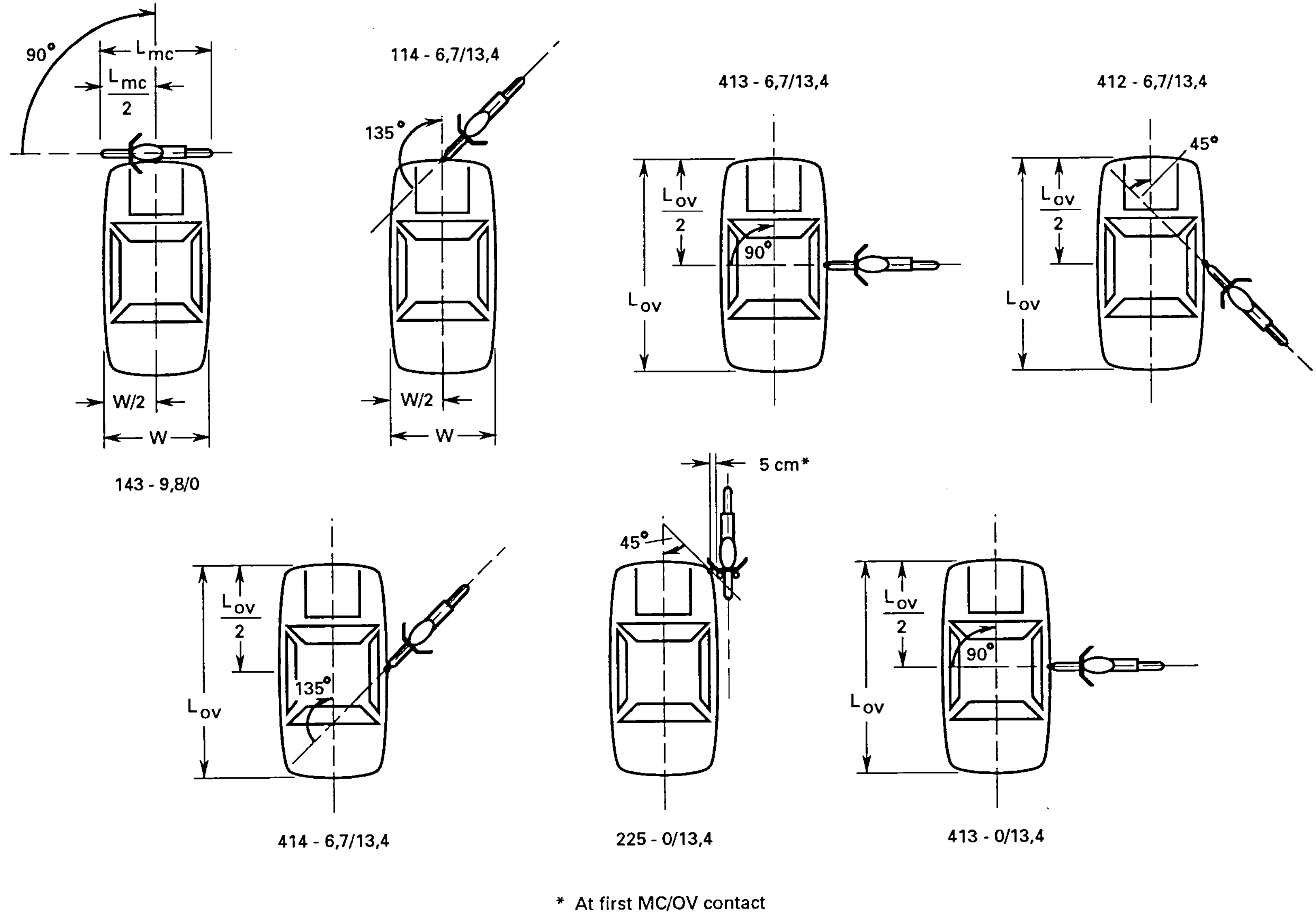
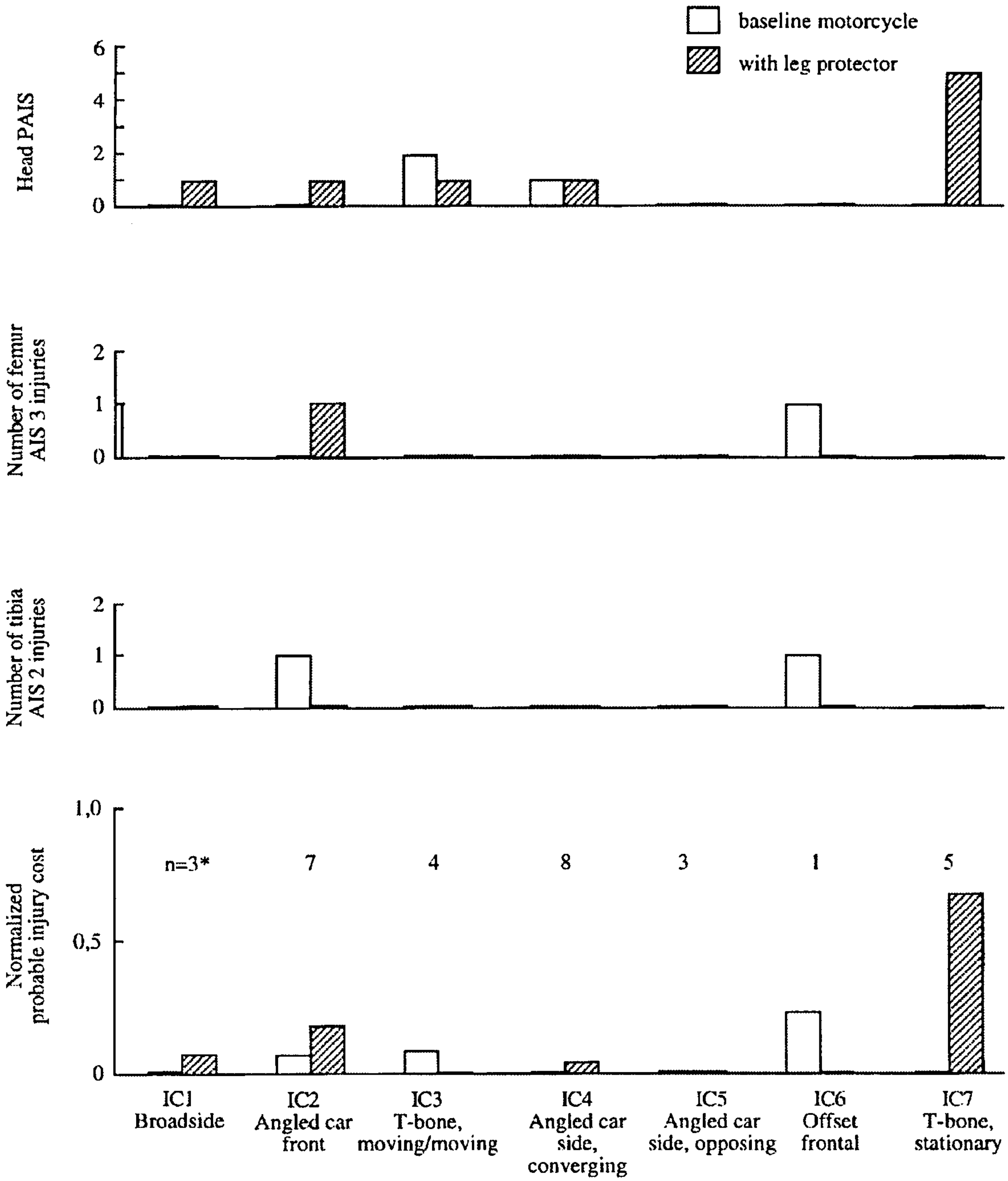


Figure 7. Target impact geometries at first MC/OV contact for seven full scale impact configurations.



Notes: 1) There were no chest, abdomen, knee or tibia AIS injuries in any of the tests.
2) * denotes frequency of occurrence of each impact configuration in the Los Angeles/Hannover accident data, ISO 13232-2, annex B.

Figure 8. Summary of injury indices for seven pairs of full scale tests, entire impact period.

Figure 9. Side View of Test IC7, Showing Helmet above Car Roof

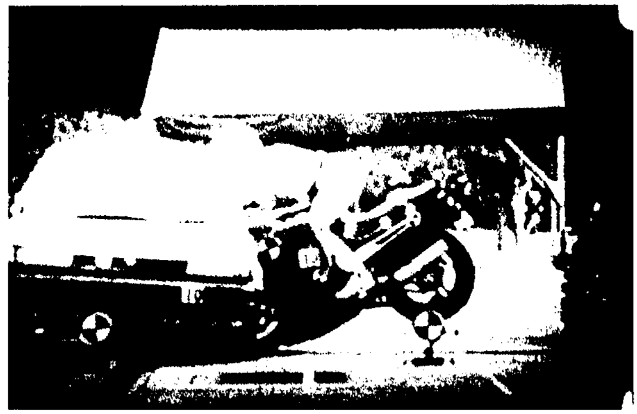


Figure 10. Side View of Test IC7, Showing Helmet into Side of Car Roof

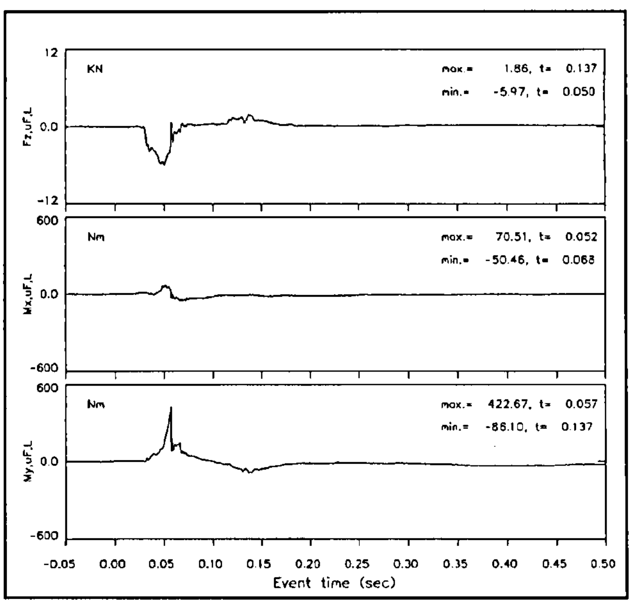


Figure 11. Electronic Data for Upper Left Femur, IC2 - Leg Protector, Indicating Femur Fracture

Annex 1: Photographs Before First MC/OV Contact

Figures 1-1 to 1-28 show the last high speed film frame before first MC/OV contact, for each of the 14 full scale tests, for the 8 m field of view motorcycle top and side views.

Annex 2: Items Not Complied With

Table 2-1 lists ISO 13232 items not complied with in the full scale tests, and associated explanations.

Table 2-1. Items Not Complied With

Test	Items Not Complied With	Explanation
All 14 tests	Dummy position retention not able to be verified, via pre test stationary photo and pre impact high speed film (ISO 13232-6, 4.5.2).	The resolution of the specified measurement method (± 2 cm) is not sufficient to verify that the tolerance (± 2 cm) is met. However, no measurable changes in position (eg, greater than 5 cm) occurred.
IC3-B IC5-B IC6-B IC3-LP IC5-LP IC6-LP	Chest $C_{ls,\ max}$ and $VC_{ls,\ max}$ were not able to be calculated (ISO 13232-5, 5.1.4, 5.1.6).	Sensor electronic cable for lower sternum (right) displacement potentiometer was intermittent in six tests; data was not useable. However, for all other chest sensors and tests, chest deflections were very small and non injurious.
IC6-B IC6-LP	Helmet velocity and percentage change in helmet velocity at first MC/OV contact was not able to be calculated (ISO 13232-8, Table 1).	Helmet/OV contact did not occur in these offset frontal tests, therefore such a measure is not applicable.
IC1-B IC1-LP	Maximum vertical difference in helmet trajectory and percentage change in helmet velocity at first helmet/OV contact were not calculated (ISO 13232-8, Table 1).	Specified photographic, measurement and calculation methods are not meaningful for this broadside impact configuration since the helmet motion is mostly in the yz plane, and the methods apply to the xz plane.
All tests	Pre test MC top view still photographs were not taken, for dummy position verification (ISO 13232-4, 4.7).	Test facility limitation (some elevated rear view photos, similar to high speed camera MC rear view, were taken instead).
IC12	1 out of 9 head accelerometers was inoperative; GAMBIT, etc, were calculated based on 8 accelerometers using an alternative method (ISO 13232-4, Annex B).	Sensor and/or cable was inoperative.
IC1-B IC7-B	Pre test MC still photos not available (ISO 13232-8, A.2).	Photos not taken.
IC6-B IC6-LP	OV left and right ride heights exceeded tolerances by very small amount (0,2 cm right; 0,7 cm left and 1,1 cm right, respectively) (ISO 13232-6, Table 3).	Oversight.

Figure 1-1. Top view, IC1, baseline

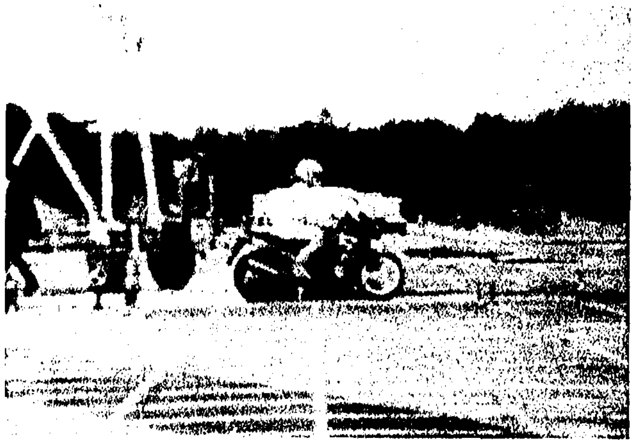


Figure 1-2. Side view, IC1, baseline

Figure 1-3. Top view, IC1, leg protector

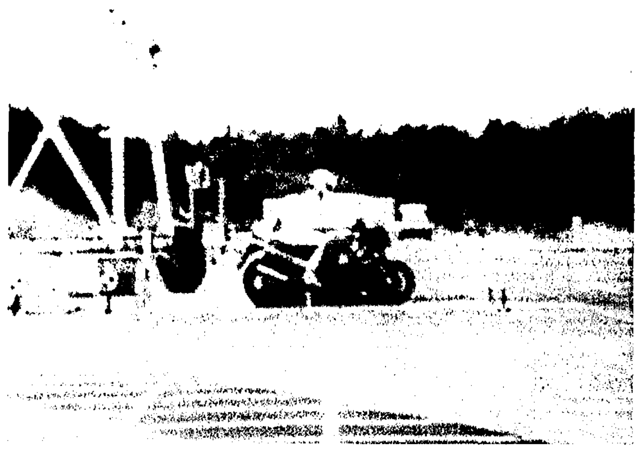


Figure 1-4. Side view, IC1, leg protector

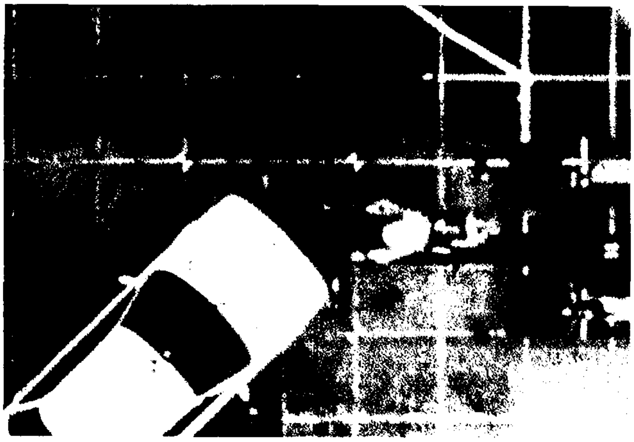


Figure 1-5. Top view, IC2, baseline

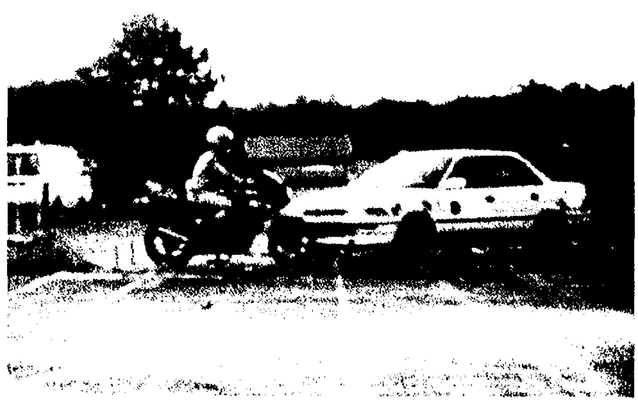


Figure 1-6. Side view, IC2, baseline

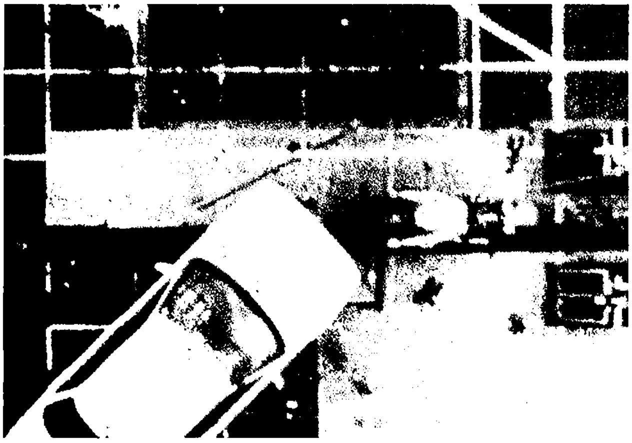


Figure 1-7. Top view, IC2, leg protector

Figure 1-8. Side view, IC2, leg protector

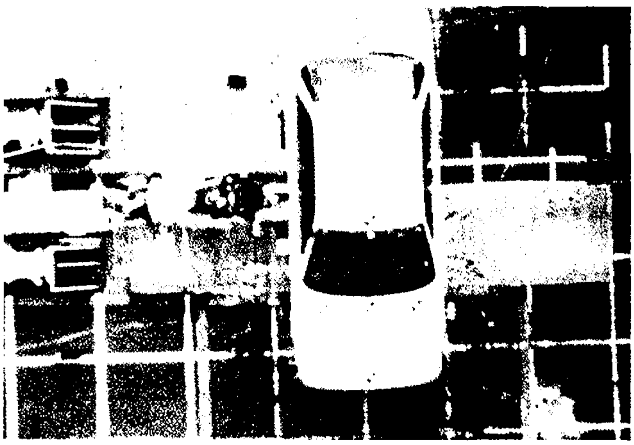


Figure 1-9. Top view, IC3, baseline

Figure 1-10. Side view, IC3, baseline

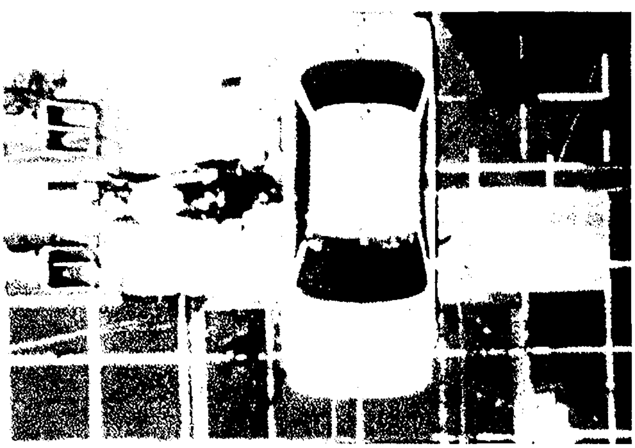


Figure 1-11. Top view, IC3, leg protector

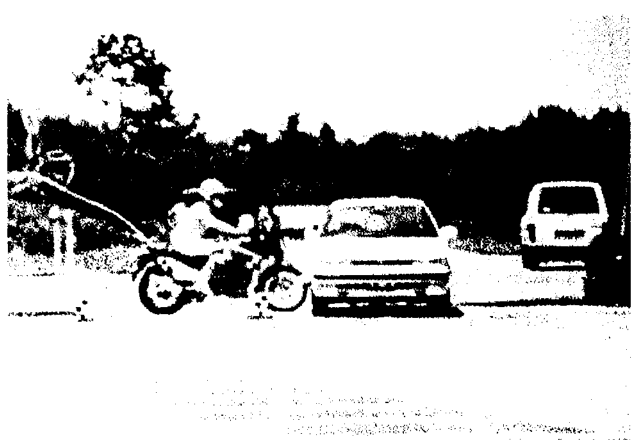


Figure 1-12. Side view, IC3, leg protector

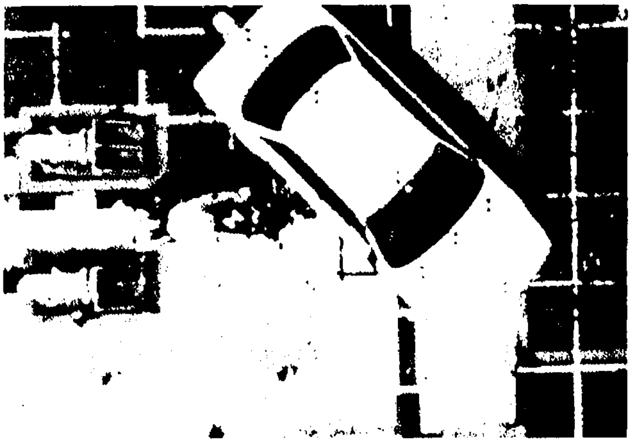


Figure 1-13. Top view, IC4, baseline

Figure 1-14. Side view, IC4, baseline

Figure 1-15. Top view, IC4, leg protector

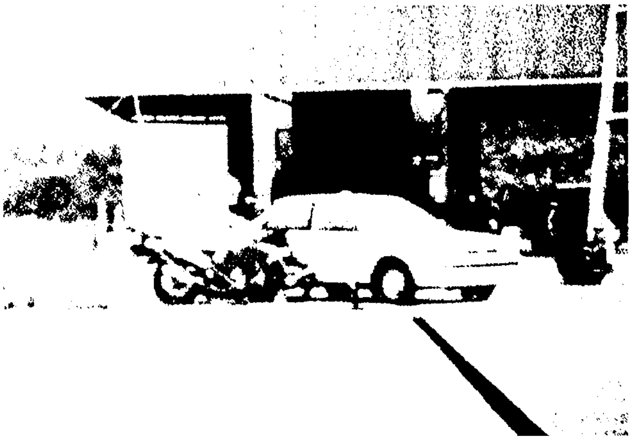


Figure 1-16. Side view, IC4, leg protector

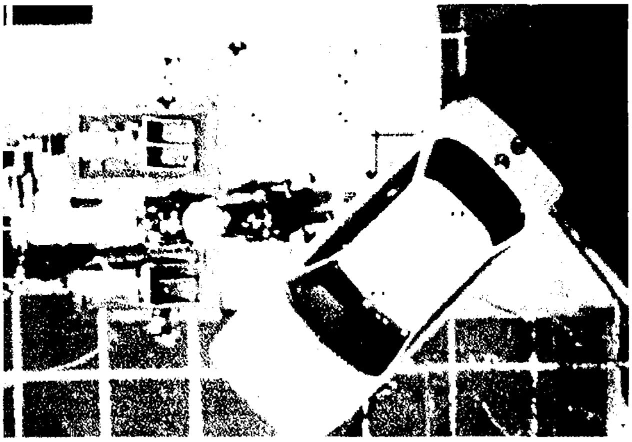


Figure 1-17. Top view, IC5, baseline

Figure 1-18. Side view, IC5, baseline

Figure 1-19. Top view, IC5, leg protector

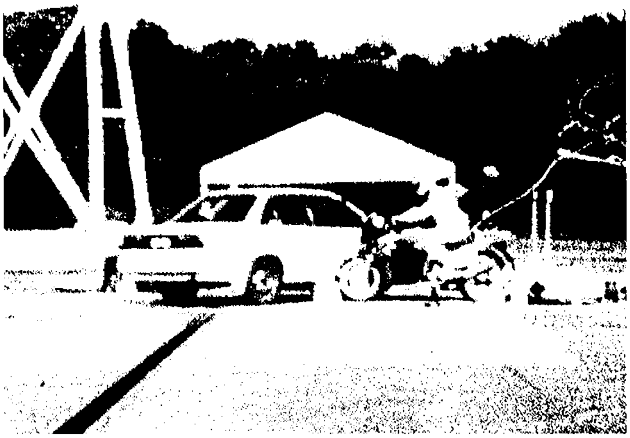


Figure 1-20. Side view, IC5, leg protector

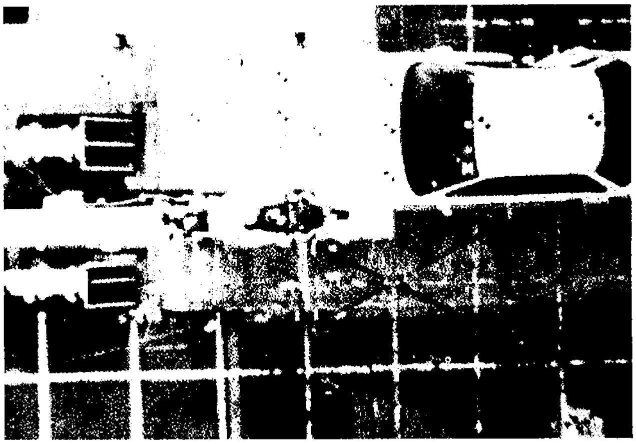


Figure 1-21. Top view, IC6, baseline

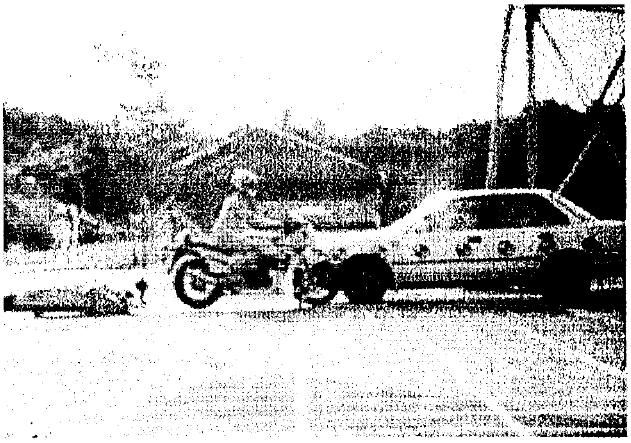


Figure 1-22. Side view, IC6, baseline

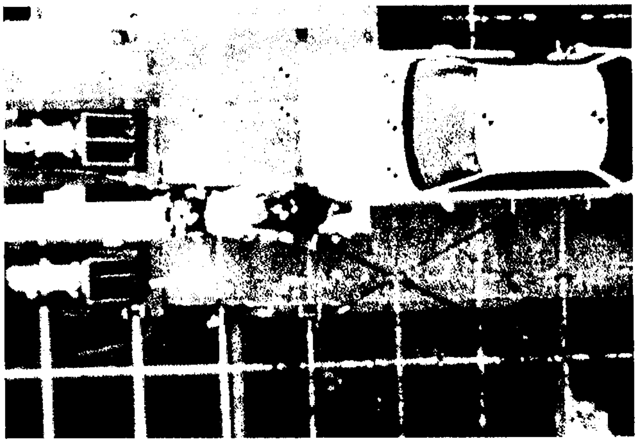


Figure 1-23. Top view, IC6, leg protector

Figure 1-24. Side view, IC6, leg protector

Figure 1-25. Top view, IC7, baseline

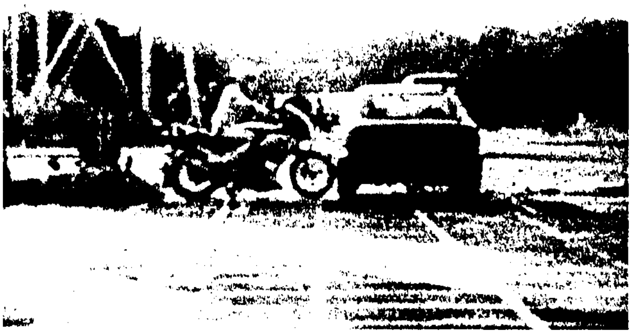


Figure 1-26. Side view, IC7, baseline

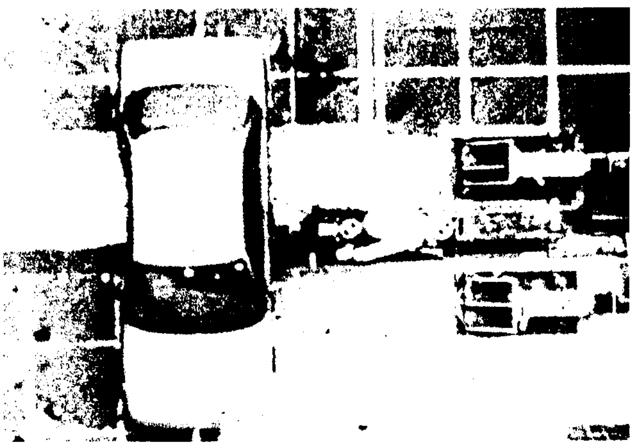


Figure 1-25. Top view, IC7, leg protector

Figure 1-28. Side view, IC7, leg protector

Annex 3: Impact Sequence Tables

Tables 3-1 to 3-14 contain the impact sequence descriptions from the 14 full scale tests.

Table 3-1. Test IC1-Baseline

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - 0°	0,000
Left elbow	contacts	OV-deformed bonnet	0,132-0,136
Left side of helmet	impacts (primary)	OV-front windshield glass	0,174-0,179
Right toe	contacts	ground	1,352
Buttocks	contact (secondary)	ground	1,620
Buttocks	contact (third)	ground	1,948
Face of helmet	contacts (secondary)	left forearm on ground	1,156-1,166
MC	stops	on ground	2,580
OV	stops	on ground	
Helmet	contacts (thirdary)	on ground	2,608
Dummy	stops	on ground	Unknown (>3,400)

Table 3-2. Test IC1-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - 1°	0,000
Left elbow	contacts	OV-deformed bonnet	0,132-0,136
Left side of helmet	impacts (primary)	OV-front windshield glass	0,180-0,182
Right toe	impacts (primary)	OV-front windshield glass	0,556
Right hand	contacts	ground	1,426
Right toe	contacts	ground	1,442
Top of helmet	contacts (secondary)	ground	1,750
Right side of hip	contacts	ground	1,532
Left knee	contacts	ground	1,702
Left toe	contacts	ground	1,720
OV	stops	on ground	2,092
Helmet	contacts (third)	on ground	2,754
MC	stops	on ground	Unknown (>3,200)
Dummy	stops	on ground	Unknown (>3,200)

Table 3-3. Test IC2-Baseline

Subject	Action	Struck object or direction	Approximate time, s
MC front wheel	rotates	right	0,016
MC head lamp	contacts	OV-deformed front fender	0,030
Left knee	contacts	OV-right rear door	0,054
Left side forehead of helmet	impacts (primary)	OV-deformed bonnet	0,116-0,154
Left side of lower helmet	impacts (primary)	OV-front windshield	0,164-0,186
Right heel	contacts (secondary)	ground	0,996
Right hip	contacts (secondary)	ground	1,127
Right forehead of helmet	contacts (secondary)	ground	1,320
Left heel	contacts (secondary)	ground	1,185
OV	stops	on ground	1,862
Dummy	stops	on ground	2,200
MC	stops	on ground	(unknown)

Table 3-4 Test IC2-LP

Subject	Action	Struck object or direction	Approximate time, s
MC front wheel	rotates	right	0,016
MC-left fairing	contacts	OV-bumper/ bonnet	0,0265
MC-L-corner of head lamp	contacts	OV-deformed front fender	0,034
Left center of helmet face	impacts (primary)	OV-deformed bonnet	0,103-,0120
Left hand	contacts	OV-front windshield	0,200-0,202
Right toe	contacts (secondary)	ground	0,998
Right hip	contacts (secondary)	ground	1,100
Left heel	contacts (secondary)	ground	1,250
Right forehead	contacts (secondary)	ground	1,156-1,166
Dummy	stops	on ground	1,620
OV	stops	on ground	1,706-1,709
MC	stops	on ground	1,630

Table 3-5.
Test IC3-Baseline

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - R 0.4° (on the OV and MC)	0,000
Face of helmet	impacts (primary)	OV-roof-edge	0,100-0,102
Right heel	contacts (secondary)	ground	0,750
Right face	contacts (secondary)	ground	0,872
OV	stops	on ground	Unknown
MC	stops	on ground	1,310
Dummy	stops	on ground	2,534

Table 3-6.
Test IC3-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - 0°	0,000
Forehead of helmet	impacts (primary)	OV-roof-edge	0,106-0,108
Back of pelvis	contacts (secondary)	ground	0,690
Dummy	stops	on ground	1,510
MC	stops	on ground	1,688-1,764
OV	stops	on ground	3,720-3,764

Table 3-7.
Test IC4-Baseline

Subject	Action	Struck object or direction	Approximate time, s
MC front wheel	rotates	right	0,005
MC-left side turn signal	contacts	OV-right rear windshield	0,024
MC left fairing	contacts	OV-right rear door	0,028
Dummy L-hand	breaks	OV R-rear door window	0,074
L-top-side of helmet	impacts (primary)	OV-roof edge	0,112-0,125
Dummy L-pelvis side	contacts	OV-C pillar	0,154
Right heel	contacts	OV-trunk lid	0,758
Right toe	contacts (secondary)	ground	>1.6 (unknown)
Left side of helmet face	contacts (secondary)	ground	>1.6 (unknown)
Dummy, MC, OV	stops	on ground	>1.6 (unknown)

Table 3-8.
Test IC4-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle 0°	0,000
Right rear door glass of OV	breaks		0,036
Left side of helmet	impacts (primary)	OV C-roof edge	0,118-0,126
Left foot	contacts (primary)	ground	0,970
Left side of helmet	contacts (primary)	ground	1,056
Left hand	contacts (primary)	ground	1,100
Right hand	contacts (primary)	ground	1,552
Right foot	contacts (primary)	ground	1,560
MC	stops	on ground	1,520
Dummy	stops	on ground	2,240
OV	stops	on ground	>3.854

Table 3-9.
Test IC5-Baseline

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - R-0.8°	0,000
Right rear door glass of OV	breaks		0,080
Right side of helmet	impacts (primary)	OV C-piller/roof edge	Unknown
Left hand	contacts (secondary)	ground	0,682-0,688
Right heel	contacts (secondary)	left foot on ground	0,842
Face	contacts (secondary)	ground	1,114
MC	stops	on ground	1,620-1,744
Dummy	stops	on ground	1,812-1,838
OV	stops	on ground	2,130-2,140

Table 3-10.
Test IC5-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)		0,000
Right side of helmet	impacts (primary)	trunk-lid panel	0,166-0,183
Left hand	contacts (secondary)	ground	0,642
Helmet	contacts (secondary)	ground	0,734-0,756
Right heel	contacts (secondary)	ground	0,978
Dummy	stops	on ground	1,756
MC	stops	on ground	2,320-2,522
OV	stops	on ground	2,680

Table 3-11.
Test IC6-Baseline

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - 0.6°	0,000
Left Knee	impacts (primary)	OV R-front corner panel	0,046
Left tibia	impacts (primary)	OV R-front corner of bumper	0,046
Forehead of helmet	contacts (primary)	OV R-rear door panel	0,264-0,272
Face of helmet	contacts (secondary)	MC front wheel on ground	0,432
Right toe	contacts	ground	0,562
Dummy and MC	stops	on ground	1,938

Table 3-12.
Test IC6-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - R-1.2°	0,000
MC L-front side of LP	impacts (primary)	OV panel & bumper of front corner	
Face of helmet	contacts (secondary)	ground	Unknown
Right & Left leg	contacts	ground	Unknown
Dummy	stops	on ground	1,464
MC	stops	on ground	about 1,900

Table 3-13.
Test IC7-Baseline

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - R 0,8°	0,000
MC-head-lamp	contacts	OV-side of front door	0,021
Chin of helmet	impacts (primary)	OV-roof edge	0,100-0,106
Right toe	contacts (secondary)	ground	0,860
Helmet	contacts (primary)	ground	0,860
OV	stops	on ground	1,310
MC	stops	on ground	1,740
Dummy	stops	on ground	2,200

Table 3-14.
Test IC7-LP

Subject	Action	Struck object or direction	Approximate time, s
Time zero (Flash on)	(on)	MC lean angle - R 0,8°	0,000
MC-head-lamp	contacts	OV-side of front door	0,021
Forehead of helmet	impacts (primary)	OV-roof edge	0,100-0,104
Back of pelvis	contacts (secondary)	OV-roof	0,690
OV	stops	on ground	1,305
Dummy	stops	OV trunk lid	1,854
MC	stops	on ground	1,880

Annex 4: Performance Data

Tables 4-1 and 4-2 present the test data for the 14 tests for the primary impact period, and for the entire impact sequence, respectively.

Table 4-1.
Primary Impact Results

Body region	IAV, IPV, or II[1]	Value													
		IC1		IC2		IC3		IC4		IC5		IC6		IC7	
		Ba[2]	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP
Head	G_{max}	0,47	0,32	0,35	0,75	0,79	0,66	0,63	0,73	0,30	0,19	0,15	0,09	0,46	1,21
	PAIS	0	0	0	1	2	1	1	1	0	0	0	0	0	5
	HIC	210	59	98	163	941	451	755	598	67	17	33	5	466	1047
	t_1/t_2	179/ 188	187/ 198	106/ 134	119/ 148	113/ 120	116/ 123	121/ 130	120/ 125	179/ 188	154/ 190	448/ 465	163/ 183	111/ 118	102/ 107
	$Risk_{HIC}$	0,0	0,0	0,0	0,0	12,7	1,2	5,8	2,8	0,0	0,0	0,0	0,0	1,3	18,3
	ΔZ_hmax	na[5]		0,088[6]		0,072		0,060		0,081		0,128		0,130	
	% Δ $V_{r,h,fc}$	na		-18,5		-24,3		-11,4		16,0		na		-23,4	
	$V_{r,h,fc}$	8,5	8,5	8,4	6,9	11,1	8,4	11,9	10,6	6,1	7,1	na	na	11,2	8,6
	$V_{x,h,fc}$	-2,7	-4,0	7,0	6,2	11,1	8,0	11,6	10,4	4,4	6,6	na	na	11,1	8,2
	$V_{y,h,fc}$	6,3	6,1	1,2	1,3	0,3	0,5	0,7	0,9	-1,0	-1,1	na	na	0,1	0,5
	$V_{z,h,fc}$	5,0	4,4	4,5	2,6	0,9	2,6	2,8	1,5	4,2	2,5	na	na	0,8	2,4
Neck	NII_{shear}	0,26	0,15	0,13	0,29	0,46	0,47	0,34	0,44	0,12	0,09	0,29	0,05	0,34	0,81
	NII_{tens}	0,19	0,20	0,30	0,65	0,21	0,21	0,21	0,17	0,22	0,14	0,05	0,10	0,31	0,36
	NII_{comp}	0,77	0,30	0,10	0,88	0,53	0,66	0,24	0,49	0,26	0,21	0,62	0,08	0,31	1,39
	NII_{flex}	0,19	0,12	0,10	0,13	0,54	0,08	0,12	0,12	0,10	0,16	0,30	0,04	0,48	0,21
	NII_{ext}	0,78	0,55	0,33	0,34	0,54	0,55	0,32	0,13	0,33	0,32	0,34	0,23	0,99	0,97
	NII_{tors}	0,31	0,33	0,43	0,31	1,13	0,99	0,30	0,70	0,25	0,23	0,36	0,24	0,46	0,86
Chest	$C_{us,\ max}$	1,35	0,87	6,10	1,96	1,23	3,60	1,09	0,54	4,92	1,19	0,53	0,20	1,33	2,01
	$C_{ls,\ max}$	0,53	0,70	8,26	2,21	na	na	2,37	0,09	na	na	na	na	1,79	0,13
	$VC_{us,\ max}$[7]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	$VC_{ls,\ max}$[7]	0	0	0	0	na	na	0	0	na	na	na	na	0	0
	PAIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abdomen	$P_{A,\ max}$	3	2	2	2	0	0	0	0	0	0	0	0	0	3
	PAIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Femur, L	Fracture	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No
	AIS	0	0	0	3	0	0	0	0	0	0	3	0	0	0
R	Fracture	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tibia, L	Fracture[3]	No	No	ND	No	No	No	No	No	No	No	ND	No	No	No
	AIS	0	0	2	0	0	0	0	0	0	0	2	0	0	0
R	Fracture	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Knee, L	Dislocation[4]	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R	Dislocation	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Overall	PPI	0,00	0,00	0,07	0,15	0,00	0,00	0,00	0,00	0,00	0,00	0,27	0,00	0,00	0,00
	$P_{fatal,\ G}$	0,001	0,000	0,01	0,055	0,059	0,006	0,004	0,021	0,000	0,000	0,018	0,000	0,001	0,600
	MAIS	0	0	2	3	2	1	1	1	0	0	3	0	0	5
	TAIS	0	0	2	4	2	1	1	1	0	0	5	0	0	5
	IC_{norm}	0,004	0,001	0,069	0,184	0,099	0,024	0,018	0,053	0,000	0,000	0,229	0,000	0,003	0,670

Table 4-2.
Entire Impact Sequence Results

Body region	IAV, IPV, or II[1]	Value													
		IC1		IC2		IC3		IC4		IC5		IC6		IC7	
		Ba[2]	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP	Ba	LP
Head	G_{max}	0,47	0,72	0,35	0,75	0,79	0,66	0,63	0,73	0,30	0,25	0,23	0,39	0,46	1,21
	PAIS	0	1	0	1	2	1	1	1	0	0	0	0	0	5
	HIC	210	76	98	163	941	451	755	598	67	113	54	144	466	1047
	t_1/t_2	179/ 188	1449/1 484	106/ 134	119/ 148	113/ 120	116/ 123	121/ 130	120/ 125	179/ 188	781/ 789	1331/1 344	584/ 590	111/ 118	102/ 107
	$Risk_{HIC}$	0,0	0,0	0,0	0,0	12,7	1,2	5,8	2,8	0,0	0,0	0,0	0,0	1,3	18,3
Neck	NII_{shear}	0,26	0,15	0,20	0,29	0,46	0,47	0,34	0,45	0,17	0,11	0,29	0,17	0,34	0,81
	NII_{tens}	0,19	0,20	0,30	0,65	0,21	0,21	0,27	0,18	0,22	0,17	0,05	0,16	0,31	0,36
	NII_{comp}	0,77	0,30	0,56	0,88	0,53	0,66	0,26	0,99	0,39	0,71	0,62	0,36	0,52	1,39
	NII_{flex}	0,19	0,12	0,10	0,13	0,54	0,08	0,12	0,12	0,12	0,23	0,30	0,04	0,48	0,21
	NII_{ext}	0,78	0,82	0,33	0,34	0,57	0,55	0,32	0,13	0,33	0,32	0,40	0,31	0,99	0,97
	NII_{tors}	0,36	0,49	0,43	0,31	1,13	1,11	0,67	0,92	0,25	0,23	0,50	0,51	0,46	0,86
Chest	$C_{us,\,max}$	1,35	1,79	6,10	1,96	4,02	9,59	1,09	1,12	6,77	8,32	2,79	0,41	2,68	2,01
	$C_{ls,\,max}$	2,80	1,74	8,26	2,21	na[5]	na	2,37	0,15	na	na	na	na	1,86	1,06
	$VC_{us,\,max}$[7]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	$VC_{ls,\,max}$[7] for $V \geq 3m/s$	0	0	0	0	na	na	0	0	na	na	na	na	0	0
	PAIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abdomen	$P_{A,\,max}$	3	2	2	2	0	0	0	0	0	0	0	0	0	3
	PAIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Femur L	Fracture	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	No
	AIS	0	0	0	3	0	0	0	0	0	0	3	0	0	0
R	Fracture	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tibia L	Fracture[3]	No	No	ND	No	No	No	No	No	No	No	ND	No	No	No
	AIS	0	0	2	0	0	0	0	0	0	0	2	0	0	0
R	Fracture	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Knee L	Dislocation[4]	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R	Dislocation	No	No	No	No	No	No	No	No	No	No	No	No	No	No
	AIS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Overall	PPI	0,00	0,00	0,07	0,15	0,00	0,00	0,00	0,00	0,00	0,00	0,27	0,00	0,00	0,00
	$P_{fatal,\,G}$	0,001	0,017	0,010	0,055	0,059	0,006	0,004	0,021	0,000	0,000	0,018	0,000	0,001	0,600
	MAIS	0	1	2	3	2	1	1	1	0	0	3	0	0	5
	TAIS	0	1	2	4	2	1	1	1	0	0	5	0	0	5
	IC_{norm}	0,004	0,048	0,069	0,184	0,099	0,024	0,018	0,053	0,000	0,000	0,229	0,002	0,003	0,670

Notes: 1) IAV, IPV, II denote injury assessment variable, injury potential variable, injury index, respectively.
2) Ba denotes baseline motorcycle.
3) ND denotes non displaced fracture; D denotes displaced fracture.
4) P denotes partial dislocation; C denotes complete dislocation.
5) na denotes not available or not applicable: see Annex 2.
6) Negative value denotes position of helmet with LP was lower.
7) In all tests with usable chest compression data, V was found to be less than 3 m/s, and in this case, ISO 13232 implies that VC_{max} should not be used for chest injury calculation. Therefore, to be consistent with the code in ISO 13232-5, Annex D, VC_{max} values for these tests have been set to zero. Actual VC_{max} values were less than 0,2 in all cases.

PRECISION REPLICATION OF MOTORCYCLE COLLISION

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Paper Number 96-S7-O-11

ABSTRACT

Crashworthiness of motorcycles has been evaluated over a period in excess of twenty-five years by means of crash testing motorcycles into automobiles. A common problem associated with this type of activity is the failure to maintain sufficient accuracy to allow repeatability. This is particularly true where both the automobile and the motorcycle are moving at the time of impact. This paper describes a highly accurate method of performing collisions between a moving motorcycle (with dummies aboard) and a moving automobile where the intent was to replicate actual on-road accidents. Summaries of eight demonstration collisions, which were performed between 1986 and 1995, are provided here. Each collision was predicated on an actual on-road accident. In each of the accident collisions the suggestion had been made that a steel loop type "crash bar" would have prevented injury. The object of these replicated collisions was to demonstrate the effects of these structures under actual accident conditions. These collisions were analyzed utilizing high speed 16mm film, real time videography and still photography. The photography, videography, crashed vehicles and dummies were reviewed to make measurements and comparisons between them and the actual persons and vehicles involved in the original accident.

INTRODUCTION

For at least 60 years motorcycle crashworthiness with respect to an operator and/or passenger lower leg protection has been a concern. In 1934 a United States patent was issued to William Harley of the Harley-Davidson Motor Company for a "Motorcycle Protecting Guard" [1]. Guards of this genre (a.k.a. "crash bars" or "engine guards") have been sold as original equipment, as accessories, or after market items since that time. It has been generally recognized within the motorcycle community that while not affording operator protection [2,3] during collisions these structures could mitigate damages to the motorcycle in a fall-over situation. They also provide a component for the mounting of additional accessories. They are sometimes attached to the motorcycle for cosmetic enhancement of the vehicle.

Studies were conducted beginning in approximately 1971, to determine the feasibility of increasing the strength of these crash bars for the purpose of providing lower leg protection to a motorcycle operator/passenger during the course of a collision [4]. As a result of these studies it was determined a proposed leg protection structure should be constructed of seamless drawn steel tubing of 2 inch outer diameter and 3/32nds wall thickness ($\approx$ 51mm x 2.38mm). The tubing was to be formed in a loop of approximately 28 inches in width by 17 inches in height ($\approx$ 71cm x 43cm). This structure and mount should be strong enough to withstand side or angle impacts by a two ton ($\approx$1800kg) vehicle at 30mph ($\approx$48km/h). The theory underlying this proposal was that this heavy-duty crash bar would maintain a protected leg space envelope in side impacts while the motorcycle and operator/passenger would be harmlessly redirected in angled impacts.

Since about 1971, the theory of providing lower leg protection has been evaluated by crash testing motorcycles under various hypothetical accident conditions and by conducting empirical analyses focusing largely on the strength of these proposed leg protection structures. It should be noted that while a structure of this type may have some hypothetical merit, it has yet to provide measurable benefits where it has been evaluated by the replication of an actual accident scenario. Extreme accuracy is required to replicate many actual motorcycle accident configurations. Dr. Chinn identified the problem of achieving accurate motorcycle crash testing when he indicated in 1985 [5] that achieving accuracy within the range of one-half meter was difficult.

The Transportation Research Center facility which was used for the eight collisions presented here, routinely controls vehicle speeds within 0.2 mph ($\approx$0.3km/h) and the impact point within 2 inches ($\approx$5cm) or less. Using the motorcycle control mechanism presented here has provided for the same accuracy with regards to motorcycle collisions since 1986.

DEMONSTRATION COLLISION METHODOLOGY

The following multi-step approach was used to provide the requisite accuracy for the demonstration collisions utilized in replicating the actual accident scenarios.

Motorcycle Control Device The motorcycle is conveyed to the vehicle impact area by a four-wheeled trolley. This trolley and the automobile are attached to separate computer controlled cables which are powered by 1000 horsepower (745 kW) electric motors. The computer provides the requisite accuracy with regard to velocity, as well as timing each vehicles arrival at the impact point. Various devices have been used in prior studies to convey the motorcycle to the point of impact; including suspending the motorcycle from outriggers attached to another vehicle (work of P.W. Bothwell, 1965-66), pushing a motorcycle attached to the frame of another vehicle [5], launching a stationary motorcycle from a moving trolley [3,4] and trolley systems that transported a freely rolling motorcycle while restraining the handlebars [2]. The system in the present study was designed to allow the motorcycle to be delivered to the impact area with minimal restraint of its dynamic characteristics. The Motorcycle Control Device consists of three parallel arms that are used to attach the freely rolling motorcycle to the four-wheeled trolley. Each of the three arms pivots about a horizontal axis, two arms are on a horizontal plane and two arms are on a vertical plane. [Figure 1.] and [Figure 3.]

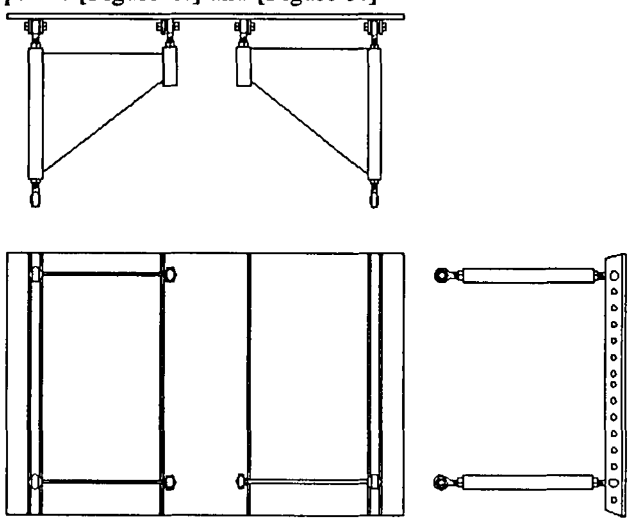


Figure 1.

Each arm has a threaded rod-end-bearing at each extremity; these provide roll and yaw adjustment of the motorcycle. Three aft-facing tapered pins are mounted on the motorcycle. These pins fit into the outboard rod end and thus attach the motorcycle to the control device. The control device couples the motorcycle to the trolley and allows relative vertical motion between the trolley and the motorcycle. More importantly it allows the motorcycle to maintain its auto-dynamic stability prior to release. The release phase is thus extremely smooth as the motorcycle has no tendency to hunt for dynamic stability upon release. In actual high speed tests a motorcycle has traveled 300 feet ($\approx$91m) after release with no more than a 10 inch ($\approx$25cm) deviation from its projected center line.

Handlebar Mount Decoupler The addition of a dummy operator creates a problem in that it needs to assume a "normal riding posture", i.e.--hands on the handlebars, but must be restrained from "steering" the motorcycle. This problem has been resolved by designing a handlebar decoupler which allows the front wheel to auto-steer approximately five degrees to the left and right of center. [Figure 2.]

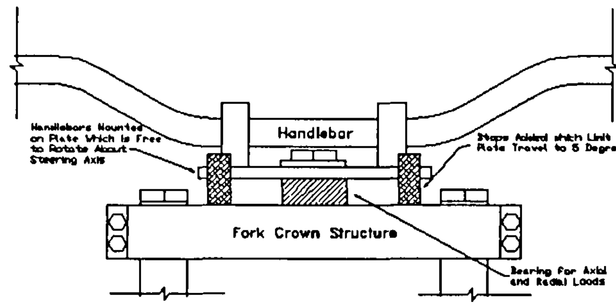


Figure 2.

At the five degree travel limit a substantial stop in the decoupler begins to rotate the handlebars left or right in a normal fashion. This resolves the problem without resorting to such extremes as fastening the dummy hands to the motorcycle fuel tank or placing the hands on the handlebars and eliminating the auto-steering capability of the motorcycle. The combination of the Motorcycle Control Device, the Handlebar Mount Decoupler, and proper setup procedures, provides accuracy which is only limited by that of the towing apparatus which will be discussed later.

Motorcycle Condition and Preparation A properly configured exemplar motorcycle is always used to accurately replicate the motorcycle involved in the actual accident. This includes: accessories, tire tread patterns, certain custom modifications that may have been made and so on. Chassis components of the motorcycle, such as tires, suspension components and bearings, are inspected and if necessary brought up to proper working conditions. Chassis and wheel alignments are also important considerations. Virtually all motorcycle chassis are totally inadequate to support the loads imposed upon them by installing a heavy-duty crash bar as outlined above. A significant portion of the mass of the motorcycle (30-35%) is concentrated in the engine

assembly. It is therefore necessary to integrate the engine/chassis/heavy-duty crash bar into one unit. This is accomplished by attaching two pieces of quarter-inch (6.35mm) steel plate horizontally through the full width of the engine cylinder head and crank case. Engine internal components are removed to compensate for the added weight. These plates extend forward of the engine assembly and aft if necessary to provide attachment points for the leg protection structure. Final preparation includes mounting a hydraulic steering damper to prevent over correcting by the motorcycle steering assembly.

Dummies The dummies used in the collisions presented here have been Alderson VIP fiftieth percentile adult United States male. The dummy is steadied on the motorcycle with light, break-away, mono-filament line.

Automobiles An attempt is always made to obtain an exact exemplar automobile. This activity is occasionally hindered by the common practice of United States automobile manufacturers in offering a wide variety of engine sizes, drivetrain options, suspension packages and trim packages. The exemplar automobile is then prepared for safety of test personnel, straight-line steering and reduced rolling resistance.

Facility The facility utilized for the collisions presented in this paper is the Transportation Research Center ("TRC") located in the northwest portion of the State of Ohio in the United States. TRC has excellent vehicle (automobile) preparation, vehicle towing and high-speed photography capabilities. The engineering and support staff responsible for the collision setup provide the expertise needed to accurately execute these collisions. [See Endnote [7] for additional information regarding the TRC facility.]

Motorcycle Delivery Vehicle The prepared motorcycle is mounted to a four-wheel trolley. The trolley has a 10 foot (≈3m) boom extending from the front to which the motorcycle is attached. [Figure 3.] The trolley decelerates at approximately 7.5g which allows it to release the motorcycle within 10-15 feet (≈3-5m) from the point of impact.

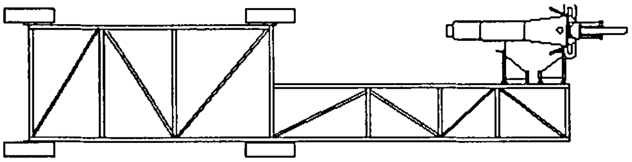


Figure 3.

This enhances the accuracy of the impact. After the motorcycle is attached to the trolley, the trolley is towed for approximately 20 feet (≈6m) for purposes of adjusting the track and balance. When the arms of the control device are properly adjusted the motorcycle will tow in a balanced mode. This provides for the release of the motorcycle without any disruptive inputs.

Cameras Photo-Sonics high-speed rotary prism with rotary-disc shutter-type cameras [8] are used to record the event. Shutter speeds are adjusted consistent with vehicle speed and lighting conditions. The two vehicles, with dummy(s) aboard, are placed statically at the impact site and optimum camera angles are selected for the demonstration collision being conducted. A drawing showing typical camera locations is included. [See Figure 4.]

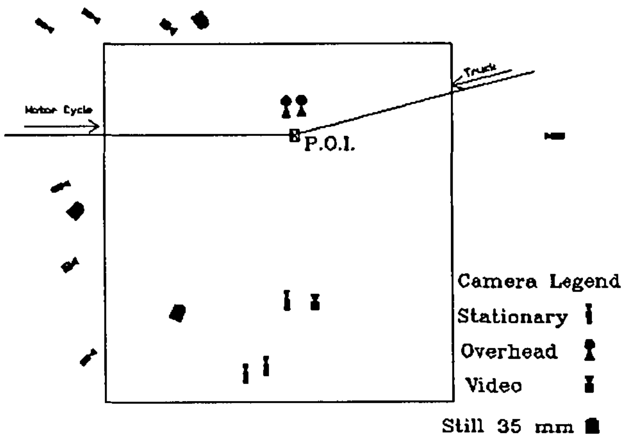


Figure 4.

ACCIDENT INVESTIGATION

Replication of an actual accident requires a thorough forensic investigation that may vary slightly from accident to accident. The following are representative of the typical investigative procedures utilized in investigating motorcycle accidents involving collisions with other vehicles and/or objects.

Scene Inspection A scene analysis is conducted by inspecting the accident scene to obtain first-hand information regarding criteria such as normal vehicle path of travel, elevation changes, surface composition/ condition/irregularities, visibility available to vehicle operators, and witness marks which may have been noted at the time of the accident and are still visible. Scene photographs taken at the time of the accident are utilized

to determine the location of witness marks that may no longer be available. Roadway construction drawings are examined to determine if the configuration of the roadway has changed since the accident. The scene inspection is documented through the use of photography and sketches.

Vehicle Inspections Both vehicles involved in the actual accident are examined, provided they are available. Damage patterns are noted and recorded for later comparative analysis by means of photography and sketches. If either vehicle has been repaired subsequent to the accident, the damage repair estimates as well as the actual repair order is reviewed in evaluating the vehicle damage.

Accident Reports Accident reports prepared by authorities at the time of the accident are carefully reviewed and parties and witnesses identified. At times the author of the report is interviewed at the scene of the accident to obtain a broader explanation of the event than that contained in the report.

Witnesses Witnesses to the accident are interviewed by the taking of statements, depositions, and/or verbal interviews at the accident site. This includes the operators and passengers of both vehicles whenever possible. In addition, emergency personnel, tow truck operators, and fire crews are interviewed.

Injuries Medical information regarding the injured motorcycle operator and/ or passenger is evaluated from a mechanical viewpoint and often the services of an anatomist or biomechanic are utilized. An attempt is made to separate injuries consistent with the primary impact from injuries incurred later in the impact sequence.

Photography Any photography available from the actual accident or of the vehicles themselves is reviewed for comparison, both to present circumstances and those existing at the time of the accident itself.

Survey A topographical survey, or scene diagram, may be obtained and/or prepared to aid in understanding the overall accident dynamics.

Static Reconstruction Once the available information and material has been acquired and analyzed, the reconstruction phase of the accident investigation can be initiated. A primary tool in the reconstruction phase is a static reconstruction or matching of vehicles. Ideally, this static reconstruction is performed using the actual vehicles involved in the accident and matching one to the other while they are still in their damaged condition. Typically, one or both of the damaged accident vehicles is no longer available at the time the static reconstruction is conducted. When this occurs the static reconstruction is conducted with exemplar vehicles and each vehicle is prepared by identifying the various points of damage and/or impact to each vehicle. The two vehicles are then brought together statically and the damaged components of one vehicle are matched to the corresponding components of the other vehicle. This procedure often requires the removal of certain components in order to identify damage that occurred later in the collision sequence. Step by step photographs are prepared of this static reconstruction for use in the determination of the relative speed and impact angle of the two vehicles. This phase of the investigation also requires the use of exemplar people to identify injury mechanisms. Once the static reconstruction is concluded, a thorough understanding of the dynamics of the accident configuration will have been achieved. It should be noted that in each of the collisions discussed here another entity had conducted an investigation of some sort and theorized the leg injuries incurred by the motorcycle operator/passenger involved in the actual on-road accident could have been prevented or greatly mitigated if the motorcycle had been equipped with some combination of the structures discussed earlier. To the extent that conflicts exist between the two reconstructions of the accident, they are always resolved in favor of the proponent of the proposed leg protection structure.

Establish Replicate Collision Parameters A determination must initially be made as to the feasibility of a crash replication. For example, if the investigation reveals speeds are too extreme for the test facilities, or the motorcycle had in fact fallen and tumbled prior to impact with the other vehicle, a collision replication may not be practical. The parameters for the eight collisions presented here were obviously acceptable candidates for replication to empirically evaluate the effectiveness of the proposed heavy-duty leg protection structures.

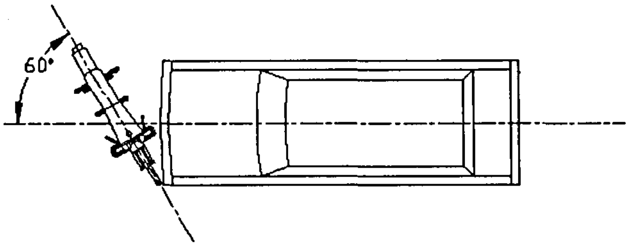
COLLISIONS

The following is intended to provide an overview of the eight collisions which are the subject of this paper.

Collision One 1986

Type of accident:

A collision at a controlled intersection of two public roadways. The automobile driver initiated a left turn into the path of the on-coming motorcyclist. The collision occurred as indicated by the accompanying diagram.



Automobile:

1972 Plymouth Scamp, two door coupe; Weight: 3020lbs (≈1370kg)

Motorcycle:

1980 Kawasaki KZ650; Weight: 478lbs (≈217kg)

Operator/Injury:

The 25 year-old male operator suffered a compound comminuted fracture of the left leg.

Passenger/Injury:

No information was available as to the female passenger's injuries.

Replicate collision parameters established as:

Automobile speed: 10mph (16km/h)
Motorcycle speed: 30mph (48 km/h)
Collision angle: 60 degrees

Modifications to motorcycle for replicated collision as compared to motorcycle in actual collision.

Heavy-duty proposed leg protection structures were affixed to the motorcycle front and rear. [See Endnote 9.]

Replicate collision results:

Point of contact:

The left side of the front bumper contacted the heavy-duty proposed leg protection structure and the front forks at the left lower front fork tube.

Accuracy:

The motorcycle and the automobile impacted within one inch (2.54cm) of target.

Automobile damage:

There was catastrophic damage to the front of the automobile.

Motorcycle damage:

The heavy-duty proposed front leg protection structure was not damaged.

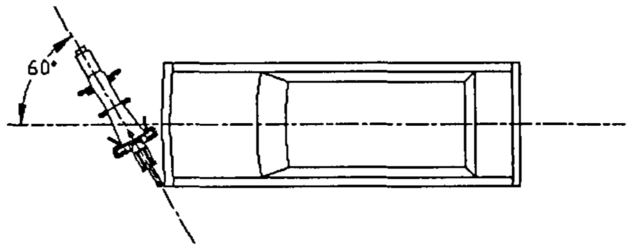
Dummy operator:

The deceleration and redirection of the motorcycle allowed the left leg to impact the automobile. The operator was violently thrown from the motorcycle and struck the ground in a head-first attitude. A passenger dummy was not included.

Collision Two 1986

Type of accident:

A collision at the uncontrolled intersection of a private driveway and a public preferential street. The automobile driver initiated a left turn into the path of the on-coming motorcyclist. The collision occurred as indicated by the accompanying diagram.



Automobile:

1975 Chevrolet Malibu, two door coupe; Weight: 3755lbs (≈1703kg)

Motorcycle:

1980 Kawasaki KZ250; Weight: 278lbs (≈126kg)

Operator/Injury:

The 33 year-old female operator sustained severe comminuted fractures and a deep laceration to her left leg above the ankle resulting in amputation below the knee.

No passenger

Replicate collision Parameters Established As:

Automobile speed: 10mph (16km/h)
Motorcycle speed: 30mph (48 km/h)
Collision angle: 60 degrees

Modifications to motorcycle for replicate collision as compared to motorcycle in actual collision.

Heavy-duty proposed leg protection structures were affixed to the motorcycle front and rear. [See Endnote 9.]

Replicate collision results:

Point of contact:

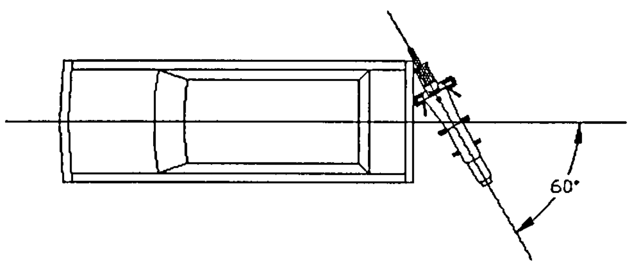
The heavy-duty proposed leg protection structure contacted the front bumper near the center of the automobile.

Accuracy:

The motorcycle and the automobile impacted within one inch (2.54cm) of target.

Automobile damage:
The heavy-duty proposed leg protection structure caused damage to the automobile front bumper. The operator leg caused damage to the automobile grill.
Motorcycle damage:
The heavy-duty proposed leg protection structure was bent slightly to the rear.
Dummy operator:
The deceleration and redirection of the motorcycle allowed the operator leg to impact the automobile and the operator was thrown from the motorcycle.

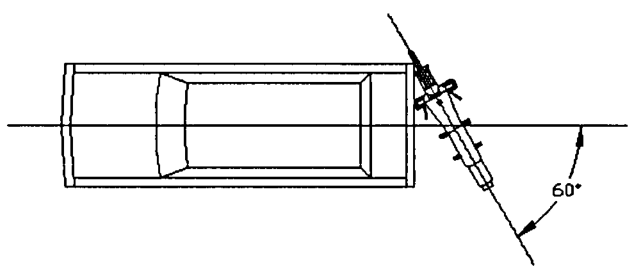
Collision Three 1988
<u>Type of accident:</u>
A collision at the uncontrolled intersection of a private driveway and a public preferential street. (Same as Collision Four.) The automobile driver backed out of a private driveway into the path of a motorcyclist. The collision occurred as indicated by the accompanying diagram.



Automobile:
1977 Oldsmobile Cutlass, two door coupe; Weight: 3729lbs (≈1690kg)
Type of Motorcycle:
1977 Kawasaki KZ650; Weight: 464lbs (≈210kg)
Operator/Injury:
The 21 year-old male operator suffered injuries to his lower left leg which required surgical amputation.
No passenger
<u>Replicate collision parameters established as:</u>
Automobile speed: 7mph (11 km/h)
Motorcycle speed: 25mph (40km/h)
Collision angle: 60 degrees into rear bumper
<u>Modifications to motorcycle for replicate collision as compared to motorcycle in actual collision</u>
A heavy-duty proposed leg protection structure was affixed to the front of the motorcycle. [See Endnote 9.]

<u>Replicate collision results:</u>
Point of contact:
The heavy-duty proposed leg protection structure struck the automobile rear bumper slightly right of center.
Accuracy:
The motorcycle and the automobile impacted within one inch (2.54cm) of target.
Automobile damage:
The heavy-duty proposed leg protection structure caused damage to the rear bumper.
Motorcycle damage:
The heavy-duty proposed leg protection structure was not damaged.
Dummy operator:
The left leg was unprotected when the motorcycle was rolled violently to the right during the impact sequence. This allowed the left leg to impact the rear of the automobile at its target velocity. The operator was violently thrown from the motorcycle and struck the ground in a head-first attitude.

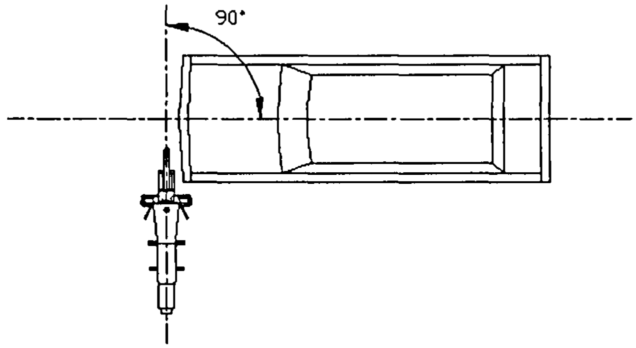
Collision Four 1988
<u>Type of accident:</u>
A collision at the uncontrolled intersection of a private driveway and a public preferential street. (Same as Collision Three.) The automobile driver backed out of the private driveway into the path of the motorcyclist. The collision occurred as indicated in the accompanying diagram.



Automobile:
1977 Oldsmobile Cutlass, two door coupe; Weight: 3729lbs (≈1690kg)
Motorcycle:
1977 Kawasaki KZ650; Weight: 464lbs (≈210kg)
Operator/Injury:
The 21 year-old male operator suffered injuries to his

lower left leg which required surgical amputation.
No passenger
Replicate collision parameters established as:
Automobile speed: 7mph (11 km/h)
Motorcycle speed: 25mph (40km/h)
Collision angle: 60 degrees into rear bumper
Modifications to motorcycle for replicate collision as compared to motorcycle in actual collision.
The motorcycle used in this collision was a 1976 Kawasaki KZ900 (513lbs/ ≈233kg) police specification motorcycle with the standard police style engine guard installed. [See Endnote 9.]
Replicate collision results:
Point of contact:
The police motorcycle left engine guard struck the right rear bumper of the automobile.
Accuracy:
The initial accuracy of the motorcycle impacting the automobile was within 3 inches (≈8cm) of target.
Automobile damage:
The motorcycle engine contacted the right rear bumper causing damage to the bumper and taillight area.
Motorcycle damage:
The standard police style engine guard was totally inadequate in this collision. The bar folded immediately inward against the engine allowing the collision sequence to proceed as though it did not exist.
Dummy operator:
The operator left foot and leg contacted the automobile in a manner identical to that which would have occurred without an engine guard.

Collision Five 1989
Type of accident:
A collision at the uncontrolled intersection of a private driveway and a public preferential street. The automobile driver initiated a right turn from the private driveway into the path of the on-coming motorcyclist. The collision occurred as indicated by the accompanying diagram.

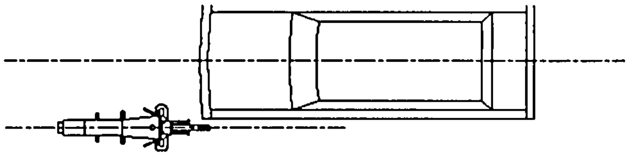


Automobile:
1976 Pontiac Bonneville, four- door sedan; Weight: 4460lbs (≈2023kg)
Type of Motorcycle:
1983 Kawasaki GPZ1100, Weight: 580lbs (264kg)
Operator/Injuries:
The 37 year-old male operator suffered a compound comminuted fracture of the shaft of the right tibia with displacement in angulation and rotation.
No passenger
Replicate collision Parameters Established as:
Automobile Speed: 8mph (13km/h)
Motorcycle Speed: 30mph (48km/h)
Collision angle: 90 degrees
Modifications to motorcycle for replicated collision as compared to motorcycle in actual collision.
A heavy-duty proposed leg protection structure was affixed to the front only of this motorcycle. [See Endnote 9.]
Replicate collision results:
Point of contact:
The right engine crank case cover and heavy-duty proposed leg protection structure contacted the left end of the automobile front bumper.
Accuracy:
The motorcycle and the automobile impacted within one inch (2.54cm) of target.
Automobile damage:
The heavy-duty proposed leg protection structure caused extreme latching between the automobile and motorcycle. During the collision sequence the automobile rotated approximately 15 degrees. The damage to the automobile included significant chassis misregistration.
Motorcycle damage:
The heavy-duty proposed leg protection structure was not damaged. Overall damage to the motorcycle was light. The motorcycle incurred a delta-v of approximately 25mph (40km/h) during the engagement phase of the collision sequence.
Dummy operator:
The impacting automobile forced the motorcycle with the proposed leg protection structure to the operator left at a rate which allowed the leg protection structure to be moved from in front of the operator leg prior to leg contact with the automobile. The operator right leg impacted the automobile in an identical manner to that which would have occurred without the proposed structure.

Collision Six 1991

Type of accident:

An offset head-on collision which occurred on an essentially straight section of road. The automobile was being driven the wrong way on a divided limited access highway. The collision occurred as indicated by the accompanying diagram.



Automobile:

1969 Chevrolet Chevelle; Weight: 3800lbs (≈1723kg)

Motorcycle:

1981 Kawasaki KZ440 LTD; Weight: 400lbs (≈181kg)

Operator /Injury:

The 55 year-old male operator suffered a severe left leg injury which required surgical amputation above the knee.

No passenger

Replicate collision parameters established as:

Automobile speed: 45mph (72km/h)

Motorcycle speed: 55mph (89km/h)

Collision angle: '0' degrees, Offset head-on

Modifications to motorcycle for replicate collision as compared to motorcycle in actual collision.

A heavy-duty proposed leg protection structure was installed to the front only of the motorcycle. [See Endnote 9.]

Replicate collision results:

Point of contact:

The heavy-duty proposed leg protection structure struck the left front corner of the automobile.

Accuracy:

The motorcycle and the automobile impacted within one inch (2.54cm) of target.

Automobile damage:

The proposed leg protection structure caused catastrophic damage to the front of the automobile creating a much more aggressive surface for the operator leg to enter. It should be noted the motorcycle tow trolley failed to completely stop and followed the motorcycle into the front of the automobile which caused total destruction of the motorcycle and automobile. However the trolley initial deceleration was sufficient to allow approximately 25 milliseconds of the initial crash sequence to be valid.

Motorcycle damage:

The heavy-duty proposed leg protection structure was not damaged.

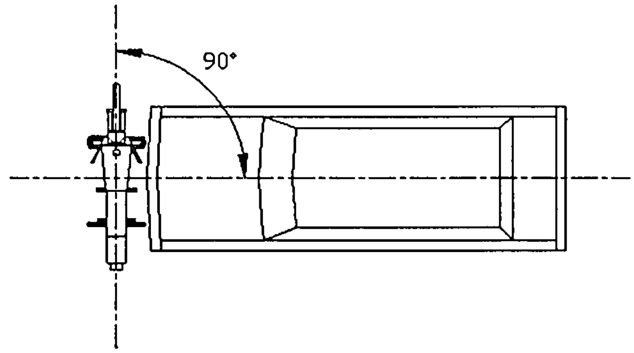
Dummy operator:

The proposed structure caused the motorcycle to latch to the automobile resulting in a much higher deceleration of the motorcycle. This caused the operator to impact the leg protection structure as well as the damaged automobile and then be thrown 63 feet (≈19m) down range. In the actual accident, although the operator leg was badly injured, the fact that the motorcycle did not latch to the automobile allowed the operator to continue with the motorcycle and simply fall over at a low speed. Thus it can be said that in the replicated collision any injury to the operator leg would have been similar, or worse, than with no heavy-duty proposed leg protection structure installed and the addition of the proposed structure caused the operator to leave the motorcycle at a much higher velocity than in the actual accident.

Collision Seven 1994

Type of accident:

A collision at a controlled intersection of two public roadways. (Same as Collision Eight.) The automobile driver ignored a red automated traffic-control device (stop light) and the automobile drove into the motorcycle right side. The collision occurred as indicated by the accompanying diagram.



Automobile:

1983 Cadillac Eldorado, two door coupe; Weight: 3748lbs (≈1700kg)

Motorcycle:

1981 Kawasaki KZ750; Weight: 495lbs (≈224kg)

Operator/Injury:

The 27 year-old male operator suffered injury to the talus and underside of his knee

Passenger/Injury:

The 20 year-old female passenger received a deep

laceration 6-8 inches (≈15-20cm) long to the right knee and a severely comminuted and dislocated ankle which required surgical amputation below the knee.

Replicate collision parameters established as:

Automobile speed: 30mph (48km/h)
Motorcycle speed: 30mph (48km/h)
Collision angle: 90 degrees

Modifications to motorcycle for replicated collision as compared to motorcycle in actual collision.

The accident motorcycle had affixed to it a standard after-market engine guard only. The replicate collision motorcycle had a standard front engine guard installed. A rear guard was constructed from the same material as the front engine guard and installed to the motorcycle. [See Endnote 9.]

Replicate collision results:

Point of contact:

In the actual collision the right front bumper contacted the side of the motorcycle immediately adjacent to the operator's foot rest and rearward. The bumper passed to the rear of the engine guard. In the two replicate collisions (Collisions Seven and Eight) the automobile front bumper contacted nearly the full broadside the motorcycle.

Accuracy:

The initial points of contact of each collision (Collision Seven and Eight) were within 6 inches (≈15cm) of each other.

Automobile damage:

The automobile received significant damage when it contacted the right side of the motorcycle and the two dummies.

Motorcycle damage:

The standard engine guards failed totally and the collision proceeded essentially as if they were not installed.

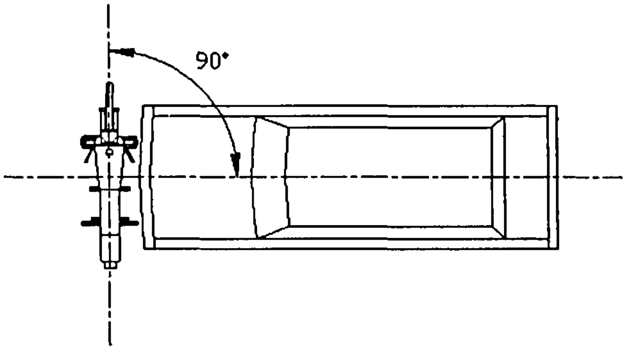
Dummy(s):

Both dummies were thrown violently from the motorcycle. The front of the automobile hood overrode the dummies pelvises. Both dummies were ejected quite violently from the motorcycle. The passenger attained an altitude of 8 feet (≈2.4m) and traveled 65 feet (≈20m) to its point of rest. Both operator and passenger in the replicate collision made contact with the automobile in a manner identical to that which would have occurred had no leg protection structure been installed.

Collision Eight 1994

Type of accident:

A collision at a controlled intersection of two public roadways. (Same as Collision Seven.) The automobile driver ignored a red automated traffic-control device (stop light) and the automobile drove into the motorcycle right side. The collision occurred as indicated by the accompanying diagram.



Automobile:

1983 Cadillac Eldorado; Weight 3748lbs (≈1700kg)

Motorcycle:

1981 Kawasaki KZ750; Weight: 495lbs (≈224kg)

Operator/Injury:

Same as COLLISION SEVEN, the 27 year-old male suffered injury to the talus and underside of his knee.

Passenger/Injury:

Same as COLLISION SEVEN, the 20 year-old female passenger received a deep laceration 6-8 inches (≈15-20cm) long to the right knee and a severely comminuted and dislocated ankle which required surgical amputation below the knee.

Replicate collision parameters established as:

Automobile speed: 30mph (48km/h)
Motorcycle speed: 30mph (48km/h)
Collision angle: 90 degrees

Modifications to motorcycle for replicated collision as compared to motorcycle in actual collision.

This collision is identical to COLLISION SEVEN. The accident motorcycle had affixed to it a standard after-market engine guard only. The replicate collision motorcycle was modified by the installation of front and rear heavy- duty proposed leg protection structures. [See Endnote 9.]

Replicate collision results:

Point of contact:

In the actual collision the right front bumper contacted the side of the motorcycle immediately adjacent to the operator foot rest and rearward. The bumper passed to the rear of the engine guard. In the two replicate collisions (Collisions Seven and Eight) the automobile front bumper contacted nearly the full broadside of the motorcycle.

Accuracy:

The initial points of contact of each collision (Collision Seven and Eight) were within 6 inches (≈15cm) of each other.

Automobile damage:

The heavy-duty proposed leg protection structure caused catastrophic damage to the automobile. The automobile effectively yielded to the bar in a manner which allowed the automobile to continue forward and contact the motorcycle, operator and passenger as though the structures did not exist. The front of the automobile enveloped both structures without significant velocity change of the automobile and before lateral acceleration of the motorcycle began.

Motorcycle damage:

The heavy-duty proposed leg protection structures, front and rear, were undamaged by the collision.

Dummy(s):

Both operator and passenger right legs penetrated the front of the automobile and contacted the radiator which was forced rearward into the fan. The front of the automobile hood overrode the dummies pelvises. Both dummies were thrown violently from the motorcycle. The passenger dummy attained an altitude of 6 feet (≈1.8m). The dummies traveled 55 feet (≈17m) to their point of rest. Both operator and passenger in the replicate collision made contact with the automobile in a manner identical to that which would have occurred had no leg protection structures been installed.

CONCLUSION

The results of the work presented here indicate precision replication of collisions involving moving motorcycles with moving automobiles is practical over most real world accident speeds. The results of the collisions presented here indicate the idea that a rigid steel loop for lower leg protection is simply not viable. At the present time it seems extremely difficult, if not impossible, to provide meaningful protection to an unrestrained motorcycle operator/passenger.

It should be noted that in many of these collisions an extremely high lateral acceleration of the motorcycle is evident. This increased lateral acceleration is likely caused by the addition of the heavy-duty proposed leg protection structure affixed to the motorcycle. The lateral acceleration is great enough to cause textile prints or material transfer into the seat material or paint of the motorcycle. It additionally commonly causes damage to the down-range side or off-side of the motorcycle fuel tank. It seems this acceleration could be an injury producing mechanism to the off-side hip area of the motorcycle operator or passenger.

ENDNOTES

1. W. S. Harley Patent #1941,801; patented January 2, 1934; filed January 5, 1933; Motorcycle Protecting Guard.

2. Bothwell, P. W., Research Report, Motorcycle Crash Tests, The Jim Clark Foundation.

3. Bothwell, P.W. and Peterson, H.C., Dynamics of Motorcycle Impact, July 1971, Final Report, DOT-HS 800-587, NTIS #PB 204 998.

4. Bothwell, P. W. and Peterson, H.C., Dynamics of Motorcycle Impact, September 1973, Final Report, DOT-HS-126-1-186, NTIS #PB 225-710.

5. Chinn, B. P., Injuries To Motorcyclists' Legs, Testing Procedures and Protection, March 1985, PHD Thesis, Brunel University.

6. Tadokoro, H., Fukuda,S. and Miyazakik, K., A Study of Motorcycle Leg Protection, 1985, Tenth Experimental Safety Vehicle Conference, Oxford, England.

7. Transportation Research Center, (TRC) Inc. East Liberty, Ohio 43319-0367, USA; Telephone: 513-666-2011; TRC is located 40 miles (64 km) northwest of Columbus, Ohio, USA. The vehicle-to-vehicle collision facility includes three tow tracks (Figure 5.) which are identified as "barrier," "remote" and "moveable." The barrier (546 ft/≈166m) and remote (510 ft/≈155m) tracks are fixed tracks and a vehicle can be towed in both directions on the barrier track to impact either a fixed barrier or to impact with another vehicle at the vehicle to vehicle impact area. The moveable track (510ft/≈155m long) can be positioned from 8 degrees to 90 degrees relative to the remote track. Crash tests can be performed with two vehicles weighing 5,000lbs (2250kg) each at closing velocities up to 127mph (204km/h). The moveable track can be used to tow vehicles weighing 5,000 lbs (2250kg) to velocities of 50mph (80km/h) and the remote track is designed to tow vehicles weighing 10,000lbs (4,500kg) up to 60mph (97km/h). The tracks can be utilized to perform an 8 degree to 172 degree side impact on either side of a vehicle with

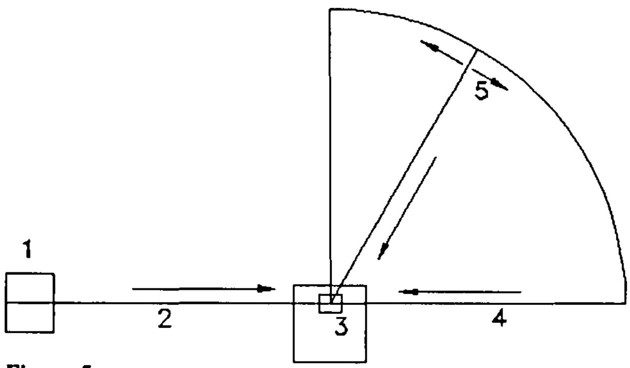
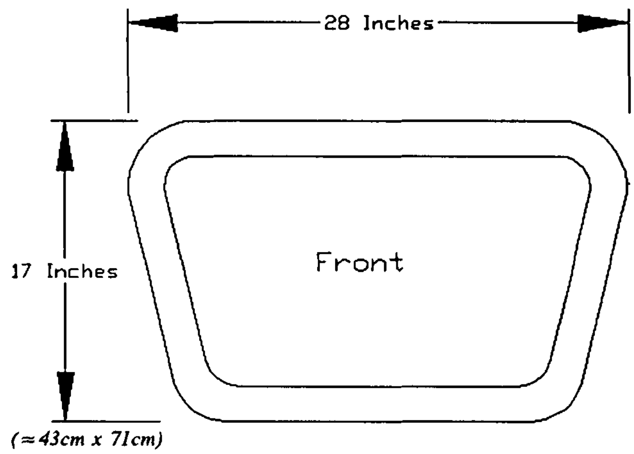


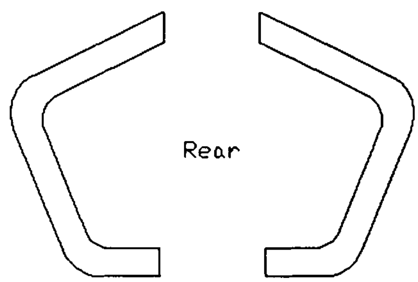
Figure 5.
1. Computer Control Console Bldg.
2. Delivery Track "barrier"
3. Vehicle to Vehicle Impact Area
4. Delivery Track "remote"
5. Delivery Track "moveable"

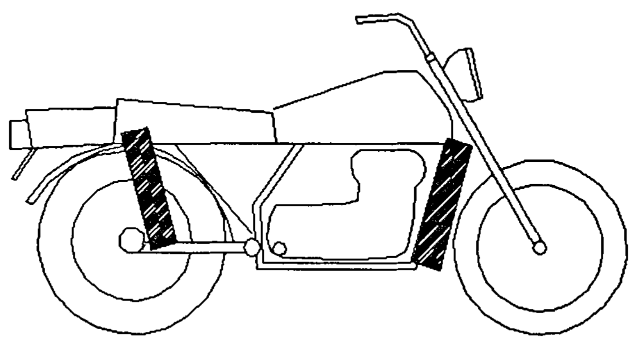
both vehicles moving and the barrier and remote tracks can be used to perform head-on and off-set collisions with both vehicles moving. Each track has an individually powered cable that is computer controlled to tow the vehicle along a rail with vehicle velocity accuracy of ≈0.5mph (≈0.8km/h). The computer calculates the release velocity of each vehicle based on its impact velocity, weight, frontal area, free rolling distance and umbilical cable drag, as well as, wind velocity and direction.

8. Photo-Sonics, High-Speed Rotary Prism Cameras; Instrumentation Marketing Corp, 820 S. Mariposa St., Burbank, California 91506, USA; Telephone: 213 849-6251. General Specifications: Continuous rotary prism with rotary disc shutter; Magazine load; 1000 frames per second; Aperture: Full frame 16mm; Film Type: ASA PH 22.5-1953; Shutter: Variable rotary disc, 9°, 18°, 36°, and 72° max.; Timing Lights: Dual LED; Heaters: To -20°F (-29°C).

9. The dimensions, 17 inches by 28 inches (≈43cm x 71cm), are approximate. A "standard" bar or engine guard is normally made from 1.0 inch to 1.25 inch by .125 inch (25.4mm to 31.75mm x 3.175mm) seamed pipe. The "heavy-duty" bars have been recommended as 2 inch by 3/32inch (≈59mm x 2.33mm) seamless drawn tubing. It should be noted in all cases presented here the heavy-duty proposed structure has been 2 inches by 1/4inch (≈50mm x 6mm) seamless drawn tubing. This additional wall thickness allows sufficient strength margin to prevent bar failure.







Shaded boxes denote general location of device installation.

IMPROVEMENT OF MOTORCYCLE RIDERS SECONDARY SAFETY BY PROTECTORS FITTED TO RIDERS CLOTHING

Hubert Koch
Motorcycle-Industry Association of Germany
Germany
Paper Number 96-S7-O-12

ABSTRACT

This paper describes the draft CEN-standard (prEN 1621-1) named "Motorcyclists Protective Clothing against Mechanical Impacts, Part 1". It contains performance requirements for impact protectors fitted to motorcyclists' clothing. Impact protectors meeting the requirements of the standard will provide some protection against injury caused by impacts with road surface in motorcycle accidents. Injuries from impacts with such objects or other vehicles may be slightly reduced, although the capacity and performance of protectors is limited. This draft standard is the result of a long period of discussion and research within CEN/TC 162 working group 9.

In his conclusion the author distinguishes between the different tasks of the motorcycle riders' clothing such as protection against atmospheric conditions and the secondary safety performance limited to protectors. He points out that further research is necessary to improve both the protectors and the standard. Quoting from an official document of the EU-Commission, the author gives a negative answer to the question if there is an additional safety potential in riders clothing. He underlines the basic conflict requirements, for example the increase of secondary safety versus the limited manoeuvrability of the rider, which may cause accidents. Another conflict of requirements is the one of secondary safety versus primary safety which may occur if the riders' ability to handle his bike safely is negatively influenced by clothing reducing the fitness. The author proposes follow-up research before further standards for every kind of riders clothing could possibly be discussed.

INTRODUCTION

The status of motorcycle safety

Motorcycle safety has been improved in many countries in the last 10-20 years. In Europe fatality rates decreased in most of the countries. For example the number of fatalities in Germany has been reduced from 266 per 100,000 registered motorcycles in 1976 to 167 in 1980 and to 42 in 1993 (see table 1)*.

Fatality Rate of Motorcycles per 100.000 Vehicles in some European Countries 1980/1990/1993

Country	Fatality Rate 1980	Fatality Rate 1990	%Change 1980/1990	Fatality Rate 1993	% Change 1993/1990
A*	116,5	101,7	-12,7	78,2	-23,1
B	150,4	78,8	-48,9	83,8	9,1
CH	101,2	53	-47,6	34,2	-35,5
D*	166,8	54,4	-67,4	41,8	-23,2
E*	61,1	73,8	20,8	59,7	-19,1
GB (1992)	106,2	87,2	-19,4	67,4	-22,7
NL (1992)	121	44,3	-63,4	40	-9,7
		ø	-34,1	ø	-17,7

* [illegible]

Reasons for this positive development are not easy to evaluate. It can be taken for granted that the improvement in primary safety has made a major contribution. In many countries driver licensing schemes proved to be effective (e.g. the European driver license directive 91/439/EWG).

Additionally, advanced training schemes for riders have been established in many of the countries, based on accident research and following scientific input. In Germany for example there are more than 1,000 advanced rider courses per year on a voluntary base.*

* IfZ-brochure "Motorradtraining, Termine 1996", Essen, Gladbecker Str. 425
* Source: IfZ, 1996

Questions of both beginner and advanced training and licensing have been discussed among experts at many scientific conferences, for example in Orlando, Florida, "The Human Element", October 31st - November 3rd, 1990, the IfZ-conference in Bochum "Safety Environment Future" in 1991 or at the FIM-symposium to be held in Luxembourg, May 30th - 31st, 1996, under the auspices of the FIM.

Beside rider education and training, the improvement of motorcycle safety is also due to the improved vehicle technology. Referring to a study done by the International Motorcycle Manufacturers Association titled "Motorcycle Safety, Decade of Progress" (Paris, 1994)*, the biggest improvement has been made in brake technology, improved stability and handling and better-lighting systems.

Secondary safety, however, could not be improved in the same way due to the lack of a protective vehicle structure.

Although a number of ideas are under discussion, both at this conference and the preceding ones, no agreement has been found among experts as to which concept should be followed. It can be predicted that the expert discussion will take some more time before feasible solutions can be presented.

A secondary safety device: Protectors fitted to motorcycle riders clothing

One element of improved secondary safety are the so-called protectors, which can be fitted to clothing worn by motorcyclists when riding. First used in Sweden in the mid 80s and introduced by only one manufacturer, protectors nowadays are used by most of the clothing manufacturers.

Whilst the material used for protectors in 1985 in most cases was temper foam, today material with much better energy absorption capacities like viscoelastic polyurethane foam covered mostly by a thermoplastic material as well as composite of a new type of polystyrene is being used.

* Motorcycle Safety: "A decade of progress" published by Association des Constructeurs Européens de Motorcycles (ACEM) and International Motorcycle Manufacturers Association (IMMA) (1994)

As the market developed in Europe, the discussion started to stardadize those protectors. This happened first at the national level, for example in the United Kingdom (BSI), in Sweden and in Germany (DIN).

After the approval of the EU-directive 89/686/EWG on personal protective equipment, the national attempts of creating standards were ceased due to so-called standstill regulations after the Comité Européen de Normalisation (CEN) was mandated by the EU-Commission under the second mandate to create a harmonised European standard.

CEN accepted this contract and its Technical Committee 162 on personal protective equipment in its meeting on October 15th/16th, 1990, in Haan, Germany, established working group 9 and named it "Motorcycle riders protective clothing" and agreed on the following scope: "Performance requirements and test methods for motorcycle riders protective clothing including hand and foot protection against mechanical impact" *.

The working group concentrated its activities on the protectors first. The draft standard (prEN 1621-1) was released in 1995 and sent out for the first enquiry. After some severe technical comments from member states, a second first enquiry was held to be necessary, which was finished in April 1996. The draft is now released for a formal vote to member states, to be completed by January/February 1997.

The draft standard prEN 1621-1 "Motorcyclists' protective clothing against mechanical impacts - part 1: Requirements and methods of test for impact protectors.

The following chapters quote from the draft standard. All parts of this chapter are taken from the document prEN 1621-1 (identified by italics).

After a foreword and the introduction the scope is defined as follows:

* European Committee for Standardization (CEN) Doc. CEN/TC 162 N 121, Nov. 1st, 1992

Scope

This part of the European standard lays down requirements and test methods for impact protectors incorporated or intended to be incorporated into motorcycle riders clothing or used as separate items.

Chapter 2 gives normative references, chapter 3 definitions.

Chapter 4

4.1 Impact areas - Protectors

The following body regions are specified as impact areas and protectors shall be catagorized as follows:

a) shoulder	*: Protector "S"*
b) elbow and forearm	*: Protector "E"*
c) hip	*: Protector "H"*
d) knee and upper tibia	*: Protector "K"*
e) knee, upper and middle tibia	*: Protetor "K+L"*
f) the front of the leg below protector "K"	*: Protector "L"*

The size of the impact areas shall comply with clause 5.3.2.

4.2 Force transmission

When impact protection is tested in accordance with clause 5, the mean value of the test results shall not exceed 35 kN and no single value shall exceed 50 kN.

5. Equipment

5.1 Apparatus

5.1.1 Dropping apparatus

The apparatus shall be such that a guided mass strikes a test anvil in a vertical drop. The centre of the mass of the falling block shall lie over the centre of the anvil. The mass shall be (5000 ± 10)g and its kinetic energy on impact shall be 50 J.

5.1.2 Drop striker

The striker face shall be made of polished steel with dimensions of 40 mm x 80 mm and 5 mm radius edges.

5.1.3 Anvil

The anvil surface shall be hemispherical with a radius of 50 mm. The anvil shall be made of polished steel and have a total height of 180 mm (± 20 mm) (see figure 1). The anvil shall be attached through a piezo-electric lead cell to a mass of at least 1000 kg. The cell shall be preloaded according to the manufacturers' instructions.

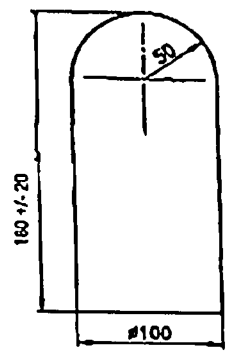


Figure 1. Anvil

5.1.4 Force measurement instrumentation

The anvil shall be mounted so that during impact testing the whole force between the anvil and the massive base of the apparatus passes through a quartz force transducer in line with its sensitive axis. The force transducer shall have a calibrated range of not less than 200 kN and a lower threshold of less than 1 N. The output of the force transducer shall be processed by a charge amplifier and displayed and recorded on suitable instruments. The measuring system including the drop assembly shall have a frequency response in accordance with channel frequency class (CFC) 1000 of ISO 6487.

5.2 Templates

5.2.1 Template material

Templates shall be prepared from a non-fraying (e.g. coated) fabric of a quality which basically maintains its shape and dimensions during all use.

Note: A suitable material is the PUR-coated PES fabric of 280 g/m² to 360 g/m² used for truck tarpaulins.

5.2.2 Shape and dimensions of templates

The templates shall comply with the shapes specified in figure 2 and the dimensions specified in table 1.

Protector	Templates for type A protectors			Templates for type B protectors		
	R	r	d	R	r	d
	mm			mm		
S	55	32	84	70	40	80
E	45	24	119	60	30	150
K	55	24	100	70	30	130
H	32	24	64	40	30	80
L	32	24	64	40	30	80
K+L	55	24	186	70	30	240

Table 1: Dimensions of the templates

The manufacturer shall provide sufficient information to the test house to allow it to select the appropriate size of testing template from the above table.

Note: The type B protector dimensions are intended to cover the needs of most motorcycle riders. However, for ergonomic reasons, in certain cases the type B protectors may be unsuitable. In such cases the alternative type A protectors may be chosen by the user.

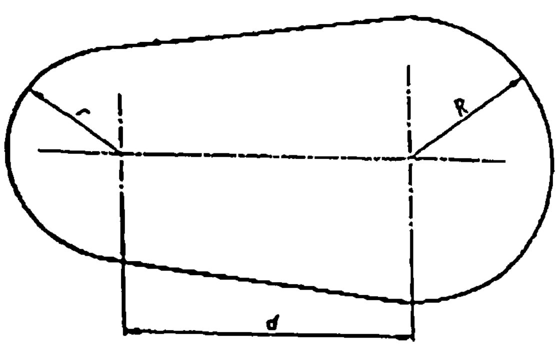


Figure 2. Shape of templates

5.2.3 Use of templates

The templates shall be used to define the minimum area of the protectors as follows:

- *The protector shall be formed to its 3-dimensional shape which can be expected during riding. A test person or a display dummy of proper size may help for that procedure.*
- *Each protector shall be adjusted on the test body. When the best correspondance has been obtained, the template shall be adjusted to the protector to check the appropriate size.*

Chapter 6 describes the test methods.

6. Test method

6.1 Conditioning and testing atmosphere

The samples shall be conditioned for at least 24 h in an atmosphere with a temperature of (20 ± 2) °C and a relative humidity of (65 ± 5)%. If the tests are carried out in an atmosphere different to these specified values, the tests have to be commenced within five minutes of being removed from the conditioning atmosphere.

6.2 Sampling

Protectors made to the same specification (e.g. material thickness, density etc.) can be considered as belonging to the same "family". The test samples shall consist of three protectors from the same "family". The test house may select the samples from any of the protector categories specified in 5.3.2.

6.3 Positioning of the sample

The samples shall be securely positioned on the test anvil.

Note: A system of elastic straps has been found suitable. These are angled downwards around the anvil and pull the sample down to the anvil but do not compress the sample significantly. The straps connected to a flat elastic ring that surrounds the impact area, but do not cover it. The downward force exerted is 5 N to 10 N.

6.4 Number of tests

Testing shall be carried out at three different points on each sample piece, at least 50 mm apart within the template/test area.

6.5 Test results

The mean value shall be calculated from the nine measurements.

At the end of the standard, Chapter 7 describes the requirements for marking and Chapter 8 the manufacturers' information to users.

Discussion

Status achieved

To evaluate the status achieved with this draft protectors standard, one has to go back to the origin of the development of this safety device.

Motorcycle riders have been wearing special clothing ever since the beginning of motorcycle riding. The reason for that, however, has not been safety considerations, but the intention to protect the rider against atmospheric conditions (cold, rain, wind) and dust and dirt because of bad road conditions.

It was only in the 70s, when the motorcycle celebrated its come back as a recreational vehicle, that a scientific discussion on motorcycle safety related to riders clothing first took place. Feldkamp* et al. published the first study based on clinic data.

A very limited number of studies were published between 1976 and the mid 80s, which more or less all came to the same conclusions summarized by Otte (1988).*

Leather clothing, which was the most commonly worn, does not influence the number of, or severity of injuries in collisions. Only in single vehicle accidents there was an influence, but limited to inner lesions and soft-tissue injuries. Again fractures have not been influenced.

Therefore, in the mid 80s the first attempts were made to improve the energy absorption capacity of riders clothing by using so-called protectors. First results were presented by Gustafsson* (Folksam), Aldmann* at the 10th ESV, Oxford, and Nygren* which gave some indications that secondary safety could be improved, although the methodology was limited.

Given the improvements in the protector development described above (new materials, new types of sandwich design), one can assume that protectors meeting the requirements of the standard prEN 1621 would be beneficial, although the threshold of 35 kN from the biomechanical point of view still seems to be too high to prevent from bone fractures.

Further research needed

However, research on the effectiveness of the new protectors meeting the requirements of the draft standard prEN 1621 is recommended. A state of the art methodology should be used to give as valid as possible results.

As far as impact configuration, impact speeds and motorcycles to be used etc. are concerned, the procedures described in ISO/DIS 13232-1/8 seem to be appropriate.

Additionally, the dummy described in this standard appears to be suitable to measure bone fractures because of the use of frangible leg bones.

Full scale tests undertaken in accordance with the ISO-standard could additionally provide researchers with the basic information needed for follow-up computer simulation research. The main objective of this research would be to prove the effectiveness of today's protectors and to improve the energy absorbing capacity of protectors in order to reduce the 35-kN-threshold.

* Feldkamp, G.: "Motorrad-Boom und Motorradunfaelle", in Fortschritte Medizin, Jg. 92., Nr. 8, Heidelberg, 1974
* Otte, D.: Sicherheitsfortschritt durch Entwicklung von Schutzkleidung für Motorradfahrer, Protektorenkombis, Faszination und Sicherheit, IfZ, Bochum, 1988
* Gustafsson, H.: "Protective clothing for motorcyclists", Insurance Company Folksam, 1984
* Aldmann, B.: "The protective effect of a specially designed suit for motorcyclists", 10th ESV-conference, Oxford, 1985
* Nygren, A.: et al.: Schutzwirkung eines besonders entwikkelten Anzugs für Motorradfahrer, Forschungsheft 5, IfZ, Bochum, 1987

In parallel to the evaluation of the effectiveness of today's protectors, real-life accident data analysis based on big enough samples should be undertaken to develop a better understanding of how the protectors should be shaped, where they should be located and how big they should be. The need and the effectiveness of additional protectors (chest/back) should also be evaluated.

As far as the standard itself is concerned, further improvement should be made in the testing procedure. There are some indications that it would be advisable to do the testing not only at one defined level of humidity, but covering a wider range. This is because there are indications that the performance of materials used differ depending on the temperature and the humidity.

In TC 162/WG9 a working group has already been established to work on this first revision of the standard. Other questions of improving the standard are related to the shape and dimension of the anvil.

Is there an additional safety potential in riders clothing?

In addition to the protectors some researchers mainly representing test houses and university-research units in the United Kingdom claim a protective capacity of riders clothing in addition to that of the protectors.

There has been some critisism of this approach because it was the poor safety performance of ordinary riders clothing that initially led to the development of the protectors (see above).

While these protectors still need a scientifically based proof of their effectiveness, one must doubt whether there is an additional safety potential in clothing, based on physical considerations e.g. thickness of material. The main purpose of motorcycle riders clothing was and is protection against atmospheric conditions and the protection of the clothing worn underneath.

This approach, which is quite common in the motorcycle community, has even been shared by the European Commission and its member states. The Committee 89/392/EWG on personal protective equipment, which was set up by the European Commission and is formed by delegates of both the Commission and the member states in a document recently released stated:

"As a general rule, clothing worn by motorcycle riders (which includes gloves, boots, shoes etc.) is for private use against the weather: rain, heat and cold".

As a conclusion this Committee stated: *"They are therefore excluded from the scope of the PPE-Directive (89/686/EEC)".*

The Committee then explains, why from its point of view protectors used in motorcycle riders clothing may be considered a PPE and should be produced meeting the requirements of the standard. The wording of the document is:

"However, if the manufacturer specifically claims or implies in sales literature or advertising, that because of particular additional features (e.g. elbow pads, knee pads and the like) this clothing offers special protection, these additional features alone shall be classed as PPE and must therefore comply with the provisions of the Directive."

While it is doubted that there can be any additional improvement of secondary safety by improved clothing, Committee 89/392/EWG allowed for this,

"If the manufacturer claims or implies in sales literature or advertising that the whole garment provides special protection in addition to that provided by individual protectors, the whole garment musts comply with all the essential requirements of directive 89/686/EEC",

only a very few manufacturers believe in this possibility. In the very limited physical range given, they have developed suits to be proved according to 89/686/EEC. However, in everyday use they have yet to prove their usefulness. When these products were put on the market, a conflict of requirements appeared.

But these products immediately after being put on the market showed that there is a major conflict of requirements. Basically there are two conflicts which will be difficult to resolve.

1. The attempt to improve the secondary safety capacity of suits must automatically lead to an increased stiffness of material which limits the manoeuvrability of the rider. In the United Kingdom policemen which were given suits of this style after some practical experience refused to wear the suits because the lack of flexibility made it impossible for them to raise their arms e.g. to regulate traffic or to defend themselves (see TIMES).*

2. The second basic conflict is between secondary safety and primary safety in terms of the riders' ability to ride his bike safely. Physiological studies done by Huber et al. proved that riding a motorcycle requires a high level of physical fitness. In test rides motorcycle riders had significantly increased cardiocirculatorical data e.g. pulse due to both emotional stress and muscular activities. Therefore clothing must allow the body to sweat to cool down the body temperature.

Very heavy, stiff safety clothing automatically puts the rider's body into an unconfortable, squashed-up position, which may substantially reduce the rider's fitness by negatively influencing his cardio-physical system. Increasing skin and blood temperature may lead to a collaps.

This conflict between requirements of active and of passive safety in its importance can hardly be overestimated.

To evaluate this, Spiegel suggested a research programme, which should measure the number of mistakes/errors done by a rider under standardised riding conditions comparing riders with ordinary clothing and those with high-level safety clothing. The hypothesis of this research design is that riders with high-level safety clothing have a higher number of errors/mistakes and therefore a potentially higher accident risk than those wearing ordinary clothing. The methodology Spiegel has developed for such research, includes measurements of pulse, blood and skin temperature and other physiological parameters.

It must therefore be stated that given the knowledge available at the time, basic research is needed to try to indentify whether these basic conflicts can be solved by developing a suitable safety clothing, which improves secondary safety without decreasing primary safety. It has thereby to be born in mind that the potential secondary safety increase is very much limited.

From the above, it can be seen that standards for "safety clothing" for motorcyclists are not only redundant, but on the contrary are counter productive, as they limit the freedom of developing and testing new products.

* London TIMES-article dated July 10th, 1995, by Stewart Tendler, Crime Correspondent

It can therefore be concluded, that while the standard described in this paper (prEN 1621) is a step forward in increasing motorcycle riders' safety, other standards for suits, gloves and boots are neither necessary nor useful.

REFERENCES

IfZ-brochure "Motorradtraining, Termine 1996", Essen, Gladbecker Str. 425

Motorcycle Safety: "A decade of progress" published by Association des Constructeurs Européens de Motorcycles (ACEM) and International Motorcycle Manufacturers Association (IMMA) (1994)

European Committee for Standardization (CEN) Doc. CEN/TC 162 N 121, Nov. 1st, 1992

Feldkamp, G.: "Motorrad-Boom und Motorradunfaelle", in Fortschritte Medizin, Jg. 92., Nr. 8, Heidelberg, 1974

Otte, D.: Sicherheitsfortschritt durch Entwicklung von Schutzkleidung für Motorradfahrer, Protektorenkombis, Faszination und Sicherheit, IfZ, Bochum, 1988

Gustafsson, H.: "Protective clothing for motorcyclists", Insurance Company Folksam, 1984

Aldmann, B.: "The protective effect of a specially designed suit for motorcyclists", 10th ESV-conference, Oxford, 1985

Nygren, A.: et al.: Schutzwirkung eines besonders entwikkelten Anzugs für Motorradfahrer, Forschungsheft 5, IfZ, Bochum, 1987

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DEVELOPMENT AND TESTING OF A PURPOSE BUILT MOTORCYCLE AIRBAG RESTRAINT SYSTEM

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Paper Number 96-S7-O-13

ABSTRACT

Previous research work has revealed that airbags offer considerable potential benefit to the rider's head and chest in many types of impact, especially those involving head-on impact of motorcycle into the opposing vehicle. However, the airbags used in the research have been either adapted or, in some cases, unmodified car airbag modules. This has led to the identification of some problems that may cause the increase of injury under certain conditions. This paper describes the development and testing of a purpose built airbag restraint system for motorcycles. The system has been developed in structured phases involving mathematical modelling, system manufacture, and then development and evaluation in a series of tests on a Norton motorcycle ranging from static fire to sled tests and finally full scale impacts. An Hybrid III dummy was used throughout the programme and a wide range of parameters were assessed. Results of the sled and full scale impact tests show kinetic energy reduction of between 79% and 100% and low neck injury measurements compared to the tolerance limits. These are discussed in the main body of the paper and the concluding remarks given at the end. Firing of an airbag is an important part of the system and TRL has undertaken research to determine the characteristics of a trigger system by the use of theoretical and experimental data. This includes data obtained from accelerometers mounted on different locations on a motorcycle during "rough riding" tests described in Appendix A.

INTRODUCTION

Results of road accident casualty studies for 1994 in Great Britain [1] show that 24300 riders were injured in motorcycle accidents, of which over 6000 were serious and 450 fatal. Seventy percent of the fatal injuries can be attributed to head and neck injuries. The total annual cost of motorcycle casualties in Great Britain is approximately one billion pounds sterling [1]. Motorcycle safety research at the Transport Research Laboratory (TRL) [2] has shown the potential benefit of the use of airbags to restrain and protect motorcycle riders in frontal impacts. At TRL, prior to the work described in this paper, airbags for car occupant restraint systems were installed into the motorcycle structure and assessed in a programme of controlled impacts both on a dynamic test rig and with a free-running motorcycle into cars and barriers. In both cases, instrumented dummy riders were used to provide data on the accelerations and loads likely to be applied to critical areas of the body.

As part of the research programme to improve motorcycle safety, the Transport Research Laboratory (TRL) commissioned Lotus Engineering to design, manufacture and supply a purpose built airbag system for a large, touring Norton Commander motorcycle for impact testing. The programme started with MADYMO computer simulation of rider kinematics at impact, using load and acceleration impact test data information supplied by TRL, to determine the most suitable location of an airbag on the motorcycle and also to assess the system characteristics. There were also parametric studies to determine the optimum airbag size and shape including tethering, suitable fire times, rate of inflation and pressure. This was followed by the design and manufacture of an airbag module mounted at the rear of the modified fuel tank consisting mainly of an uncoated polyester airbag and a hybrid inflator. Knee bolsters designed to control the rider trajectory but retain the energy absorbing properties defined in the TRL leg protection specification were also mounted into the motorcycle front fairings.

The test phases of the programme included firing the airbag system statically to assess its performance and integrity during deployment. This was followed by a series of sled tests to develop the system and consider the effects of an out of position rider (for example crouching or prone riders) as well as simulating angled impacts. The sled phase was assessed for compliance with the design and performance criteria defined at the beginning of the programme. This was immediately followed by the full scale crash tests in which a free-running Norton Commander motorcycle, fitted with an airbag system, was impacted into stationary and moving cars at different speeds, angles and directions to assess performance of the airbag in as many road accident conditions as possible.

It is well known that the performance of an airbag system depends critically upon the time at which the airbag is deployed during the impact and this in turn depends upon the

characteristics of the firing switch. For this reason, the airbag system in these tests was fired remotely with a delay at impact based on the motorcycle fore/aft deceleration pulse obtained from equivalent standard test.

The characteristics of an airbag switch must be chosen so that the bag is deployed efficiently during an accident but does not deploy when the motorcycle is being ridden even when this is over an extremely uneven surface such as potholes or a kerbstone or very rough off-road terrain. Motorcycle vibrations during such extreme circumstances were evaluated, and the results of this research were used in the development of the system. This work is described in Appendix A.

The airbag programme testing is still continuing and more tests are planned to assess the effectiveness of the airbag for a further range of speeds, angles and impact locations to cover many road accident configurations. The design of the tests was in general accordance with ISO DIS 13232 [3]. As in the sled phase, the final outcome of the full scale impact tests will be assessed with respect to the performance criteria defined at the beginning of the programme.

DEVELOPMENT PHASES AND PERFORMANCE CRITERIA

Objectives and Constraints

<u>**Objectives**</u> - The Norton Commander motorcycle was chosen as the test bed for which the airbag system was to be developed. It is a large touring machine (221kg) with a full glass-fibre fairing and is representative (in weight and size) of the larger machines on the market. Although the system was developed specifically for this machine it was intended that the development would formulate principles which are readily applicable to other machines of this class and may, in general, be applicable to many motorcycles of conventional design.

In theory the ideal position for an airbag on the Norton Commander may have been a site in that part of the fairing at the base of the screen. This would have provided a large surface against which the bag could react and thus potentially hold the rider very effectively. However, because this would almost certainly not be possible with most other motorcycles a more general position was sought and a site in the region of the petrol tank was also chosen to be investigated. Previous research [4] had shown that this would be appropriate and such a position does not rely upon the presence of a fairing.

There are two principle methods by which an airbag system can protect a motorcycle rider. One is ejection, whereby the airbag helps to raise the rider clear of the opposing vehicle, and the other is restraint whereby the airbag is used to absorb most, if not all, of the rider's energy. Previous results had indicated [4] that the restraint method was preferred and therefore the objectives were based upon achieving this at motorcycle impact speeds of up to 48km/h (30 mile/h) and accepting that at higher speeds full restraint may not be possible.

The main objective, and therefore the main function of the system, was to protect the rider in impacts, approximately head-on to the motorcycle, into moving and stationary vehicles. Additionally, the system should be of some benefit in a range of other impact configurations but it must not be of serious detriment to the rider in any configuration.

It should be noted that approximately 75% of motorcycle accidents occur at motorcycle impact speeds of up to 48 km/h and 96% up to 64 km/h (40 mile/h)and that 93% of the serious and fatal head injuries occur at speeds of up to 64 km/h (40 mile/h) [5][6]. It should also be noted that the majority of fatal and serious head and chest injuries occur in impacts approximately head-on to the motorcycle and that in the majority of accidents with an opposing vehicle, the speed of the opposing vehicle is 25 km/h (15 mile/h) or less. It was decided therefore to aim to optimise the airbag system performance for impacts approximately head-on to the motorcycle into stationary and slow moving vehicles (up to 25 km/h) with the additional requirement that injury potential in head-on impacts at speeds up to 64 km/h (40 mile /h) must be reduced.

It was intended that the overall performance of the system be judged against the performance of a standard motorcycle and that the criteria for the optimised case ie 50th percentile single rider in normal seating position travelling at 48 km/h, head-on into the side of a stationary vehicle should be:

- That the kinetic energy at the plane of initial impact be reduced by at least 70% at the motorcycle to opposing vehicle first contact plane AA'. The AA' plane is a fixed vertical plane normal to the direction of motorcycle travel passing through the point at which the motorcycle front wheel first contacts the opposing vehicle.
- That the instrumentation measurements for the head, neck and chest should be substantially reduced.

<u>**Constraints**</u> - It is known, from previous TRL research, that in impacts head-on into vehicles moving across the path of the motorcycle, the motorcycle yaws and the lower half of the rider twists with the machine as the upper part tries to maintain its original direction of travel, therefore the airbag

was also required to be of benefit in this type of impact up to a yawing rate equivalent to that measured in an impact where both vehicles were travelling at 48 km/h (30 mile/h).

It is common practice, when assessing automotive safety, that the evaluation is based predominantly on the use of a 50th percentile male dummy and therefore it was decided that the airbag performance should be optimised using a single 50th percentile Hybrid III dummy in a "normal" riding position. Nevertheless, there must be some benefit to a rider in the crouching position and to riders greater and smaller than 50th percentile and "due care" must be taken for:

- A rider lying close to the tank.

- A rider with a pillion passenger.

The final constraint was that the airbag system must be able to be fitted to the motorcycle such that the overall appearance remained largely unaltered.

DEVELOPMENT PHASES

After careful consideration of the objectives and constraints it was decided that the development should consist of six phases as outlined below.

__Phase 1: Assessment of existing data__ - This phase was devoted to an extensive assessment of existing impact test data both from instrumentation records and film analysis. From this, the type, number, and sequence of tests and the manufacturing processes needed to complete the development of the system was established. The vibration data from the abuse trials (rough riding) and the implications of this information for the system performance were also considered.

__Phase 2: System design and computer simulation__ - The use of computer simulation is vital to the efficient development of modern automotive safety systems. It was used in this project to:

1) Determine the best tank mounted position optimised for a single rider normally seated.

2) Determine the best tank mounted position as in 1) additionally benefiting a crouching rider and large and small riders; with due care taken for prone riders and riders with pillions.

3) Investigate the bag and inflator parameters, and expected level of protection.

4) Assist in the provision of engineering plans for the system installation.

The package used for the simulation was MADYMO. The processes and results are described later.

__Phase 3: Procurement and manufacture__ -This phase was designed to achieve the following:

- Procurement and manufacture of the inflators and the bags for the chosen design.
- Modification of a Norton Commander motorcycle to provide a static test facility.
- Assembly of the airbag modules and covers.

__Phase 4: Static fire tests__ - This phase comprised static airbag deployment tests to assess and develop the following:

- Inflation time and rate.
- Airbag shape and size.
- Airbag folding pattern.
- Housing design.
- System cover.
- Potential airbag/rider interaction during deployment.
- System generated temperature effects.

__Phase 5: Sled tests__ - This phase comprised a series of tests on TRL's dynamic sled test rig and was designed to evaluate the system, with a dummy rider, over a range of parameters covering speed, angle (to simulate yaw of motorcycle in impacts where both vehicles are moving) and seating positions. This series of test was considered a vital step before the evaluation in expensive full scale impact tests. The tests and results are described later.

__Phase 6: Full scale impact tests__ - Full scale impact tests are the culmination of this project and the results are needed to evaluate the potential benefit of the chosen airbag system. The tests consist of impacting the motorcycle, with and without the airbag system, at different speeds and angles into the side, front and corner of a car travelling at different speeds. This series of tests is not complete but a description of the method, test pairs successfully completed to date and the corresponding results analysed are discussed later.

SYSTEM DESIGN AND COMPUTER SIMULATION

The model was constructed using the TNO MADYMO simulation package. The simulation was used to investigate different bag sizes and types in combination with different inflator characteristics and with the system mounted at three principal positions. The objective was to optimise the system for a 48km/h (30mile/h) motorcycle impact at 90° into the side of a stationary vehicle with a 50th percentile rider in the normal seating position. However, also considered were crouched and prone riders, 95th and 5th percentile riders and the presence of a pillion passenger. The computer simulation results were used to determine the optimum design and position for the airbag system.

Computer Simulation

Motorcycle - The geometry was based upon the Norton Commander and the motorcycle was modelled using ellipses and planes fixed in space, (see Figure 1). The component characteristics were based upon TRL dynamic and quasi-static laboratory tests.

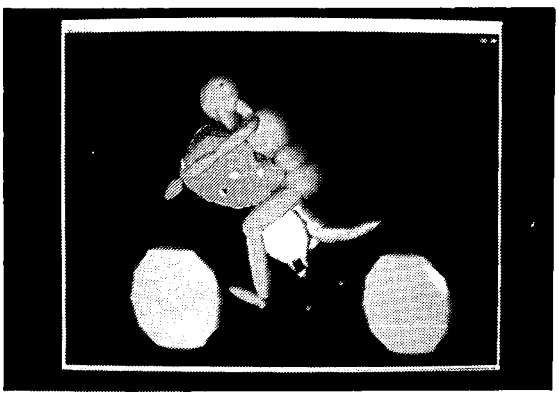

Figure 1. Normal position rider

Bag Models - Four bag models, one existing (car model) and three especially constructed were used for the simulation studies. Table 1 below gives brief details of each. Design volume refers to the unpressurised bag. Peak volumes, during inflation, are greater.

Table 1.
Bag Models

BAG *	DESIGN VOLUME Litre	POSITION	ELEMENT	NODE
Bag 0 (car design)	100	Front fairing	4002	2003
Bag 1	80	Front tank	1236	620
Bag 2	87	Rear tank	1832	918
Bag 3	107	Rear tank	2102	1053

* It should be noted that all bags were fitted with vents, the size of which could be varied.

Inflator Models - Five different inflator models were used in the study, one was an existing car design and was used with the car bag (Bag 0) the rest were constructed especially for the simulation studies. Table 2 below gives brief details of the inflators.

Table 2.
Inflator models

	Tank Test Volume Litre	Peak Pressure bar	Time to Peak Pressure ms
Inflator 0	120	3.13	100
Inflator 1	85	6.00	50
Inflator 2	85	4.20	50
Inflator 3	107	4.74	50
Inflator 4	100	3.78	50

Dummy - A Hybrid III (50th percentile) dummy data base, supplied by TNO with MADYMO, was used for the simulations with the following modifications:

- Head mass and shape modified to represent the mass and size of the rider with helmet.
- Knee joint properties modified to give kinematics more representative of a motorcycle rider.

The riding positions were defined relative to the Norton Commander geometry, and those used in the simulation were normal, crouching and prone. Also defined were positions for a pillion (50th percentile) and a large (95th percentile) and small (5th percentile) rider. The measurements were based upon the ISO DIS 13232 [3] standard and the dummy was positioned with his hands on the handlebars.

Pulse - The pulse used for the simulation was based upon the acceleration measured at the centre of gravity of a Norton Commander in an impact at 48km/h and 90° into the side of a stationary Vauxhall Cavalier.

Model Verification - The model was verified against previous results with the car airbag system (Bag 0+Inflator 0) and against measurements of kinematics from film analysis of impact tests with the Norton commander.

Simulations and Results - There were over 50 simulations using various combinations of bag, inflator and vent size in the three different positions and covering the range of size and attitude of rider as described above. It is not the purpose of this paper to describe all the results in detail. However, of particular importance is that the simulation showed that the preferred system was Bag 2 with Inflator 4 in the rear tank position described below. Those results of particular interest, when the preferred system was used, are given in Tables 3 below.

Table 3a
Simulation Results for 50th Percentile Rider

Body Region	Rider Attitude			
	Normal No Airbag	Normal With Airbag	Prone No Airbag	Prone With Airbag
Head Max Accel (g)	184	43	150	90
Max HIC (36)	5409	243	3620	361
Chest Max Accel (g)	97	30	38	38
Max 3ms Exceed (g)	40	29	1	27
Deflection (mm)	1	32	1	31
Pelvis Max Accel (g)	58	72	30	37
Femur Left (kN)	0.9	1.8	2.4	1.8
Right (kN)	0.9	2.0	2.4	2.3

Table 3b.
Simulation Results for 5th and 95th Percentile Riders

Body Region	95th Percentile Rider		5th Percentile Rider	
	No Airbag	Airbag	No Airbag	Airbag
Head Max Accel (g)	141	41	180	60
Max HIC (36)	6329	241	3661	174
Chest Max Accel (g)	53	34	52	40
Max 3ms Exceed (g)	53	34	51	39
Deflection (mm)	1	35	0	22
Pelvis Max Accel (g)	43	33	44	51
Femur Left (kN)	5.8	3.4	No Contact	3.0
Right (kN)	5.6	3.5		3.2

Table 3c.
Simulation Results for Rider and Pillion Passenger

Body Region	Rider		Pillion Passenger	
	No Airbag	Airbag	No Airbag	Airbag
Head Max Accel (g)	183	45	49	14
Max HIC (36)	4106	82	73	10
Chest Max Accel (g)	63	56	15	17
Max 3ms Exceedence (g)	58	46	13	17
Deflection (mm)	0.9	26	-	-
Pelvis Max Accel (g)	54	44	45	44
Femur Left (kN)	1.4	2.0	1.4	1.4
Right (kN)	1.4	2.0	1.4	1.4

It should be noted, when considering the results, that although the simulation is that of a motorcycle into a car, by virtue of the pulse selected, the target for the rider is a stiff

barrier. The most significant trend in all the cases shown above is that the presence of an airbag reduced the potential head injuries from almost certainly fatal (as indicated by the HIC values) to a low level as indicated by both the peak acceleration and HIC values [7]. It should be noted that HIC was calculated in these simulations based on a 36 ms period. The peak head acceleration values for the cases without an airbag ranged from 141g to 184g which represent AIS values of AIS2 and AIS3 respectively [7]. With an airbag present, the peak head acceleration values range from 41g to 90g representing AIS values of AIS0 and AIS1 respectively. For all the above conditions the airbag successfully restrained the rider (and pillion) and the dummy measurements recorded, when the airbag was deployed, were from contact with the airbag alone.

There were also simulations (at 48km/h) over a range of impact angles and even at a relative heading angle of 60° (30° impact angle) the results showed that with the airbag the rider was restrained such that there was a 50% reduction in kinetic energy at the impact plane.

The trajectory of the 95th percentile rider in normal riding position without and with an airbag is shown in Figures 2 and similarly for the rider with pillion passenger in Figure 3. These simulations are shown because the results are particularly interesting and encouraging and because neither sled tests nor full scale impacts were planned for these cases within the current project.

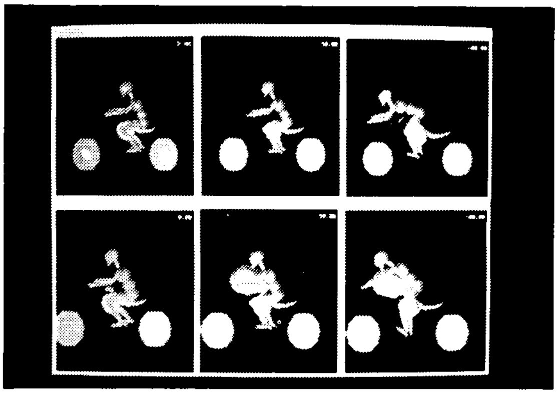

Figure 2. 95th percentile rider (Normal riding position)

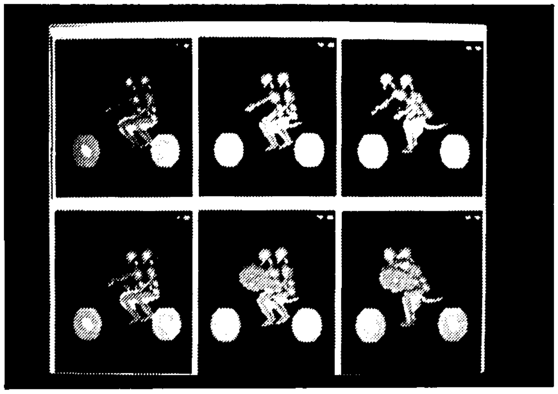

Figure 3. Rider with pillion passenger

SYSTEM CONSTRUCTION

Inflator and Airbag

<u>**Inflator**</u> - The computer simulations (using MADYMO) had indicated the optimum bag size and inflator characteristics and therefore it was upon these that choice of inflator was to be based. The type of inflator most frequently used in car systems is pyrotechnic using either sodium azide or nitro-cellulose propellant. However, the pyrotechnic inflator had two main disadvantages, the residual temperatures are high (typically 200-250°C) and the initial inflation rate is low because the chemical reaction has to accelerate through the propellant to generate the gas. To deploy the airbag within the short time available would have required an aggressive pyrotechnic charge that could be potentially injurious to an out of position (eg prone) rider.

It was considered that the solution was the use of a hybrid inflator. This consists of a compressed gas charge and a small quantity (eg 30 g) of solid thermal charge such as Arcite. The principal benefits of this type of inflator are :

- Short filling time and controlled onset rate.
- Low gas temperatures.
- Moderate inflator surface temperature rise.
- Easily adjusted performance parameters.
- Small output variation over wide ambient temperature range.
- Friendly emissions; mainly potassium chloride (44%) and carbon dioxide(33%) plus water, oxygen and lithium chloride.
- Potential for future development; output may be varied through the use of two separate charges fired independently.

It should be noted that the use of hybrid inflators in car airbag systems is increasing for the above reasons.

Bendix - Atlantic Inflator Company (a division of Allied Signal) were chosen to supply inflators to the specification and were able to vary the performance as needs arose.

Airbag - The bag used was an 87 litre uncoated, 470 Dtex, Nylon 66 material for the main panels. Additional material was used for reinforcement of the neck (neoprene coated) and back (uncoated) of the bag. The folding pattern is critical to the airbag performance and a pattern was devised which was designed to deploy the bag in the following sequence:

1. Lift the rider (if prone) from the tank area.
2. Unroll forward
3. Fully inflate

Other Components

Chute - The chute was moulded from a polyurethane mix designed to provide a very stiff structure. Steel inserts were used to provide mounting points for the canister.

Cover - The cover was made using a semi-rigid polyurethane and was moulded with diagonal split lines. The profile was moulded to match that of the Norton fuel tank.

Housing - The canister housing was mild steel and the motorcycle fuel tank and tank fairing were modified to accommodate the airbag module and inflator at the rear of the tank as indicated by the simulation. The tank capacity was reduced by these modifications but there was sufficient space elsewhere within the motorcycle structure for a supplementary fuel tank.

A photograph of the system, with the motorcycle fairing removed, is shown below in Figure 4.

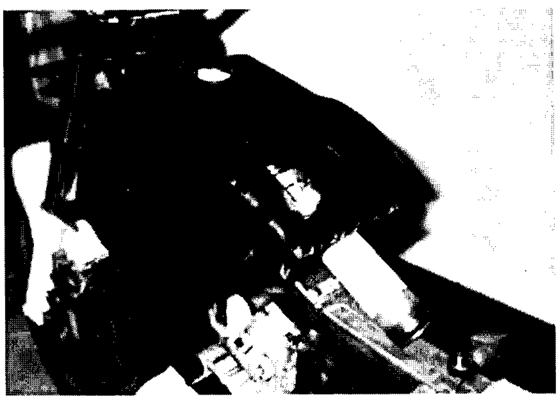

Figure 4. Airbag module (Fairing, cover and airbag removed)

STATIC FIRE TESTS

Tests

There was a series of five tests to evaluate the airbag statically. In four of the tests the airbag was inflated alone and in the fifth test a pre-inflated airbag was struck by a pendulum.

Results

Airbag Integrity - Initial tests were used to develop the detailed bag design. Two tethers were introduced to control the deployment of the bag by limiting the upward travel and hence reducing the loading on the side panels. Also the number of panels and hence seams was reduced by increasing the size of the main panels and the main panels were further reinforced.

The pendulum impact test was used to examine the integrity of the modified bag under loads similar to those needed to restrain a dummy rider. The absence of damage in this test indicated that the design was satisfactory.

Airbag Folding pattern - The original airbag fold was a "roll" designed to encourage forward deployment to prevent unwanted interaction with the rider and avoid excessive loads on the airbag during deployment. However, high speed film showed that the inertia of the rolled section prevented an even deployment. The fold was modified to introduce a concertina style in place of the roll and this eliminated the need for the material to develop rotational as well as translational velocity.

Airbag shape and size - The airbag, as manufactured, was shown in static deployments to fill to the shape envisaged by the design. The addition of tethers served to improve the shape and the size of the fully deployed bag. It was sufficient to fill the space between the rider's chest and the reaction surfaces provided by the fuel tank and instrument panel fairings.

It was observed that there was noticeable gas leakage through the permeable airbag material just before and during full deployment. This was thought to be caused by excessive pressure and the Arcite charge was moderately reduced from 32g, which produced a peak pressure of 3.79 bar into a 100 litre tank, to 30g which produced a peak pressure of 3.6 bar.

Inflation Time and Rate - Full deployment was achieved within 30 ms, thus with a firing time of 19ms, time to full deployment would be 49ms. This fitted well with the time taken for a rider to move a short distance (taken to be 125mm) in a 48 km/h (30 mile/h) impact for which the time was found to be approximately 50 ms.

Chute and Canister Integrity - Throughout the static test programme there were no failures of either the polyurethane chute or the steel fabricated canister that housed the inflator.

Cover Performance - The cover performed satisfactorily in all the deployment tests, opening along the preformed diagonal split lines and remaining fully attached to the motorcycle throughout the tests. This is a critical requirement because it is essential that no part of the cover can come lose and be thrown into the rider's face. The clip-on design in conjunction with the close fitting aperture proved an effective approach for this application.

Rider Airbag Interaction - High speed films were viewed to assess the likely interaction with rider. It was concluded that the principal directions of deployment were upwards and forwards, and thus unlikely to cause a problem for a normally seated rider. However, it was accepted that for a crouching and prone rider some interaction with the chest was unavoidable.

System Generated Temperature effects - The temperature was measured at three locations on the surface of the airbag module. The measurements were taken over a 27 minute period to ensure that the maximum was recorded. The locations measured and the time to maximum temperature are as follows:

	Max Temp	Time to Max Temp
• Inflator top	84°C	4.5 minutes
• Canister bottom	45°C	1.0 minutes
• Canister rear	47°C	0.5 minutes

The ambient temperature was 15°C, thus the maximum recorded rise (above ambient) for the module surface temperature was 69°C. This causes little concern with respect to the close proximity to the fuel tank and there is room for adding insulation if necessary.

The very satisfactory results from the first four phases enabled the project to proceed to the sled tests described below.

SLED TESTS

Equipment

System - The motorcycle rig used in the test was a modification of the Norton Commander motorcycle. It was fitted with a standard tyred wheel at the rear with the front wheel replaced by a plate for mounting onto the sled trolley. The plate was pivoted at the front wheel axle location to allow pitching of the motorcycle at impact. This action was controlled by webbing attached to the rear wheel of the motorcycle in an attempt to simulate the pitching observed in earlier motorcycle to car impact tests at TRL. The MATD (Motorcycle Anthropometric Test Dummy) Hybrid III dummy was mounted onto the motorcycle rig which, in turn, was bolted onto the trolley. The trolley was then propelled forwards by a cable attached to a falling 4.5 tonne weight via a pulley system. The impact velocity of the sled was determined by the drop height of the weight. A bomb release mechanism detached the trolley from the towing cable just before impact. The deceleration pulse experienced by the trolley at impact was determined by three arrestor tubes. Both the dummy and motorcycle are described below.

Dummy

The dummy used at TRL for motorcycle tests was the MATD Hybrid III. This is a sit-stand dummy which has been specially modified to comply with ISO DIS 13232 [3] recommendations (eg upright lumbar spine, modified neck, 9-axis head acceleration, frangible leg bones, gripping hands etc). The dummy was fitted with a new 48 channel, 12 bit on-board data acquisition system.

Motorcycle

This was a large touring machine, the Norton Commander, weighing about 220 kg with a full glass-fibre fairing. This machine was fitted with an airbag system designed and built, by Lotus Engineering, for these tests.

TESTS

Crash Pulse Determination

It was decided that the airbag system performance should be optimised for head-on impacts into stationary and moving vehicles because the majority of serious and fatal head and chest injuries occur in impacts approximately head-on to the motorcycle [5]. The trolley pulse was therefore matched to that of a 90° full scale impact test of the Norton Commander motorcycle at 48 km/h into the side of a stationary Ford Mondeo car by means of three crumple tubes. The reasons for using this car as the opposing vehicle are described below. However, it was also decided that the system should be evaluated in a range of other impact configurations covering speeds, angles (to simulate yaw in impacts where both vehicles are moving and assess airbag stability) and rider out of position (i.e. due care) conditions (to ensure that the system is not detrimental to the rider). From TRL's experience of impact tests, the dummy develops small angles relative to the motorcycle in oblique angled impacts. For this reason and

because the basic shape of the pulse does not change for tests at different speeds, the same pulse was used to assess the airbag performance for all impact conditions devised for testing on the sled.

Airbag Evaluation

Tests at Different Speeds - The dummy was seated in normal position, as recommended in ISO DIS 13232 [3], and the motorcycle longitudinal axis was aligned with the direction of sled travel for all the sled tests in this group. There were nine tests of which six were at 48km/h (medium) because optimum performance at this velocity was seen as crucial for success in other test conditions. The remaining two tests were at 32km/h (low) and 56km/h (high) (the maximum possible for the particular mass on the sled). The airbag module fitted to the rear of the tank was fired remotely at impact by means of a special delay unit. Airbag fire times for tests were based on the sled velocity change/time graphs. The dummy results for these tests are discussed below.

Angled Impacts - In these tests the motorcycle was attached to the sled so that the longitudinal axis was at an angle relative to the direction of travel of the sled. This was designed to apply lateral acceleration to the dummy, as happens when a motorcycle impacts another vehicle obliquely, and thereby assess to what extent the rider tended to slide to one side of the bag and thus not be fully restrained.
Previous TRL research of oblique impacts showed that the angle of trajectory of the rider relative to the direction of motion of the motorcycle was typically 20°, with a worst case of 30°, at the time when the dummy's head contacted the car. There were, therefore, two tests, one with the motorcycle at 20° and one at 30° to the direction of the motion of the sled. These tests were at 48km/h with the Hybrid III dummy seated in normal riding position. The motorcycle was firmly strapped to the sled to prevent damage to the equipment which, in turn, resulted in negligible pitching. The airbag remained stable and fully arrested the dummy with very little vertical motion of the rider, producing results in both tests which indicated low injury potential. The airbag remained stable, confirming the simulation results, and this further increased confidence for successful performance in angled full scale impact tests.

Crouching and Prone Riders - Deployment of an airbag with an out of position rider may injure the rider's upper body as a result of loading applied to the chest, neck and head. For this reason, it was necessary to assess the airbag performance under these conditions. There were therefore sled tests with a rider in a prone position (chest contacting fuel tank fairing) and in a crouching position (intermediate between normal position and prone) to assess injury measurements during interaction between the dummy and airbag as shown in Figures 5 and 6 respectively. Both tests were at 48 km/h with the motorcycle aligned with the direction of trolley travel. Some important results are discussed below.

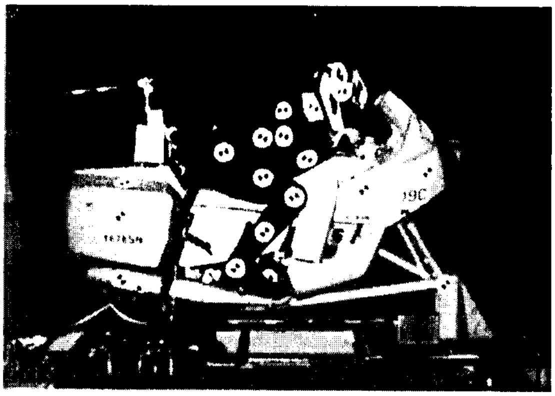

Figure 5. Prone rider configuration

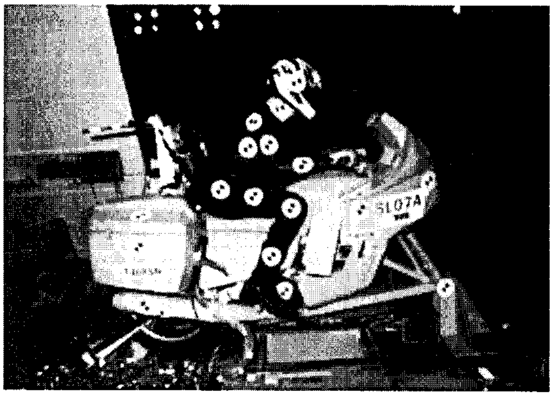

Figure 6. Crouching rider configuration

RESULTS

Injury Analysis

The results of several sled tests were used to develop the airbag system. A number of parameters including the size of airbag vent, airbag inflation rate, bag tethers and fire time were changed to optimise the performance of the airbag restraint system. The main results of three of these tests are described below.

32km/h, 48km/h and 56km/h Impacts - The dummy was fully arrested by the airbag in all tests. Head translational and rotational accelerations were measured by an array of nine accelerometers allowing HIC and GAMBIT (Generalised Acceleration Model for Brain Injury Tolerance) to be calculated, the peak values of which were used to assess injury probabilities according to ISO DIS 13232 [3]. Table 4 shows injury measurements for the high and low speed tests, and an

example of one of the medium speed tests. These results show that peak head, neck and chest injury measurements recorded from the dummy were all below 50% of stated human tolerance limits. The following AIS probabilities were achieved:
head - AIS1(0.01) and chest - AIS1(0.42), AIS2(0.11), AIS3(0.00). In the low and high speed tests, the following head AIS probabilities were achieved: Low speed- AIS1(0.04), AIS2(0.01) and High speed- AIS1(0.07), AIS2(0.02). For the high speed test the normalised chest compression was increased but this was still only a maximum of 18.5%, equivalent to 35 mm chest deflection. The following chest AIS probabilities were calculated for the same test: AIS1(0.66), AIS2(0.28), AIS3(0.02). Chest deflection measurements in all the three tests were low compared with the stated human tolerance levels.

Table 4.
Measured Injury Results for Low, Medium and High Speed Tests

Injury criteria	Human Tol. limit	48km/h MEDIUM	56km/h HIGH	32km/h LOW
HIC(15ms)	1000	30	79	93
GAMBIT	-	0.18	0.35	0.29
Neck flexion moment, Nm	300	25.2 (0.08)*	55.6 (0.19)*	56.5 (0.19)*
Neck extension moment , Nm	90	8.63 (0.1)*	42.8 (0.47)*	24.2 (0.27)*
Neck torsion moment, Nm	40	16.9 (0.42)*	6.57 (0.16)*	7.20 (0.18)*
Normalised sternum compression ,%	40	12.5 (0.31)*	18.5 (0.46)*	12.9 (0.32)*
Sternum velocity compression , ms^{-1}	1.0	0.16 (0.16)*	0.32 (0.32)*	0.20 (0.2)*

* Normalised results, i.e. result divided by tolerance limit.

Angled Impacts - The rider was restrained with low injury potential in both tests. Head, neck and chest injury measurements for both tests were less than the tolerance limits and in the majority of cases, significantly so.

Prone and Crouching Sled Tests - Table 5 shows the prone and crouching test results. The HIC value of 1056 for the prone test, calculated over a 15ms period to comply with ISO DIS 13232 [3], just exceeded the human tolerance limit. The following head AIS probabilities were calculated from GAMBIT: AIS1(0.21), AIS2(0.11) and AIS3(0.0), that is, quite different from what might be expected from the HIC values recorded. The chest velocity compression equalled the tolerance limit giving the following chest AIS probabilities: AIS1(0.96), AIS2(0.83), AIS3(0.32) and AIS4(0.09). The crouching position test resulted in an HIC of 412 which is well below the human tolerance limit but the GAMBIT was higher than for the prone test because the corresponding head rotational accelerations were higher. The following head injury AIS probabilities were calculated from GAMBIT: AIS1(0.55), AIS2(0.41), AIS3(0.10), AIS4(0.06) and AIS5,6(0.01).

It must be borne in mind that these tests on out of position riders were only carried out on machines fitted with air bags. Similar tests on standard machines were not done. If a rider were to impact a car in a prone or crouching position on a standard motorcycle it is probable that his injuries would be very severe.

Table 5.
Crouching and Prone Rider Results

Injury criteria	Human Tol. limit	Prone	Crouching
HIC (15ms)	1000	1056	412
GAMBIT	-	0.5	0.71
Neck flexion, Nm	300	120.0 (0.4)*	110.0 (0.37)*
Neck extension , Nm	90	61.0 (0.68)*	38.0 (0.42)*
Normalised sternum compression, %	40	21.0 (0.53)*	14.0 (0.35)*
Sternum velocity compression, ms^{-1}	1.0	1.0 (1.0)*	0.21 (0.21)*

* Normalised results

Legs Injuries - The Hybrid III dummy used in the sled tests was fitted with solid tibia legs to avoid wasting frangible components at the initial evaluation stage of airbag performance. However, frangible femurs were used to evaluate, the effect of the fairing in front of the knees. No fractures of the femurs were witnessed in any of the airbag sled tests. The legs were all replaced by frangible bones in the full scale impact tests to comply with ISO DIS 13232 [3] recommendations.

Trajectory and Kinetic Energy Analysis

It is clearly not feasible to compare the injury assessments from instrumentation results of an airbag test, in which the dummy rider is restrained, with those of a standard test where the dummy is simply thrown off the motorcycle and caught in a net to reduce dummy damage. It is important therefore to compare the velocity and hence kinetic energy of the dummy at a position in the impact critical to injury potential and use this as a measure of the airbag effectiveness.

For the purposes of analysis the plane AA' (described earlier) through the point of impact was chosen as a reference. In the case of a sled test, this is a fixed vertical plane (normal to the direction of trolley travel) passing through the point at which the leading edge of the motorcycle front wheel would have been located at the instant of trolley impact if the wheel had not been replaced by a plate.

The results were to be based upon the velocity of the head measured at the time when the head crosses the impact plane AA'.

In fact, all the sled test results show that the airbag was very effective in reducing the rider forward velocity and hence kinetic energy at the impact plane AA'. Trajectory analysis showed that the dummy head never crossed the impact plane in any airbag test, indicating 100% reduction in kinetic energy.

FULL SCALE IMPACT TESTS

Impact Test Facility

TRL's Impact Test Facility was used for all of the motorcycle impact tests. This has a computer controlled hydraulic motor drive system to achieve test speeds very accurately with low acceleration of the launch trolley. The secondary winch used for impact testing when both vehicles are moving is also connected to this system and controlled by the same computer in a closed loop allowing very close impact tolerances to be met. Both the motorcycle and dummy used in the tests have been described above.

ISO Procedure

General Requirements - The Toyota Corolla four door Sedan, currently recommended by ISO DIS 13232 [3] for impact testing, has been impossibly difficult to purchase in the UK because it is an old model stocked by very few dealers. The Ford Mondeo car which is a recent model with stiffer side structures designed for occupant side impacted safety protection, and also readily available in the UK, was therefore selected to replace the Toyota Sedan. The stiff structure is a common feature in modern cars and this may influence the level of injuries sustained by a rider, particularly in head-on impacts. Other aspects of ISO DIS 13232 [3] impact testing recommendations (e.g. camera positions, focal lengths, field of views, dummy and vehicle preparation etc) were observed in all tests.

Impact Tolerances - The ISO standard for motorcycle impact test methods, ISO DIS 13232 [3], recommends that the difference between two tests in a single paired comparison shall not be greater than the following values:
- relative heading angle: 3°;
- opposing vehicle impact speed: 5% of the target speed;
- Motorcycle impact speed: 5% of the target speed;
- motorcycle roll angle: 5°;
- positions of the helmet centroid point and of the joint locations with respect to the motorcycle relative to the pre-test set up photograph: ±2 cm.

ISO Compliance - Analysis to date indicates that the majority of test pairs in the series of tests reported in this paper complied with the relative tolerances specified.

TESTS

Impact Tests With a Stationary Car - Two impact test pairs involving moving motorcycles and stationary cars have been completed. Figure 7 shows the configuration (i.e. RHA 90°, 48/0km/h) of the first test pair in which a motorcycle moving at 48km/h impacts the side of a stationary car at 90° without and with airbag respectively. RHA is the relative heading angle of the two vehicles measured from the direction of motorcycle travel to the direction of the opposing vehicle as defined in ISO 13232 [3]. Figure 7 is a head-on impact configuration and head-on impacts in total are responsible for the majority of head, neck and chest injuries in road accidents [5]. It is therefore a very appropriate configuration with which to assess the effectiveness of the airbag in an impact.

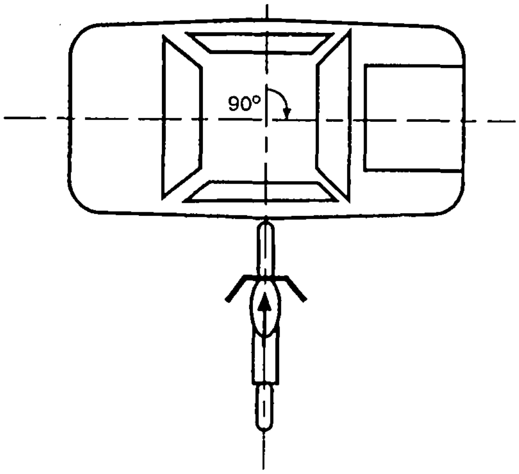

Figure 7. Head-on impact configuration (90°, 48/0 km/h)

The second test pair was with a motorcycle moving parallel to the longitudinal direction of a stationary car at 48km/h and impacting the corner of the car at 180° (i.e. RHA 180°, 48/0km/h) offset from the motorcycle front fork assembly as recommended by ISO DIS 13232 [3]. This configuration is illustrated in Figure 8 below.

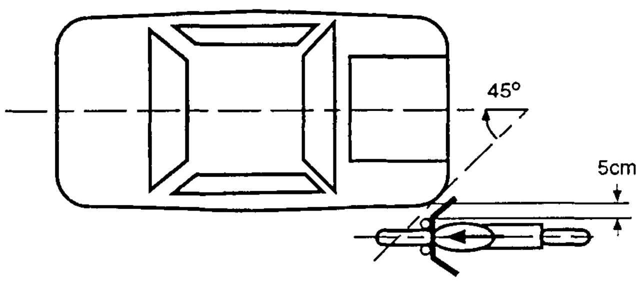

Figure 8. Off-set front impact configuration (180°, 48/0 km/h)

__Impact Tests With a Moving Car__ - Three impact test configurations have been successfully completed with both vehicles moving. The first one involves a 90° impact of a motorcycle at 32km/h into the side of a car moving at 16km/h. This configuration (i.e. RHA 90°, 32/16km/h) is shown in Figure 9 and was also tested without and with airbag respectively. This configuration was tested to assess performance of the airbag at relatively low speeds in head-on impacts.

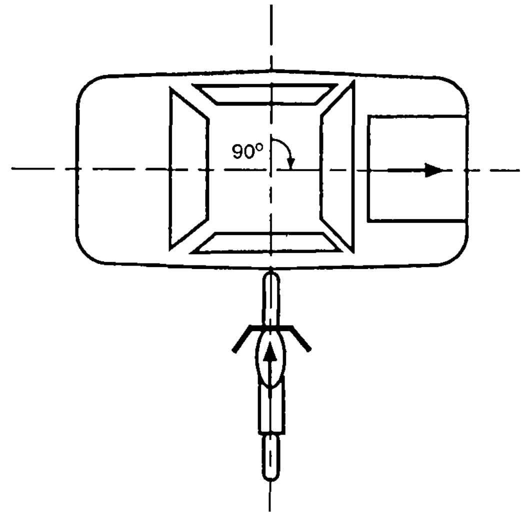

Figure 9. Head-on impact configuration (both vehicles moving: 90°, 32/16 km/h)

Figure 10 illustrates the configuration of the second test pair in which a motorcycle at 48 km/h impacts the side of a car moving at 24km/h at an angle of 240° with and without the airbag respectively. This configuration (i.e. RHA 240°, 48/24km/h) was intended to test the stability of the airbag in an angled impact.

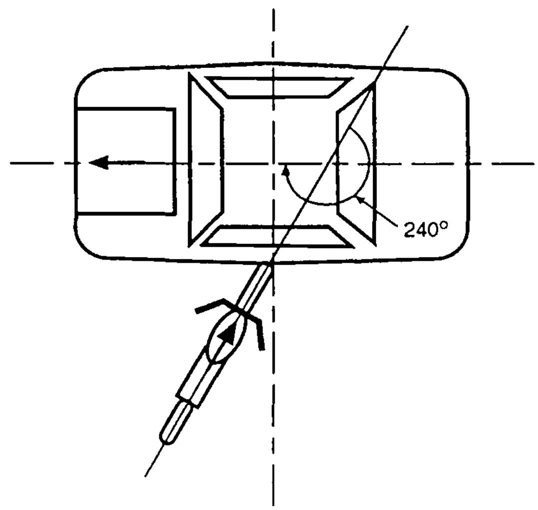

Figure 10. Angled impact configuration (both vehicles moving: 240°, 48/24 km/h)

The configuration of the third test pair (i.e. RHA 225°, 48/24km/h) in which a motorcycle at 48 km/h impacts the side of a car moving at 24 km/h at an angle of 225° is shown in

Figure 11. This configuration is particularly appropriate for examining the stability of the rider on the airbag in an oblique angle impact.

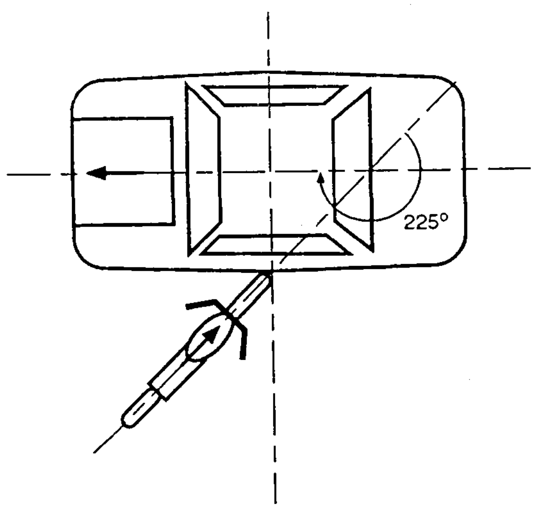

Figure 11. Angled impact configuration (both vehicles moving: 225°, 48/24 km/h)

RESULTS

General Observations

<u>Impact Tests With a Stationary Car</u> - In the first test pair of this group (i.e.RHA 90°, 48/0km/h configuration), the dummy was fully arrested by the airbag preventing head and chest contacts with the car, which is in contrast with the standard test. These are illustrated by Figures 12 and 13 without and with airbag respectively. There were substantial reductions in injury potential for most parts of the body and none of the human tolerance limits were exceeded during the critical period of airbag deployment. However, forward pitching of the motorcycle fitted with airbag was greater because of the coupling of the rider to the motorcycle through the airbag. Nevertheless, this had little effect on the rider during the critical restraint period. It is possible that pitching would be of greater importance for lighter motorcycles because the inertia is less.

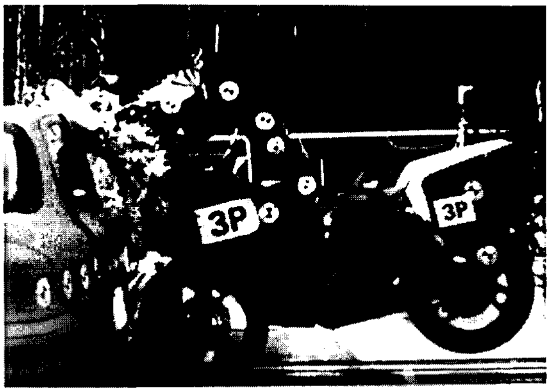

Figure 12. Head-on impact of standard motorcycle into a stationary car (90°, 48/0 km/h)

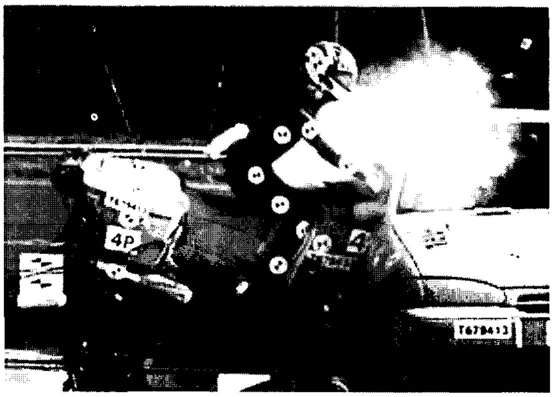

Figure 13. Head-on impact of airbag equipped motorcycle into a stationary car (90°, 48/0 km/h)

In the second test pair (i.e. RHA 180°, 48/0km/h offset front configuration), the airbag deployed normally and in both tests the rider's hands became detached from the handlebars at impact, although the rider and motorcycle remained upright until they were arrested by a net. The injury potential was similar and low (well below the tolerance limits) in both tests hence details are not presented. These tests are part of the series required by ISO DIS 13232 [3] and possibly have little relevance to airbag performance although it is interesting to note that the airbag did not dislodge the rider from the motorcycle during this type of glancing impact.

Impact Tests With a Moving Car - In the first test pair of this group (i.e. RHA 90°, 32/16km/h configuration), the dummy was fully restrained by the airbag thus preventing head and chest contacts with the car. This is illustrated by Figures 14 and 15 respectively. However, in the standard test, the rider contacted the opposing vehicle during impact and then was thrown over the rear of the vehicle. It is therefore possible that higher injury potential may have been sustained on landing but the results reported in this paper were recorded during the critical impact period. With the airbag fitted, there were reductions in rider injury potential for most body parts and a significant reduction in neck axial compression. None of the human tolerance limits were exceeded. It is possible that the reductions will be greater when the impact data are analysed to include dummy to ground impact.

In the second test configuration (i.e. RHA 240°, 48/24km/h), which is a higher speed test at an oblique angle, the airbag still restrained the rider extremely well and prevented body contact with the car in contrast to the standard test. The tests are illustrated in Figures 16 and 17. These tests also showed a reduction in injury potential for most body parts, especially neck tension and torsion, when the airbag was deployed, although none of the human tolerance limits were exceeded in either test.

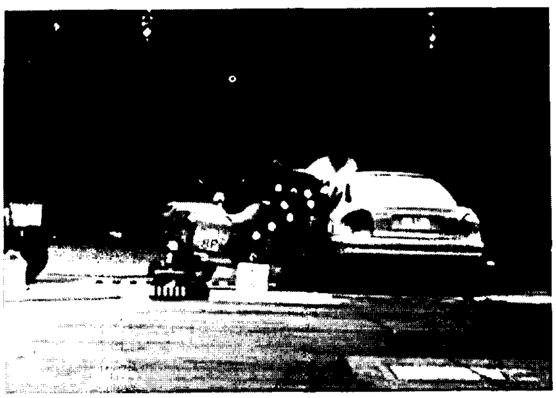

Figure 14. Head-on impact of standard motorcycle into moving car (90°, 32/16 km/h)

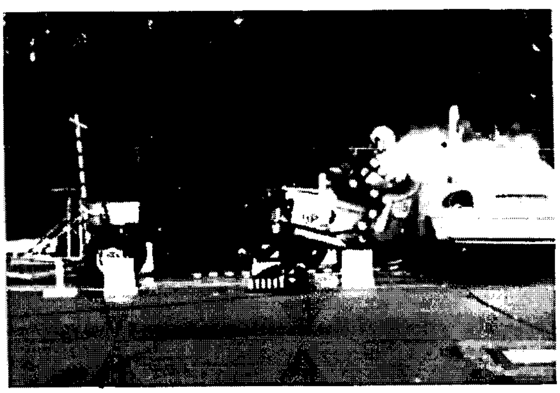

Figure 15. Head-on impact of airbag equipped motorcycle into moving car (90°, 32/16 km/h)

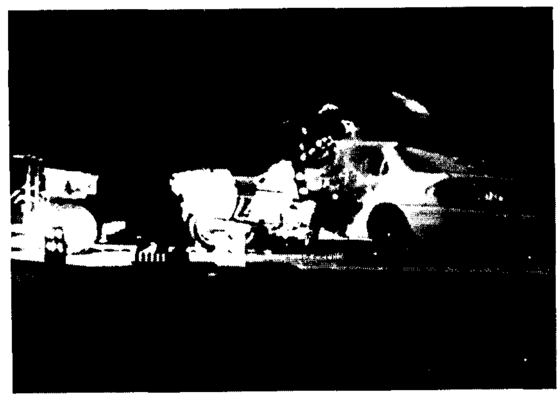

Figure 16. Angled impact of standard motorcycle into moving car (240°, 48/24 km/h)

Figure 17. Angled impact of airbag equipped motorcycle into moving car (240°, 48/24 km/h)

airbag performed equally well. Again, as in the second test pair, the airbag fully restrained the rider avoiding head impact with the car in contrast to the standard test. The tests are shown in Figures 18 and 19. The potential injury levels were reduced with the airbag fitted although none of the human tolerance limits were exceeded in either test.

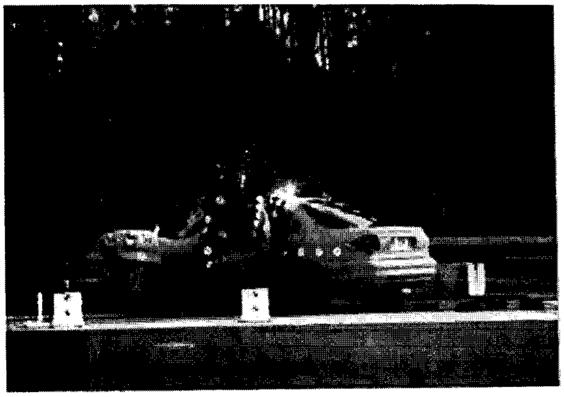

Figure 18. Angled impact of standard motorcycle into moving car (225°, 48/24 km/h)

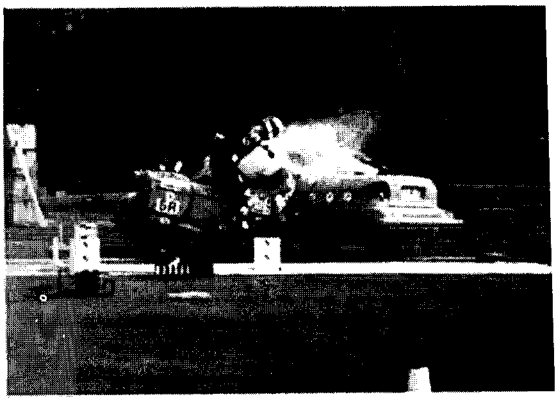

Figure 19. Angled impact of airbag equipped motorcycle into moving car (225°, 48/24 km/h)

In all of the tests with both vehicles moving, there was a tendency for interaction between the two vehicles to cause the motorcycle to yaw towards the car. However, the largest angle through which the dummy turned in these tests was less than those simulated in the sled tests where the motorcycle was angled relative to the direction of motion. The forward pitching of the motorcycle fitted with the airbag was only slightly greater than in the standard tests which indicates that the effect of coupling the rider to the motorcycle through the airbag was small.

Injury Analysis

Head - The maximum values for HIC and GAMBIT were calculated and the probability of injury was determined from the maximum values of GAMBIT by following the ISO DIS 13232 procedure [3]. The reductions in injury severity potential produced by the airbag system for the full scale tests are shown in Tables 6, 7, 8 and 9.

It can be seen from these results that the airbag system gives an overall benefit to the rider in configurations when the car is both moving and stationary. Most of these results show that both HIC and GAMBIT are reduced, especially for the 90°, 48/0 km/h configuration where the head AIS values are correspondingly reduced to 0. Results of the rider potential head injury measurements for the 90°, 32/16 km/h configuration show a slight increase (see Table 7) but none of the human tolerance limits are exceeded for either test.

Table 6.
Configuration: RHA 90°, Side Impact, MC speed: 48km/h
Car (OV) speed: 0km/h

Head Measurements			
Tests		Standard	Airbag
HIC (15 ms)		839	9
GAMBIT		0.84	0.11
Probability of Head Injury of at least: (ISO 13232- 5)	AIS4	0.20	0.0
	AIS5	0.09	0.0
	AIS6	0.09	0.0

Table 7.
Configuration: RHA 90° Side Impact,
MC speed: 32km/h, Car (OV) speed: 16km/h

Head Measurements			
Tests		Standard	Airbag
HIC (15 ms)		31	37
GAMBIT		0.15	0.22
Probability of Head Injury of at least: (ISO 13232- 5)	AIS1	0.00	0.01
	AIS2	0.00	0.00

Table 8.
Configuration: RIIA 225° Side Impact,
MC speed: 48km/h Car (OV) speed: 24km/h

Head Measurements			
Tests		Standard	Airbag
HIC		158	67
GAMBIT		0.27	0.16
Probability of Head Injury of at least: (ISO 13232 - 5)	AIS1	0.03	0.00
	AIS2	0.00	0.00

Table 9.
Configuration: RIIA 240° Side Impact,
MC speed: 48km/h Car (OV) speed: 24km/h

Head Measurements			
Tests		Standard	Airbag
HIC (15 ms)		111	84
GAMBIT		0.24	0.26
Probability of Head Injury of at least: (ISO 13232- 5)	AIS1	0.02	0.02
	AIS2	0.00	0.00

Neck - In fatal motorcycle accidents most deaths are attributed to head and neck injuries [5]. It has also been postulated [8] that neck injuries are likely to increase if an airbag is fitted to a motorcycle. For this reason, the neck is examined separately to the head in the injury analysis. The Hybrid III neck was modified to conform to ISO DIS 13232 [3] recommendations which are intended to provide a more realistic response to rotation about the Z-axis (torsion). The airbag system has provided benefit to the rider although in some instances the results are similar. However, none of the neck tolerance limits were exceeded. The results are given in Tables 10, 11, 12 and 13 below and they show considerable improvements over previous airbag research [8] which commented adversely on the potential for increased neck injuries. This could be attributed to the inappropriate use of car airbag systems which were not designed for use on a motorcycle.

Table 10.

Configuration: RIIA 90° Side Impact,
MC speed: 48km/h, Car (OV) speed: 0km/h

Neck Measurements		
Tests	Standard	Airbag
Flexion, Nm	200.0 (0.67)*	27.0 (0.09)*
Extension, Nm	32.0 (0.36)*	22.0 (0.24)*
Torsion (Mz), Nm	7.2 (0.18)*	3.5 (0.09)*
Tension, kN	0.96 (0.19)*	1.0 (0.2)*
Compression, kN	2.3 (0.58)*	0.0 (0.00)*

*Normalised results

Table 11.
Configuration: RIIA 90° Side Impact,
MC speed: 32km/h, Car (OV) speed: 16km/h

Neck Measurements		
Tests	Standard	Airbag
Flexion, Nm	70.5 (0.24)*	65.3 (0.22)*
Extension, Nm	33.0 (0.37)*	34.3 (0.38)*
Torsion (Mz), Nm	9.0 0.28)*	4.8 (0.12)*
Tension, kN	1.23 (0.25)*	1.5 (0.30)*
Compression, kN	3.9 (0.98)*	0.53 (0.13)*

* Normalised results

Table 12.
Configuration: RIIA 225° Side Impact,
MC speed: 48km/h Car (OV) speed: 24km/h

Neck Measurements		
Tests	Standard	Airbag
Flexion, Nm	42 .0 (0.14)*	51.9 (0.17)*
Extension, Nm	41.0 (0.46)*	33.4 (0.37)*
Torsion (Mz), Nm	12.6 (0.32)*	23.7 (0.59)*
Tension, kN	1.1 (0.22)*	1.36 (0.25)*
Compression, kN	0.77 (0.19)*	0.46 (0.12)*

*Normalised results

Table 13.
Configuration: RIIA 240° Side Impact,
MC speed: 48km/h Car (OV) speed: 24km/h

Neck Measurements		
Tests	Standard	Airbag
Flexion, Nm	79 .0 (0.26)*	52.0 (0.17)*
Extension, Nm	21.4 (0.24)*	14.8 (0.16)*
Torsion (Mz), Nm	20.0 (0.5)*	3.8 (0.1)*
Tension, kN	1.3 (0.26)*	1.9 (0.38)*
Compression, kN	0.5 (0.13)*	0.1 (0.03)*

*Normalised results

<u>Chest</u> - The Hybrid III chest deflection is measured by means of four chest potentiometers. This part of the body is very important for airbag tests because a substantial part of the force restraining the rider in an impact is transmitted through the chest. Thus chest deflection in airbag tests is likely to be greater than in the standard tests except in the cases where the chest contacts the car. It should be noted that approximately 20% of motorcycle fatalities are from chest injuries [5].

Chest compression and velocity compression are calculated for both the upper and lower sternum for each test and the larger of the two values is shown in Tables 14, 15, 16 and 17 respectively. It can be seen that the chest compression was generally increased for the airbag tests but was still only a maximum of 19.4% (equivalent to 37mm deflection) compared with the compression tolerance limit of 40% and none of the results exceeded the tolerance limits. The probability values of AIS for chest potential injury for the corresponding tests are shown in Table 18. For AIS1 and AIS2 these values are also generally higher for the airbag tests as was to be expected. Nevertheless, for AIS3 they are quite similar for the majority of cases.

Table 14.
Configuration A: RIIA 90° Side Impact,
MC speed: 48km/h Car (OV) speed: 0km/h

Chest Measurements		
Tests	Standard	Airbag
Maximum Normalised Compression, %	4.2 (0.11)*	18.0 (0.45)*
Maximum Velocity Compression, ms^{-1}	0.0 (0.0)*	0.26 (0.26)*

*Normalised results

Table 15.
Configuration B: RIIA 90° Side Impact,
MC speed: 32km/h, Car (OV) speed: 16km/h

Chest Measurements		
Tests	Standard	Airbag
Maximum Normalised Compression, %	1.7 (0.04)*	14.7 (0.37)*
Maximum Velocity Compression, ms^{-1}	0.0 (0.0)*	0.27 (0.26)*

*Normalised results

Table 16.
Configuration C: RIIA 240° Side Impact, MC speed: 48km/h, Car (OV) speed: 24km/h

Chest Measurements		
Tests	Standard	Airbag
Maximum Normalised Compression, %	7.5 (0.19)*	19.4 (0.49)*
Maximum Velocity Compression, ms^{-1}	0.07 (0.07)*	0.51 (0.51)*

*Normalised results

Table 17.
Configuration D: RIIA 225° Side Impact, MC speed: 48km/h Car (OV) speed: 24km/h

Chest Measurements		
Tests	Standard	Airbag
Maximum Normalised Compression, %	2.0 (0.05)*	17.3 (0.41)*
Maximum Velocity Compression, ms^{-1}	0.0 (0.0)*	0.37 (0.37)*

*Normalised results

Table 18.
Chest Potential Injury AIS Probabilities

Tests		AIS1	AIS2	AIS3
STD	A	0.16	0.02	0.00
ABG		0.58	0.22	0.01
STD	B	0.01	0.01	0.01
ABG		0.59	0.23	0.01
STD	C	0.26	0.05	0.00
ABG		0.83	0.50	0.06
STD	D	0.00	0.00	0.00
ABG		0.71	0.34	0.02

STD: Standard test, ABG: Airbag test
A: 90°,48/0 km/h; B: 90°,32/16 km/h;;
C: 240°, 48/24 km/h;D: 225°, 48/24 km/h

Legs - The leg injuries were evaluated by means of strain gauged frangible femur and tibia bones. However, leg bone fracture was not witnessed in any of the full scale tests reported in this paper. Similarly, there was no damage to the knee shear pins and deformable inserts for any of the tests reported here and hence there was no potential for knee dislocation.

Airbag Performance - As an example of airbag performance in these tests, the full range of results of a test pair comparing standard and airbag equipped motorcycle is presented in Figure 20. As can be seen from these results, the airbag system has performed very well reducing the injuries quite significantly for most of the body parts except for chest deflection. No potential injury measurements exceeded 40% of tolerance limit. Head HIC, for example, has been reduced by well over 80% when compared with the standard test.

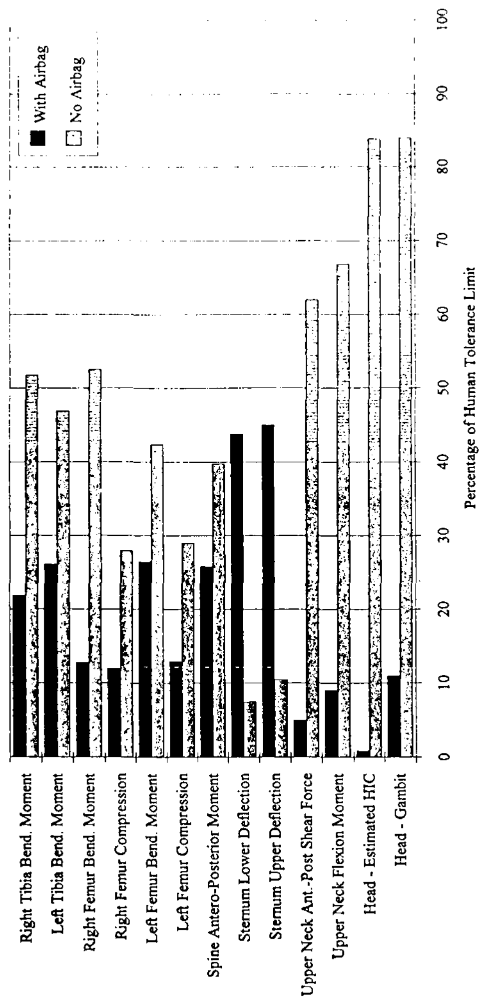

Figure 20. Comparison of injury measurements with and without an airbag in a head impact (90°,48/0km/h)

TRAJECTORY AND KINETIC ENERGY ANALYSIS

The trajectory, velocity and kinetic energy analysis as described for the sled tests above is also very important in the full scale impact tests. Although there can be a direct comparison between the instrumentation results from a test on the standard motorcycle and one fitted with an airbag, this is a very specific comparison. It does not provide information on the overall potential of an airbag in a particular impact configuration over a range of conditions such as motorcycle speed and type of target. It is therefore important to consider the velocity and hence kinetic energy of the dummy at a position critical to the injury potential. The impact plane AA' discussed above was used. The velocity of the head at the moment the head crossed the AA' plane was determined and used to calculate the energy reduction for a range of tests. Results of these calculations are given in Table 19 below.

<u>Trajectory Analysis</u> - Results obtained from the tests show that the airbag is effective in reducing the rider velocities at impact. This is illustrated by the results of a test in which a motorcycle at 48km/h impacts the side of a car moving at 24km/h at an angle of 225° (i.e. test configuration D). Head velocity is reduced by 64%. The chest velocity is reduced by 75%.

<u>Kinetic Energy Assessment</u> - The rider trajectory analysis of the full scale impact tests shows that the dummy was fully restrained by the airbag with significant reduction in rider forward velocity and corresponding kinetic energy reduction of between 79% and 100% as shown in Table 19. The kinetic energy was assessed by comparing the head velocity at the initial point of impact with the velocity at the AA' plane. If the head did not cross the AA' plane then the final velocity was 0 km/h. Results presented in Table 19 comply fully with the kinetic energy performance targets defined above and therefore confirm the successful performance of the airbag system as predicted by the earlier phases.

Table 19.
Kinetic Energy Reduction for Full Scale Impact Tests

Tests	Configuration	Kinetic Energy Reduction
STD	90°, 48/0km/h	17 %
ABG		79 %
STD	90°,32/16km/h	14 %
ABG		100 %
STD	240°,48/24km/h	54 %
ABG		100 %
STD	225°,48/24km/h	51 %
ABG		87 %

STD: Standard test, ABG: Airbag test

Injury Cost Assessment

The cost of injury in motorcycle accidents is assessed for different body regions (i.e head, chest, abdomen and legs) by means of an injury cost model provided by ISO DIS 13232 [3]. This gives an indication of normalised costs of survival and death as well as the probability of fatality associated with different AIS values for different body parts. However, such injury cost assessment is only appropriate if all the tests have been completed. Thus, it was decided that the injury cost assessment will be left until the end of the impact test programme .

DISCUSSION

It should be noted that the injury results indicated by the tests with the standard motorcycle were lower than might have been expected. The Norton Commander motorcycle used in these tests is a large touring machine with a full glass-fibre fairing. The design of the Norton fairing provides partial protection to the rider during the critical impact period. It is clear from both observation and test results that the fairing design plays a very important role in protecting the rider and therefore needs to be considered seriously by the manufacturer during the design stage.

In the impact tests where both vehicles were moving, the rider was thrown over the rear of the vehicle in the non airbag tests and landed on the ground. It is therefore likely that higher injury potential may have been sustained on landing. However, the results reported in this paper were assessed only for the data recorded during the critical impact period. It is intended to further analyse the results to cover the period during which

the rider lands on the ground. This may reveal that the airbag is giving greater protection than has been currently measured. It should also be noted that where such impacts are into the side of a larger vehicle, the rider of a standard motorcycle would hit the opposing vehicle, in contrast to the rider of an airbag equipped motorcycle who is arrested by the bag. It is for this reason that the kinetic energy of the rider is considered to be very important in this paper.

It would be interesting to compare the injuries indicated in these tests with risks predicted from the accident data included in the ISO DIS 13232 [3]. It is hoped to carry out this comparison as a further stage of this research.

Another point to be considered with regard to the low injury results found in this series of tests is that the ISO DIS, groups accidents into cells covering a range of speeds and impact angles. A test to represent a group of accidents is performed at a speed and impact angle defined within the range represented by the cell. It may be that the injuries recorded in the accident data sample are mainly occurring at the top end of these ranges, at higher speeds and more severe angles than are represented by the ISO test configurations.

CONCLUSIONS

1. The airbag module, purposely designed and built for the Norton Commander motorcycle, is a novel system for which the computer simulation was successfully used to determine the system parameters. Design, optimisation and manufacture of a system tailored for a specific motorcycle was considered paramount to the success of the system. The process of development starting with computer simulation and proceeding through design, development and evaluation using static fire tests, sled tests and finally full scale tests and aiming for clearly defined performance targets has proved very efficient and effective.

2. The sled test results showed that the airbag system fully restrained the rider with 100% reduction in rider kinetic energy for all test conditions assessed.

3. The sled test results and those of the full scale impact tests analysed to date comply fully with the design and performance criteria defined at the beginning of the programme and thus confirm the successful performance of the airbag system to date.

4. Full scale impact test results analysed to date indicate that the dummy has been successfully arrested by the airbag. Rider forward velocities are greatly reduced with a corresponding reduction in kinetic energy of between 79% and 100%.

5. All of the neck results for airbag tests reported in this paper are significantly less than the tolerance values, and the majority are low compared to those recorded in standard tests. They show considerable improvements over previous airbag research which commented adversely on the potential for increased neck injuries.

6. The TRL full scale impact test data and the motorcycle rough ride and misuse results, summarised in Appendix A, indicate that a fire time is possible within the limits imposed by the requirements for total airbag deployment time. Full mapping of sensor operation at threshold impact speeds in different configurations will be required to develop a commercial system.

ACKNOWLEDGEMENTS

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The support of all component suppliers such as Woodville Polymer, Allied Signal, Hamlin Electronics and Temic who showed great interest in this work is very much valued.

REFERENCES

1. **Road Accidents** , Great Britain 1994. Casualty Report.

2. **Chinn, B. P, Donne G. L, Hopes, P. D.** "Motorcycle Rider Protection in Frontal Impacts." The 10th International Technical Conference on Experimental Safety Vehicles, Oxford, UK 1985.

3. **ISO.** "Motorcycles - Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices fitted to Motorcycles, **ISO DIS 13232."**

4. **Finnis, M.** Airbags and Motorcycles: Are they Compatible?, SAE International Congress and Exposition (SAE 900744), Detroit, Michigan, USA, 1990.

5. **Whitaker, J. W.** "A survey of Motorcycle Accidents." T.R.R.L. Laboratory Report LR 913. 1980.

6. **Sporner, A, Langwieder, K, Polauke, J.** "Risk of leg injuries to Motorcyclists - Present Situation and Countermeasures." The 12th International Technical Conference on Experimental Safety Vehicles, Gothenburg, Sweden, 1989.

7. **Newman, J. A.** "Head Injury Criteria in Automotive Crash Testing." Proceedings of the 24th Stapp Car Conference, Troy, Michigan, USA, 1980.

8. **Zellner, J. W, Newman, J. A, Rogers, N. M.** "Preliminary Research into the feasibility of Motorcycle Airbag Systems." The 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, 1994.

9. **McDonough, P. J.** "Airbag Switch Development: Coarse Road Vibration Tests and Field Trials." Progress Report (Part I - Project S101D/VD, Motorcycle Safety Group). Transport Research Laboratory, 1994.

APPENDIX A

MOTORCYCLE ABUSE TESTS

Introduction - The performance of an airbag system depends critically upon the time at which the airbag is fired during an impact. This, in turn, has to be balanced between the need for optimum efficiency in an accident and the necessary and indeed vital prevention of an inadvertent firing.

It is therefore important to obtain and analyse data from events during which airbag deployment is not required and which typify the most severe to which the motorcycle is likely to be subjected. This analysis must then be compared with similar analysis of pulses from impacts in which the airbag must be deployed.

Previous TRL research [9] described analysis of data from tests whereby the motorcycle was ridden at constant speeds of up to 30 km/h over two very rough suspension courses at a UK military vehicle proving ground (TEE,Chobham). However, it was considered important that data from tests which represented a sudden severe disturbance, such as striking a kerbstone or a pothole, was also analysed. It was envisaged that such an event could occur at a speed somewhat greater than could be achieved over a continuously rough surface. The tests and results of this second stage of the research are described briefly below and the results of the two stages are considered together.

Motorcycle and rider- The airbag system is being developed for a Norton Commander and hence this was used in the trials. The same motorcycle and professional rider were used in both test series, thus a comparison between the two series is valid.

Instrumentation - For the second series of tests it was decided to test all four potential sensor sites simultaneously both to provide direct comparison and reduce wear and tear on the motorcycle (previously the sites were examined separately). A single, handlebar mounted, push button switch was used to start both data recorders simultaneously. The switch was positioned near, and to the right of, the left hand handlebar grip so that it could be reached easily by the rider.

Accelerometer sites - In the previous tests two possible airbag sites were investigated, the top of the fairing and the petrol tank. However, as explained in the main body of the paper, the petrol tank became the preferred site for the airbag. It was decided therefore to move the upper fairing accelerometers to the front wheel axle, a position which is likely to provide rapid sensing of a frontal impact and thus give more time either for bag inflation or discrimination between fire or non-fire events. The other three sites (i.e. fork crown, motorcycle centre of gravity and fuel tank) remained the same. The centre of gravity site was of interest because it was thought that this might provide low pitch sensitivity.

KERB STRIKE TRIALS

Kerb design - A concrete base, 250mm deep, was sunk into TRL's Research Track, to provide a rigid support for the simulated kerb which was bolted to the base by a stud at each end. The top section of the barrier consisted of a 75mm (3") thick hardwood block counterbored so that the retaining bolts lay flush. The top face was chamfered to represent a kerb. Wood sections of various thickness could be fitted between the top section and the base to provide heights of up to 200mm (8").

Trials - Tests began at the lowest height and at a speed of 16km/h. The speed was then increased gradually, with each run repeated, until a maximum safe speed of 56 km/h was reached. The barrier height was increased and the trials repeated. The maximum height and the maximum speed at this height was 114 mm and 32 km/h.

The complete test series was repeated but with the front brake being applied just before the front wheel was in contact with the barrier. It is likely that a rider would brake before hitting an obstruction and this test series was designed to represent this action.

The rider approached quickly, braked to the required speed and kept the brake on as the front wheel crossed the barrier. The effect was to compress the front suspension and this in turn increased the severity of the impact with the kerb..

RESULTS

The acceleration data was analysed and the pulse duration and velocity change was determined for the most severe pulse in each test. Results from all series of tests are given in Figure A1 together with the results of similar calculations for a range of impact tests. The switch operating curve is plotted and events below this line will not fire the switch whereas events which cross the line, or are above it, will operate the switch.

It can be seen that all the data from the abuse (rough riding) tests lie below the line whereas the curves generated from the impact tests cross the line at various times. This indicates that the switch would not fire inadvertently, even under extreme circumstances, and that the airbag would be deployed in the range of impacts analysed. The times for airbag deployment are consistent with efficient and safe restraint of the rider.

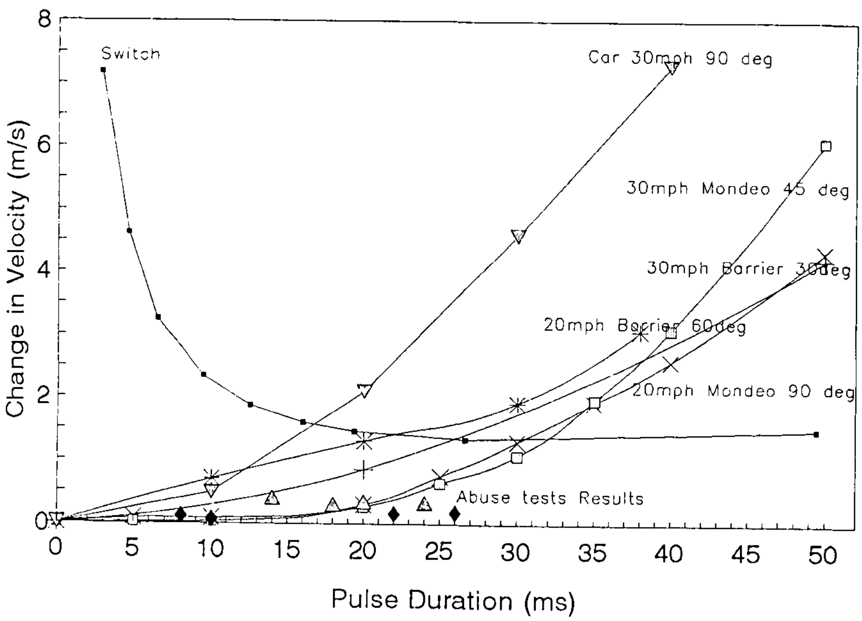

Figure A1. Pulse Duration vs Delta V for Various Crash Tests

AGING PROCESS AND SAFETY ENHANCEMENT OF CAR OCCUPANTS

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ABSTRACT

Seat belts, knee-bolsters, air bags have been developped since many years and are being used more widely. But passive safety still can be enhanced and must take a greater account of the occupants' specificities. In industrialized countries it is expected that by 2025, nearly 22% of the population will be more than 60 years old. Meanwhile new technologies, mainly electronic control, could soon be used to monitor a number of components of the restraint system even anticipating the crash initiation. For example, air bags and pretensioners are activated by crash sensors, belt anchorages are movable on the B-pillar as well as head restraints on the seat-back.

It is therefore advisable to look at the ways to improve the restraint systems' efficiency for elderly drivers and passengers.

After recalling the issue at stake from accident statistics, a literature search aims at investigating how and to what extend the human tolerance to impact is weakened by aging so that the variation of tolerance levels to impact could be estimated and proposed for consideration when developing intelligent restraint systems.

INTRODUCTION

Seat belts, knee-bolsters, air bags have been developped since many years, are being used more widely and have proven there efficiency. But passive safety still can be enhanced and must take a greater account of the occupants' specificities. In industrialized countries it is expected that by 2025, nearly 22% of the population will be more than 60 years old. Meanwhile new technologies, mainly electronic control, could soon be used to monitor a number of components of the restraint system, even anticipating the crash initiation. For example, air bags and pretensioners are activated by crash sensors, belt anchorages are movable on the B-pillar as well as head restraints on the seat-back.

This paper tries to give an overview to the actual knowledge in biomechanics of impact in relation to age influence through the literature survey of :

- the physiological alterations such as osteoposis,
- the mechanical properties of bones,
- the body segments and whole body behaviour under experimental impact loadings.

ISSUE OF AGING IN ROAD SAFETY

In industrialized countries the elderly are a growing proportion of the population. 12 to 16 percent of the population is over 65 years of age and during the last decades a major increase has been experienced by some European countries (Germany, Sweden for example). As stated by the Organization for Economic Cooperation and Development, it is expected that by 2025, nearly 22% of the population will be more than 60 years old. This aging phenomenon has implications in road safety for many reasons. Mobility of elderly people will be more and more ensured by the private car (Rosenbloom, 1995). A greater number of them will have their driving license, all the more noticeable for females. In the USA to day 90% of the men and 75% of the women over 65 were licensed drivers. Comparable rates will be reached in most European countries and most of the old drivers wish to keep on driving for as long as possible. Moreover elderly people still need and appreciate travelling : when comparing the non-professional trips, the retired people cover nearly the same mileage as the working part of the population (Orfeuil, 1992).

Decentralization and suburbanization are another trend in European countries which follow the past North American pattern. The subsequent dispersion of homes and social activities increases the need to travel by car for the elderly. If it is not in their own car, they will possibly take a ride in a taxi or a friend's car.

Since many years, the general accident statistics have highlighted that the involvement rates depend of the car occupant's age, which is clearly shown by the "U-shape" curves of fatal or injury involvements per 100 million miles by age groups (figure 1, Massie, 1993).

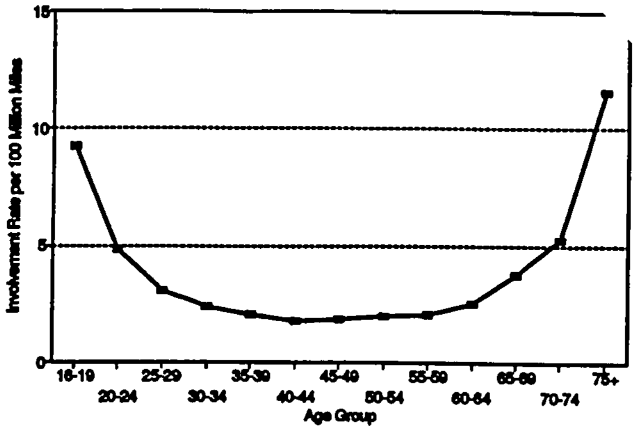

Figure 1. Fatal involvements per million miles (source : Massie 1993, USA).

When they are involved in an accident, the older occupants are more vulnerable than the others (the same trend is recorded for pedestrians and cyclists). In France, the fatality rate is 6 for 100 involved passengers over 65 years of age when it is 3 for the whole passengers (Fontaine, 1994). In the USA, the number of fatalities per 1,000 crashes increases from 2 (younger drivers) to 5 by age 80. The findings are similar for less severe injuries (NHTSA, 1993). In Germany, Miltner (1995) has shown from the investigation of car-to-car frontal collisions that the probability of being fatally injured was 30-45% higher for occupants over 59 years than those under 20 with an EES of 50 km/h (Estimated Equivalent Speed). Moreover it must be acknowledged that women are more frail than men.

We won't comment on the involvement of elderly drivers in car accidents, related to their responsabilities and decreased abilities to control their cars but we will focus on the consequences of road accidents and analyse more thoroughly the case of car occupants. Investigation of crash injury data have shown that the localization and severity of injuries are directly influenced by age. In their recent study of fatally injured car drivers (using autopsy and police reports of 514 cases), Sjögren et al. found that fatal head injuries decreased whilst chest injuries increased with age. As indicated on figure 2, chest injuries were most dominant since the age of 50 years and abdominal injuries for the group over 70 years of age. Moreover a larger proportion of the older drivers died from complications than the younger drivers.

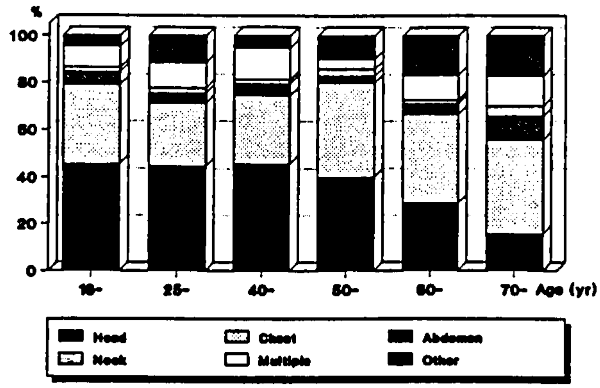

Figure 2. Fatal injuries by age of drivers (source : Sjögren, 1993).

As expressed by Patricia Waller et al (1977) , **the older drivers can correspond to the "miner's canary". Many measures aimed at improving older driver safety may improve safety for all ages.**

PHYSIOLOGICAL CHANGES WITH AGE

When addressing the issue of impact trauma for elderly people, it is quite clear that the decreased bone strength has a direct link with osteoporosis. This phenomenon mostly involves the female population. Indeed, from 50 years of age , women loose their ability to fix calcium ions due to diminished oestrogenic secretions. So that osteoporosis is most damaging the vertebrae the lower arm bones and the upper femur and consequently, without appropriate medical treatment, women often suffer from a decreased tolerance to impacts (and falls). Moreover the female to male predominance of osteoporotic fractures decline from a ration of 10/1 in the sixth decade of life to a ratio of 3/1 in the eigth decade and beyond (Kleerekoper, 1986).

Apart from this phenomenon, there is evidence that aging affects the bony structure of both genders of the population : effectively bones undergo continuous remodeling throughout life. Peak bone mass is achieved at about 35 years, after the bone mass declines slowly. For women bone mass decreases rapidly for three to four years after menopause (that is 40 to 50% of hte bone mass). For men the bone mass dicreases more slowly (20 to 30%). It has been demonstrated that reduction of bone mass is the most important reason for the higher frequency of bone fractures in the elderly population : a 10% reduction of bone mass induces a two times higher risk of fracture (Ribot, 1994). Other factors have such an influence as age : race, body weight-for-height.

EVALUATION OF THE BONE STRENGTH

The mechanical properties of bone have been assessed by using the static or quasi-static standard tests in tensile, bending and torsional conditions. One of the most comprehensive data were collected by Yamada (1970) who identified the influence of age on the femoral compact bone strength (see appendix 1).

Parallely, techniques have been looked for the bone characterisation in vitro. The content of mineral salts in the bone is an important factor (Currey, 1969). After calcination of bone pieces, the bone mineral content is given by the ratio : %C = 100*Mashes / Mdry bone. It has been shown that there is a direct link between the bone mineral content and the ultimate strength : a too high mineral content diminishes the modulus of elasticity.

So, for biomechanical research in crash conditions, it appeared very important to take into account the bone characteristics of the tested human subjects. The Laboratory of Accidents and Biomechanics of PSA/Renault team has studied the bending breaking load of the 7th rib for 151 cadavers (Sacreste-1982, Foret-Bruno-1989) and their mineral contents. They came up with the "Bone Condition Factor" which is well correlated to the maximum bending force (figure 3).

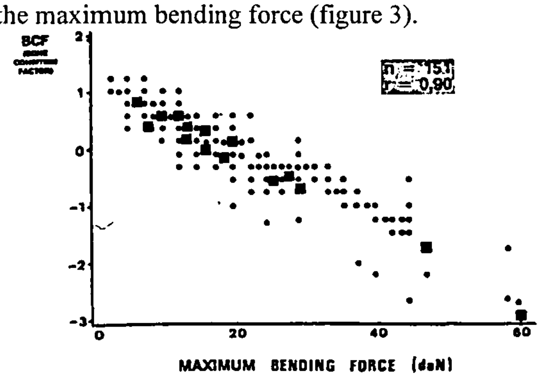

Figure 3. Rib Bone Condition Factor versus maximum bending load (source Foret-Bruno, 1989).

And even if there are inter-individual discrepancies, the results indicate that the Bone Condition Factor increase with age has a reasonably good significant level (figure 4).

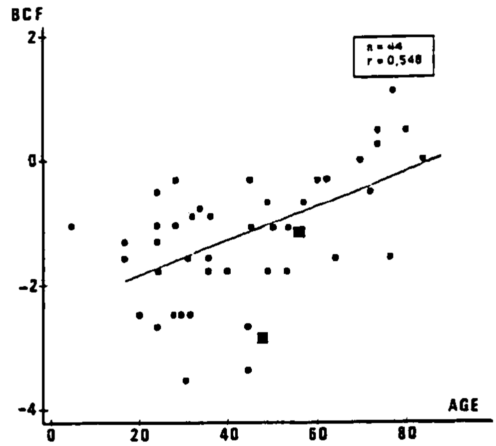

Figure 4. Bone Condition Factor versus age (source Foret-Bruno, 1989).

New techniques are now investigated with the aim to get an evaluation of the bone characteristics in vivo. Computed Tomography is used to quantify the bone density and the influence of osteoporosis. Berthel (1980) performed measurements on the left radius of 235 subjects (iodine 125 densitometry). As shown on figure 5, the mineral bone index is quite constant with age for males while it decreases markedly after menopause for females.

Smith (1969) obtained comparable results by using the Standard Aluminium Equivalent technique on the third metacarpal bone of volunteers (312 males and 317 females).

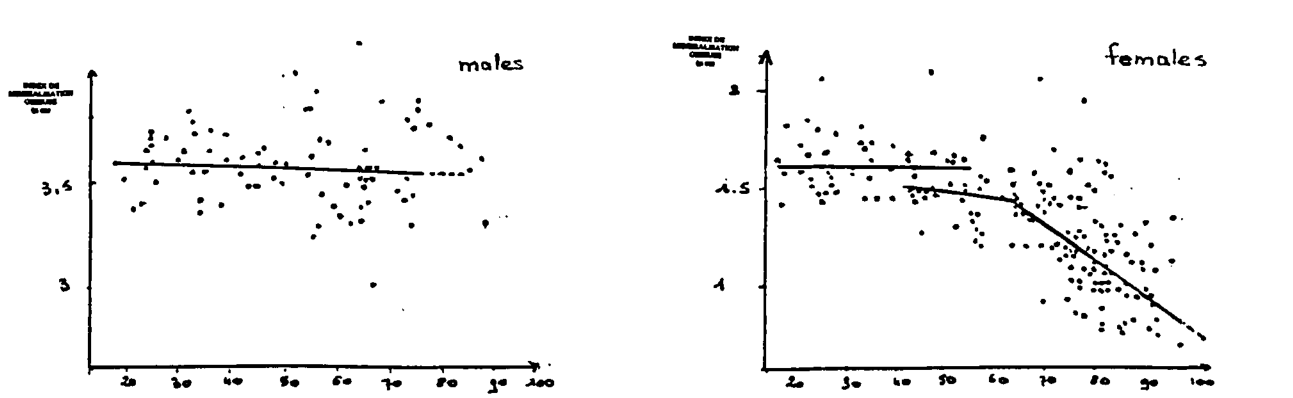

Figure 5. Mineral Bone Index versus age and gender (source Berthel, 1980).

Recently, Schueler (1994) investigated the mechanical properties of the skull bone. Interestingly he looked at the measurement of bone mineral density. His analysis of a large data set indicates that the compression fracture stress and the shear fracture stress were highly predicted by the combination of parameters determined by Quantitative Computed Tomography whereas they were less predicted by age. Such results are quite encouraging for the future researches which could benefit from a non-invasive technique applied in the accident investigation of injured patients or during the experiments with human cadavers.

INFLUENCE OF AGE ON TOLERANCE TO IMPACT

Both in-depth accident investigations and experimental impact loadings are currently used in order to get a better knowledge of the human tolerance to impact. Biomechanical research tries to combine various approaches based on static and dynamic tests and with surrogates of the human being volunteers, animals and human cadavers - to devise relevant physical parameters to be transfered on a biofidelic dummy.

Looking for the influence of age on the tolerance levels, our analysis will be based on the data available from the literature dealing with the most concerned body parts as indicated above : the thorax and the abdomen.

Thoracic frontal loadings

In frontal car crashes the injury mechanisms are either a blunt trauma by impact against the rigid parts of the dashboard or a localised loading by the belt restraint. Thoracic acceleration, force deflection are the parameters considered as injury criteria.

The accident investigation performed by the Laboratory of Accidents and Biomechanics of PSA/Renault has provided a set of frontal accidents in which the front occupants were wearing a three-points belt with a load limiter. Foret-Bruno (1978, 1989) conducted a comprehensive analysis of the injury outcome of 386 car occupants and compared these data to the behaviour of the load limiters whose characteristics were known by design. The influence of age appeared to be very important for the risk of rib fractures for those aged over 50 (table 1).

Table 1.
Rib fractures and age in real accidents
(source Foret-Bruno, 1989)

	< 30 years	30 to 49 years	≥ 50 years	TOTAL
Number of cases	3/160 *	10/169	17/57	30/386
%	1.9%	5.9%	29.8%	7.8%

*Number of cases with rib fractures/number of occupants involved in accidents.

The occurrence of rib factures increases with the belt load estimated from the tears of the load limiter at the shoulder level. Given the necessary approximations made depending on the type of limiter, the author has been able to show how the shoulder belt load influences the thoracic injuries versus age (figure 6).

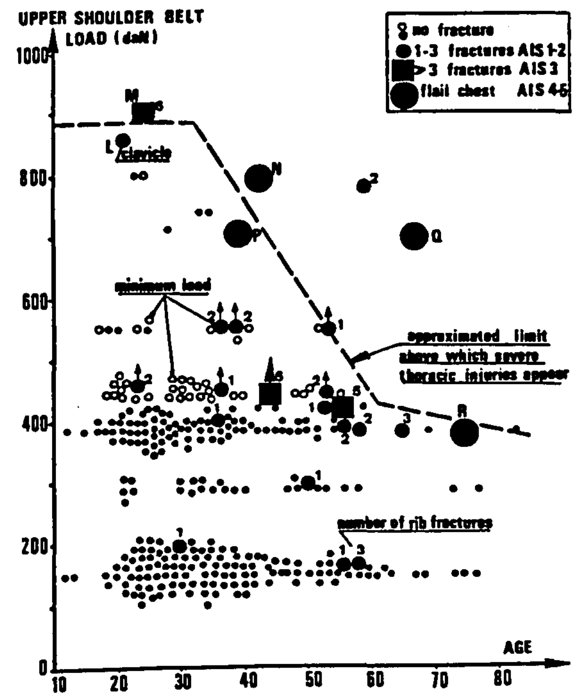

Figure 6. Upper shoulder belt load and thoracic injurie versus age (source Foret-Bruno 1989).

Even if inter-individual differences were high, the shoulder belt load thresholds were therefore classified by age group for the occurrence of serious injuries as follows :

under 35 yrs	8000 - 9000 N
35 to 50 yrs	6500 - 8000 N
50 to 65 yrs	5000 - 6500 N
over 65 yrs	4000 - 5000 N

These results are very interesting because they come from real field accident experience. They have the drawback to express the thoracic tolerance limit under belt loading by the measurement of the shoulder belt loads which depend on the anchorage points geometry relative to the occupant and on the occupant's weight.

In fact many researches led to the evidence that deflection could be the more relevant parameter for thoracic injuries in case of both belt loading and distributed loading (impactor or air bag). Foret-Bruno completed his work with sled tests with cadavers, but he obtained a measurement of deflection in only three tests. Provided this limitation and after having compared the measurements on the Hybrid III dummy in two tests in identical conditions, he concluded that *"a low deflection criterion (e.g.50 mm) corresponding to a load of 5000 N which could be withstood by the most elderly population". And "for the youngest population, a load of 8000 N corresponding to a deflection of 80 mm for the Hybrid III (similar to cadavers) can be withstood without thoracic injury".*

In our opinion a further work should be undertaken in order to take into account a greater number of tests both with cadavers and Hybrid III in order to draw more reliable limits depending on age. Similarly the same insight should be got into the Viscous Criterion proposed as a predictor of skeletal and internal organs injuries severity (Lau and Viano, 1986).

Thoracic lateral loadings

During lateral loadings the prevailing injury mechanism is a blunt trauma due to direct intrusion of the side door and impact on the passenger's body. Experimental tests have been performed with flat circular impactors, rigid or padded, then with a simulated armrest to study more concentrated impacts (Stalnaker 1974, Melvin 1976, Sacreste 1982).

The predominant trauma is rib factures which are quite sensitive to age. As an example, the data of 58 side experimental tests performed in Germany have been analysed by Zobel (1994). He showed that the number of rib fractures increases tremendously from the age group 36-55 years and the age of 40 seems to be critical (figure 7)

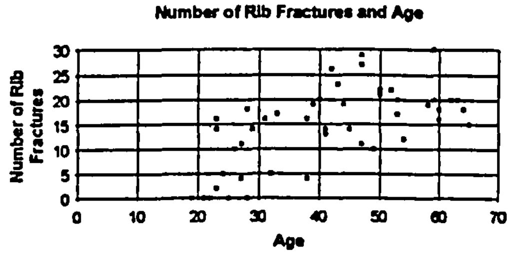

Figure 7. Rib fractures and age in lateral loading (source : Zobel, 1994).

Marcus (1983) had previously gathered and analysed the results of 42 sled lateral tests performed with human cadavers. He found out that there was an increase of approximately 0.025*AIS thorax for each year of age (figure 8).

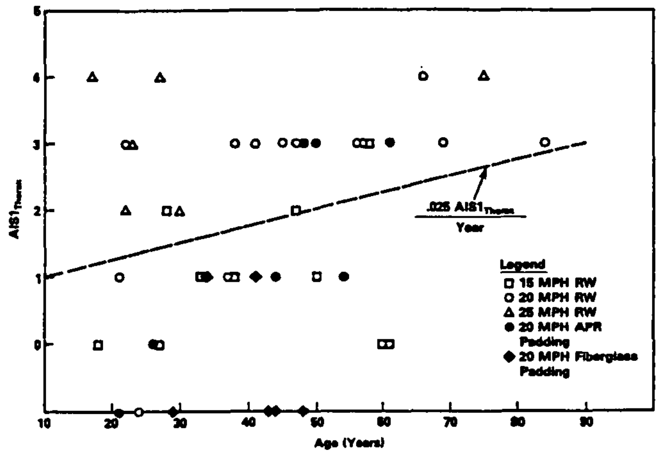

Figure 8. Thoracic AIS and age in lateral loading (source Marcus, 1983).

Deflection has been found as the most relevant injury criterion. Then the Thoracic Trauma Index TTI has been developped by Eppinger and his co-authors (1984). From their statistical analysis of a great number of cadaver tests performed in various laboratories, they suggested the TTI which is based on chest acceleration measurements combined with anthropometric data. Its formula includes the age of the test subject so that the limit value for standard application is chosen with reference to a 45 years old occupant weighting 75 kg as follows :

$$TTI = 1.4*Age + 0.5\,(RibY+T12Y)*Mass / Mstd$$

The Viscous Criterion VC has been devised by Lau and Viano (1986) which look for a criterion more suitable to predict injury severity of both skeletal and internal organs. It is a time function of the chest deformation velocity and the instantaneous deformation :

$$VC = V(t)*C(t)/D$$

There is still debate about the more relevant injury criteria. Kallieris (1994) and Zobel (1994) have recently tried to find out their significance in predicting the protection level. They concluded that TTI, VC or compression were not well correlated with injury level and that TTI could best predict the injury cost severity. Whatever the injury criterion may be, there should be enough available data to find out some appropriate limits depending of age.

Abdominal loadings

Among the abdominal organs, only the liver and the spleen lie under the lower rib cage. There is a lack of knowledge on the tolerance to concentrated loading (such as from the steering-wheel rim), to blunt trauma in side impact and there is some concern about submarining under the belt restraint which can result in loading the belly and the kidneys.

As concerns the age sensitivity, if the accident statistics tend to show an increased risk for car occupants over 70 years of age, the tests performed with human cadavers do not illustrate such a fact. It should be mentioned that the methodology and the surrogate model are critical issues for the biomechanical research on this body segment so that more work is needed in this field.

CONCLUSION

Owing to aging of the population and to longer lasting driving period, the issue of a better protection of the elderly car occupants should be now considered. It is our feeling that a good opportunity arises with the development of "Intelligent Restraint Systems". Thanks to electronic control and new technologies, they could integrate some modulated characteristics which could be tuned to the occupant's specificities, among them age. As an example, the case of a small old lady driving close to the steering-wheel wouldn't be neglected any longer.

Our survey of previous works on injury tolerance to impact shows that some useful data are available to propose age dependent limits for thoracic loading in frontal impact. Further work is needed for thoracic lateral loading. As concerns abdominal loading, consequence reduction may be of higher priority than enhancement of occupant protection systems. Finally computed tomodensitometry is a promising technique to investigate the influence of age and gender on the modification of bone structure and its correlated strength.

REFERENCES

Berthel M.,Kuntzmann F., Moyses B., Bouket J.L., "La perte minérale osseuse liée à l'age", Médecine et Hygiène 38, pp. 1828-1831, 1980.

Currey J, "The mechanical consequences of variations in the mineral content of bone". Journal of Biomechanics vol. 2, pp. 1-11, 1969.

Eppinger R, Marcus J, Morgan R, "Development of dummy and injury index for NHTSA 's thorax side impact protection programs", SAE paper 840885, Government/Industry Meeting, 1984.

Fontaine Hélène, Gourlet Y, "Sécurité des véhicules et de leurs conducteurs", Rapport de recherche INRETS n°175, 1994.

Foret-Bruno J.Y et al.,"Correlation between thoracic lesions and force values measured at the shoulder of 92 belted occupants involved in real accidents", 22nd Stapp Conf., pp 271-289, 1978.

Foret-Bruno J.Y, Brun-Cassan F, Brigout C, Tarrière C, "Thoracic deflection of Hybrid III : dummy response for simulations of real accidents", 12'h ESV Conf, pp. 650-660, 1989

Kallieris D, Boggasch F, Mattern R, "Protection for the thoracic injury severity in the 90° lateral collision", 14th ESV Conf, pp. 89-99, 1994.

Kleerekoper M., Feldkamp L., Goldstein S., "The effect of aging on the skeleton" - Implications for changes in tolerance", SAE P 186, pp. 91-96, 1986.

Lau I, Viano D, "The viscous criterion - bases and application of an injury severity index for soft tissue", 30th Stapp car crash Conf, pp. 123-142, 1986.

Marcus J et al., "Human response to and injury from lateral impact", 27th Stapp car crash Conf, pp. 419-432, 1983.

Massie Dawn L, Williams A.F, "Involvement rates by driver age and gender based on the 1990 NPTS", 37th AAAM Conf., pp.345-363, 1993.

Melvin J, Robbins D, Stalnaker R, "Side impact response and injury", 6th ESV Conf. pp. 681-689, 1976.

Miltner E, Salwender H-J, "Influencing factors on the injury severity of restrained frontseat occupants in car-to-car head-on collisions", Accid.Anal.and Prev. vol 27 n°2, pp. 143-150, 1995.

Orfeuil Jean-Pierre, "Is the population getting older or the pensioners being younger ?", 6th Inter.Conf on Mobility and Transport for Eldrely and Disabled People, ed. INRETS, vol.1, pp. 99-106, 1992.

Rosenbloom Sandra, "Appropriate solutions in North America : on the way to developing comprehensive responses to the needs of the elderly and those with disabilities", 7th Inter.Conf. on Mobility and Transport for Eldrely and Disabled People, ed. Cranfield Press, vol.1, pp. 3-11, 1995.

Sacreste et al., "Proposal for a thorax tolerance level in side impacts based on 62 tests performed with cadavers having known bone condition", 26th Stapp car crash Conf., pp. 155-172, 1982.

Sjögren Harmeet, Björnstig U, Eriksson A, Oström M, "Differences between older and younger drivers : characteristics of fatal car crashes and driver injuries". 37th AAAM Conf., pp. 237-253, 1993.

Stalnaker R, Mohan D, "Human chest impact protection criteria", SAE paper 740589, 3rd Intern. Conf on Occupant Protection, 1974.

Schueler F et al., "Assessment of mechanical properties of the human skull-cap through basic biomechanical tests and quantitative computed tomography (QCT)", IRCOBI Conf, pp. 23-32, 1994.

Tarrière C, et al. "Synthesis of human tolerances obtained from lateral impact simulations", 7th ESV Conf, pp. 359-373, 1979

Waller P.F., House E.G., Stewart J.R. "An analysis of accidents by age", Univ. of Carolina HSRC, Chapel Hill, 1977.

Yamada H, Evans F, "Strength of biological materials", The Williams & Wilkins Company, Baltimore, 1970.

Zobel R et al.,"Prediction of thoracic injuries by means of accelerations, deflections and the viscous criteria from full-scale side-impacts", 14th ESV Conf., pp. 78-88, 1994.

NHTSA, "Addressing the safety issues related to younger and older drivers- A report to Congress". Report DOT/HS 807 957, 1993.

Appendix 1

Age Differences in the Mechanical Properties of Standardized Specimens of Human Wet Femoral Compact Bone (Source : Yamada, 1970)

Mechanical Properties	Age Group (yr)								Avg
	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	
Ultimate Tensile Strength (kg/mm²)	11.6 ± 0.15	12.5 ± 0.10	12.2 ± 0.19	11.4 ± 0.25	9.5 ± 0.14	8.8 ± 0.24	8.8 ± 0.24	—	10.9
Ultimate Percent Elongation	1.48	1.44 ± 0.007	1.38 ± 0.014	1.31 ± 0.027	1.28 ± 0.015	1.26 ± 0.005	1.26 ± 0.005	—	1.35
Ultimate Comp. Strength (kg/mm²)	—	17.0 ± 0.44	17.0 ± 0.42	16.4 ± 0.37	15.8 ± 0.44	14.8 ± 0.23	—	—	16.2
Ultimate Percentage Contraction	—	1.9 ± 0.07	1.8 ± 0.02	1.8 ± 0.02	1.8 ± 0.02	1.8 ± 0.02	—	—	1.8
Ultimate Bending Strength (kg/mm²)	15.4	17.7 ± 1.1	17.7 ± 1.1	16.5 ± 2.1	15.7 ± 2.0	14.2 ± 2.9	14.2 ± 2.9	—	16.0
Ultimate Specific Deflection	0.086	0.075 ± .0041	0.066 ± .0054	0.062 ± 0.007	0.062 ± 0.007	0.053 ± .0045	0.053 ± 0045	—	.062
Ultimate Torsional Strength (kg/mm²)	—	5.82 ± 0.11	5.82 ± 0.11	5.37 ± 0.05	5.37 ± 0.05	4.96 ± 0.12	4.96 ± 0.12	4.96 ± 0.12	5.41 ± 0.06
Ultimate Distortion	—	0.028 ± .0009	0.028 ± .0009	0.025 ± .0005	0.025 ± .0005	0.027 ± 0.001	0.027 ± 0.001	0.027 ± 0.001	.027 ± 5e-4
Modulus of Elasticity (torsion) (kg/mm²)	—	350	350	320	320	300	300	—	320
Cleavage Strength (radial direction)	—	9.0 (est)	8.8 ± 0.44	8.6 ± 0.20	—	8.2 ± 0.10	8.2 ± 0.13	8.2 ± 0.13	8.6

AN UNIVERSITY'S VIEW ON MOTORCYCLE SAFETY - RECENT RESEARCH RESULTS AND FUTURE PERSPECTIVES

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ABSTRACT

Safety is of great importance for the future of motorcycles on public roads, yet it lags far behind 4-wheel-vehicles in almost every aspect. Attitudes, behaviour, abilities and actions of riders are of great influence on safety, but are poorly researched and given little attention by motorcycle manufacturers, particularly for critical or emergency situations, in comparison with primary safety investigations elsewhere.

In order to get a wide range for a general investigation relevant sources of world literature were evaluated.

Motorcycle accidents are diverse and small changes in accident parameters can cause big differences in accident processes. The motorcycle braking is very important for accident processes and the safety in general.

Within the motorcycle research of the Department of Automotive Engineering (fzd) of Darmstadt University driving dynamics and braking of motorcycles are focal points since 1980.

Funded by the Bundesanstalt für Straßenwesen fzd intensified experimental man-machine-interface-(MMI-)research by looking into the braking behaviour of motorcyclists in real traffic. Measurements and video data documented, that even in "normal" driving situations the braking behaviour differs from the ideal braking. Extraordinary requirements asked from the driver in certain driving situations decrease the braking performance even more. In many situations higher decelerations were possible and necessary. The fear of locking the front wheel seems to be fixed in the riders consciousness of the subjects and prevents maximum deceleration.

The braking performance of riders on motorcycles equipped with today's standard independent braking system is insufficient in dangerous situations.

An outlook on future perspectives of enhancing the safety of motorcycles is given at the end.

INTRODUCTION

The comparatively high number of accidents with casualities or fatalities of motorcycle riders (Figure 1.), the resulting high risk of being injured while riding, the higher safety margin of cars in contrast, and the increasing traffic density accelerated and still accelerates the safety research and development on motorcycles.

Statistics can help to declare a substantial improvement in motorcycle safety in the last few years /2, 3, 4, 5/. Yet, the accident statistics are depending on many factors. In most statistics published, there are side-effects not taken into consideration, which might have changed within the time frame given, like driven or transportation kilometres per year.

To understand the meaning of safety for motorcycles a look on passenger car safety may be helpful. In nearly all industrialised countries the number of injuries and fatalities in individual road traffic had risen progressively from the 1960ies to 1970ies. This circumstance had an ever increasing influence on legislation at the beginning of the 1970ies. Until then, the main aim of vehicle development was raising the reliability. Under the pressure of legislation the car manufacturers were then forced to largely increase their effort on the development of safer cars. Looking back today, it can be seen that the number of casualties and fatalities reached its all time high in the mid 1970ies, although the amount of cars and especially the number of kilometres driven per year has risen dramatically since then.

The legislation's pressure on car manufacturers differs from country to country, therefore the car manufacturers used items developed for countries with a strict legislation (e.g. the US) as a means for public relations in those with a less strict one (e.g. several countries in Europe). This way the subject safety became more important to the customer, and nowadays, it is stated among the most important topics for a buying decision.

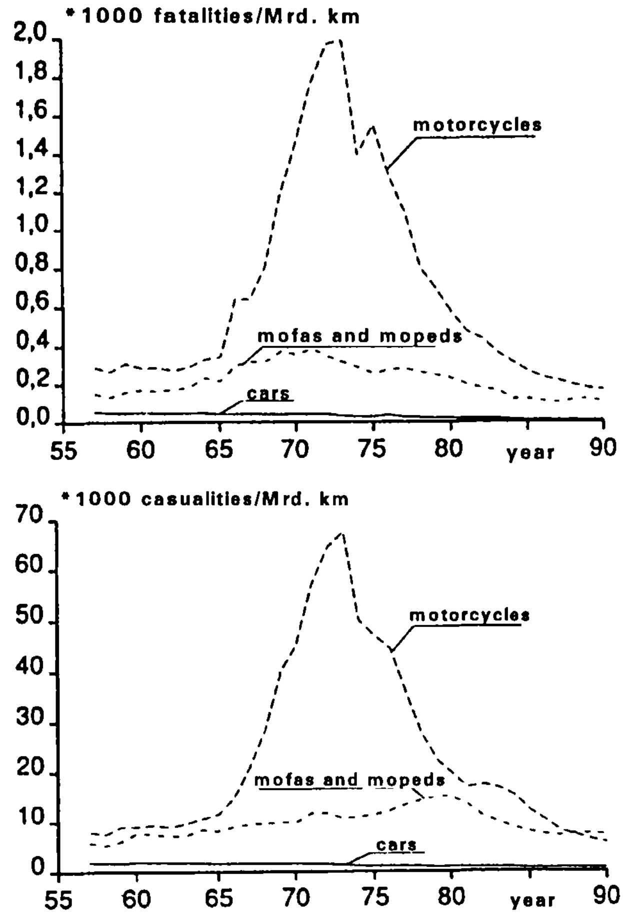

Figure 1. Accident statistics /1/, modified

For this reason the safety of passenger cars was jointly pushed forward by everybody concerned (producer, driver and legislation). Unfortunately this unique aim can not be observed in its clearness when looking at motorcycles.

For motorcycles the development went an entirely different way. In the industrialised countries the motorcycle changed from a cheap transportation to a mostly fun and leisure time vehicle /6/ with the respecting disadvantages and effects.

Safety items attached to motorcycles do not belong to the most important topics among customers and so they do not for the manufacturers. Perhaps motorcyclists know or think that motorcycling is principally more dangerous than car driving and therefore are principally prepared to take a higher risk. However, the adaptation of safety features substantially depends on the customers demand (system of competitive profit) and apportionment possibilities of e.g. developing costs (few motorcycles relative here).

It can be observed that many primary and secondary safety items lack far behind comparable items in passenger cars.

VIEW ON MOTORCYCLE SAFETY

Motorcycling is, like many other activities, connected to a certain risk to be injured or even killed; the size of the risk can be influenced in different ways. The objective risk often differs from the rider's perception ("This does not happen to me").

Looking at the reasons for accidents the percentage of the so-called "mechanical problems" decreased. Today they even contribute little. Human mistakes are stated to be the most frequent accident cause today /3, 4/.

In /4/ 1/3 of all motorcycle accidents are said to be "solo accidents" (including avoidance of collisions with others), so other traffic participants are involved in more than a half of all motorcycle accidents /8/. In about 2/3 of all accidents car/motorcycle the motorcycle rider is not guilty. But this can unfortunately soothe the endangered motorcyclist in the legal sense only. The percentage of falls with an indirect collision following is rather high: 23,2%, /9/.

All in all this is a high price for the single-track vehicle, which has to be paid today. Nevertheless, future automotive research should deal with this field without changing the single-track characteristics.

Safety measures can be divided into three planes. The first plane contains the possibility that a certain happening is taking place (dangerous situation). The second deals with the possible consequences if the rider gets into such a situation (injury), and the third plane consists of the action taking place within the situation (the rider needs to have the chance to influence the outcome in some way).

Safety is normally subdivided into primary safety dealing with the avoidance of dangerous situations and the possibility to get out of such a situation without any consequences, and secondary safety concerning the minimisation of crash consequences.

Primary Safety

A large number of publications deals with primary safety. Herein most important aspects shall be regarded. It has to be kept in mind that different aspects are closely related to each other on behalf of interaction.

<u>Driving Dynamics of Motorcycles</u> - After the large increase of engine power of motorcycles, driving stability turned out to be a severe problem, which had to be worked on /e.g. 10, 11, 12, 13/. The driving stability is very

important for the rider and therefore for the producers of motorcycles. Especially the high speed stability has been improved significantly until today. But it remained a very important topic for design (e.g. chassis stiffness) and tuning (e.g. tyre choice) as it is system immanent.

Criteria of stability are often subject of compromises, e.g. the tuning of straight ahead stability and handling ability. Since the late 1980ies the high engine power of the big bikes requires more stiffness of the fundamental motorcycle parts.

A problem appearing frequently today is the so-called kick-back. If intensive kick-back occurs, the handle-bars are smacked out of the hands of the motorcycle rider. Only few accident caused by kick-back are known. Kick-back occurs rarely and is therefore difficult to investigate. Ongoing investigations on this field are considered important.

Motorcycle Braking - Because of the overall relation to fzd's research activities this aspect of the primary safety is intensively regarded in chapter "Some Own Research Activities".

Rider Behaviour- The rider behaviour has a large influence on accident statistics. Often the "human factors" are referenced to cause most accidents. This is principally correct. Undoubtly efforts shall be made to educate the rider better and adjust him to the motorcycle dynamics. However, the question of the limits of human performance must be asked, particularly if efforts for education/training/exercises are exceeding a suggestive/realistic/feasible extent. In addition to that, there are "intelligent" assistant systems used in sectors and applications where principally human fallibility has been detected and accepted.

The most frequent reasons for accidents caused by the rider-behaviour are too high velocity, incorrect distance to the vehicle ahead, and overtaking in wrong places /13/. The two topics excessive velocity and incorrect distance to the vehicle ahead are strongly related to braking (see chapter "Some Own Research Activities").

In /14/ tests for steering behaviour and maneuverability were conducted with 2 500cc-class street motorcycles. One result was that riding a motorcycle is a difficult task, for which the necessary skills can be obtained only gradually! On the opposite the specific motorcycle dangers and the large performance are present from the beginning. Thereby the experience increases normally very slowly, due to short driving distances (leisure and fun activity).

Riding a motorcycle requires actions that do not belong to common behaviour patterns of human beings. Especially the tolerable roll angle takes long to get acquainted with /15/. Although managing standard situations can be learned by training, the same situations can cause serious problems whenever the rider acts in shock. Panic and stress, which make up a shock, can lead to either hyper activity or on the other side block necessary actions /16/. Shock is a state which usually occurs whenever something unexpected and dangerous happens suddenly. Experienced riders have less shock situations, for they do not assess as many situations as dangerous as novices do, and in addition, less situations are unexpected. The second is e.g. because of the selectivity of the perception of the eyes. The eyes tend to perceive pictures which contain a lot of information within the field of vision. These pictures are not necessarily the ones, which are relevant to assess traffic situations correctly. The perception structure can, nevertheless, be influenced by the expectation of the rider. This way dangerous situations may be recognised earlier as the eye puts a focus on this kind of information /17/.

Besides the experience, the risk taken by riders has a large influence on accident statistics. Both risk and lack of experience make the age group of 18 - 21 years to the most endangered. There are many publications dealing with this age group e.g. /18/. The risk behaviour not only includes the riding behaviour but also the habit of not wearing the necessary protective clothing /19/.

The subjective point of view of the rider has a large influence on measurements concerning primary safety. Many of the measures described below may be used up by the rider for reason of a so called risk compensation /20, 21/.

Rider education - The amount of publications dealing with rider education confirms that this subject is generally considered to be very important. Besides the driving schools with final examination to get a driver's licence, suggestions range from educating pupils e.g. in the UK /22/ to motorcycle camps for especially young people /23/. These courses are aiming at teaching riding skills just as well as teaching an awareness of the risk connected to riding. The ability to be able to assess the own possibilities correctly is considered very important /24/.

Conspicuity In a publication dated back to 1980 /25/ in about 50% of the cases, in which a car hit a motorcycle, the car driver claimed that lack of conspicuity was the reason for the accident. Many publications deal with various methods to raise the conspicuity /26, 27, 28/ also regarding other road members and the road furniture /29/. But since then, little has been done to improve it. It is mostly the headlamp that got brighter, but this has little

effect on problems e.g. the underestimation of the motorcycle speed and the small silhouette.

Ergonomics - Ergonomics are a very wide field which includes the comfort of helmet and protective clothing as well as the motorcycle itself, ranging from sitting position to weather protection.

The protective clothing has a major effect on the constitution of the rider. In southern Europe hardly any rider wears protective clothing for example. This is mostly because of the heat in the summer and the lack of adequate clothing for these weather conditions.

The problems which are caused by helmets are mostly a result of noise annoyance and a bad view through the visor under adverse weather conditions. Noise annoyance is especially created by wind noise. Even in modern helmets the levels above a certain speed are too high to hear environmental sounds, and even the possibility of not hearing warning signals is rather high /30/. The problem of noise annoyance is not only the impaired hearing of warning signals, but the fatiguing effect of it as well. Also wearisome, especially under cold or wet weather conditions, is the unsolved problem of visors which are scratched and steamy. For both problems the solutions supplied by the market are considered insufficient. Especially at night time a scratched visor reflects the light of oncoming vehicles in various directions.

The physical constitution of riders is not only influenced by clothing and helmet but also by the motorcycle. Altogether the working place motorcycle should fit the demands of the rider. On the one hand it has to keep him alert and therefore not let the level of strain sink below a certain value, on the other hand a fast fatiguing of the rider must be avoided.

Due to the large number of different motorcycle types there is nothing like a uniform 'perfect' sitting position. Generally sportive motorcycles should be ridden with more weight on the hands to establish a good contact to the front wheel and the road, touring motorcycles should offer a more upright position to keep the strain low over longer distances. The leg angle should be as large as possible and wind, rain and vibrations should be kept away from the rider /31/.

Secondary Safety

Every measure dealing with the minimisation of consequences for the health of human beings resulting from a motorcycle accident belongs to the field of secondary safety. It therefore includes the investigation of protective clothing and motorcycle design just as well as improvement of possible collision objects such as cars and the road furniture. Since motorcycle accidents are in comparison to car-crashes more variable, as far as the motion or trajectory of the rider and a possible pillion is concerned /32/, there seems to be not as much effort spent on secondary safety as on primary safety. The fact, that the number of fatalities is rather constant between 20 - 25 per 1000 accidents in Germany from 1980 to 1986, can lead to the conclusion that the secondary safety has not improved in this time /33/. In fact, many secondary safety items that have been developed in the past were never built in, on account of customer acceptance problems.

In order to improve secondary safety strategies an accident analysis is needed. From this analysis together with a precise evaluation of injury patterns concrete measures for accident simulation can be derived. The simulation consists of crash-simulation with a special motorcycle dummy and computer simulation. Dummies used so far usually are an improved typical car-crash-dummy Hybrid I - III. The improvements are frangible bones by using bakelite /34/ or fibre with different fill material, a moveable neck, and especially a head which allows the use of a helmet with a chin-strap. No dummy has been developed exclusively for use in motorcycle crash research so far.

Motorcycle design - Any item fixed on the motorcycle to protect the rider in case of a crash can only have an effect as long as the rider is in contact with the motorcycle. Since it is advisable for the rider to be separated from the motorcycle in an accident, its design must not hinder the rider from leaving. The design can only give the rider's trajectory a wanted direction. Since frontal collisions are the most frequent kind of accident and additionally bear the highest risk of serious injuries /1/, the most design investigations published on this subject deal with this accident configuration.

In /35/ a motorcycle with adequate secondary safety features was developed starting with a special very human-centered approach. Based on the survivable accelerations a one-track vehicle has been designed, which can be roughly described as follows: stiff, the complete vehicle surrounding structure with doors, restraint system (driver does not need protective clothing), roll over protection and special collapsable handlebar (Figure 2.). The vehicle looks very awkward and the driving dynamics will probably be different from motorcycles normally used today. Emphasized is the advantage of such a vehicle for the rider's education. Falls are possible but seem not to be dangerous so that limits (maximum roll angle and braking in bends) can be experienced.

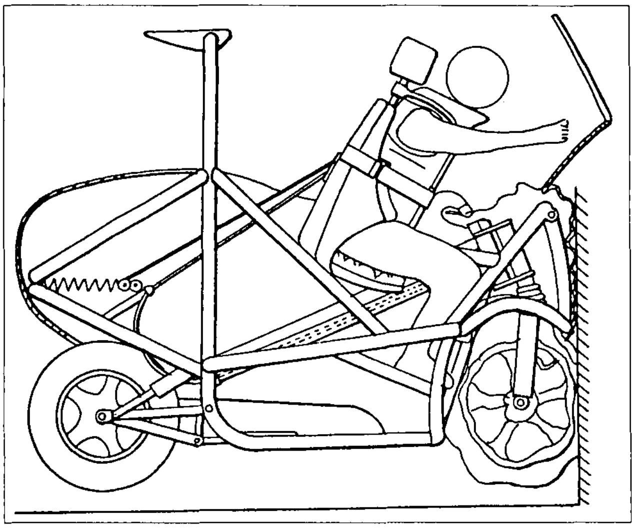

Figure 2. Safety motorcycle by human limits approach /35/, modified

Sitting position - The sitting position can have a major effect on the rider trajectory in a frontal impact. There are many publications dealing with the accident configuration of a motorcycle driven into the side of a car. The worst case for the rider in this configuration is hitting the cantrail with his head. To avoid the contact with this very stiff part of the car, the rider has to be lifted in order to fly over. The trend to more vans and off-road cars with high roofs on the streets can not be welcomed in this aspect. There are many possible ways to keep the rider's head up /36, 37/. Anti-Dive systems belong to the most effective measures in modern motorcycles like the new front wheel suspension TELELEVER (BMW).

Leg protectors - Leg protectors are a very controversially discussed subject. The TRL in the UK published crash-tests and computer simulations to prove the effectiveness /38/. The European Experimental Vehicles Committee consisting of a number of respected scientists also published a paper stating an improvement in 61% of the conducted tests and a detriment in only 11% /3/. The motorcycle industry represented by the International Motorcycle Manufacturers Association (IMMA) has found many reasons not to support the idea of a leg protector especially since it is claimed that a detriment occurs in a far higher percentage of cases /4/.

All in all, every device adapted to a motorcycle to raise the secondary safety, consisting of any kind of crashbars, that has been proposed so far, changes the motorcycle's character in an unacceptable way, (Figure 2). Therefore, any research work done on the improvement of secondary safety by using some kind of a device should not change the character of the motorcycle.

Airbag - An airbag might be a solution to not only cushion an impact, but to influence the rider trajectory in a desired way as well. To develop such an airbag a lot of crash tests are necessary. On behalf of this, there are only few publications about airbag tests. Unsolved problems until today are the rather free moveability of the rider and the short time between sensing an accident and ignition. Airbags, that have been investigated so far, can even cause injuries like neck fractures, depending on the sitting position of the rider /4, 38, 39, 40/.

Collision objects - Collision objects of motorcycles are mostly cars and the road and road side. Hazardous to the rider is any edge of the car with a high stiffness. Publications on the shape aggression of cars exist since many years /41/. Nevertheless, the automobile industry is naturally more concerned about the safety of the car driver. Safety measures for pedestrians and two wheelers in general seem to be of a lower priority.

The road itself can be dangerous to the motorcyclist because of differing adhesive properties of the road surface. Especially the use of different materials like tarmac, gravel or steel expansion joints for bridges but also the topography like severe unevenness of the road surface, can lead to a fall of the rider. A fall will result in a sliding phase, during which the road side design may become important. Any aggressive shape there can lead to unnecessary injuries /42/.

Protective clothing and helmet - In Europe an ISO standard called ECE-R 22 regulates the features of helmets. Until 1994 a second impact on the same spot of the helmet was required, whereas the acceleration resulting from this second impact had to be below a certain value. For reasons of this second impact the damping material had to have a rather high stiffness. An analysis of accident data proved that a second impact on the same spot of the helmet hardly ever occures. Hence this standard blocked the use of softer material with adequate damping abilities /43/.

The new ISO standard does not require the second impact anymore and therefore a use of the best material for a single impact available is possible today. This way the head injury criterion index HIC described by the head acceleration, can be lowered to an extent depending mostly on the material abilities.

With respect to feasibility and effectiveness protective clothing is considered to be of importance. But without any doubt protective clothing acceptable from the rider's point of view can not substitute the safety of a passenger car

compartment. Resulting from maximum available deformation heights of protective clothings clear force reduction limits are given. So main tasks of protective clothing are reducing the severity of injuries and protecting the rider from results of less dangerous accident patterns (sliding on road surfaces, falling from the motorcycle onto the road surface). Protective clothing is subject of primary safety too /44, 45/.

Motorcycle Safety today

Looking at a motorcycle as it is built today, it can be seen that there are big differences in safety items built in. The differences result mostly out from the kind of motorcycle, depending very strongly on the customer group the motorcycle is aiming at. Roughly seen there are 4 types of motorcycles: choppers, sport motorcycles, touring motorcycles, and enduros.

Looking from the secondary safety point of view, there are only touring motorcycles and to a smaller extent enduros equipped with safety items (high upright sitting position, spoke wheels, ABS, anti-dive, flat tank-shapes). Especially riders of touring motorcycles are willing to spend more money for comfort and safety. Because of the cost of these motorcycles, the riders usually belong to the older age group. Riders of other types of motorcycles put a higher emphasis on either weight (sport motorcycles) or design (choppers), which often contradicts to safety measures.

Looking from a primary safety point of view, things are very much different. All in all, the primary safety is considered more efficient /46/, and the improvement of primary safety items has been realised to a greater extent. Improving the primary safety of a motorcycle does not necessarily change the image of it in a way many secondary safety measures do. Not to change the image of a motorcycle is very important when thinking of customer acceptance.

Primary safety measures on the motorcycle, that were enhanced to a great extent within the last 10 years, are the driving stability, the tire characteristics in general, the ergonomics of the operation panel at the handlebars, the lighting, the integration of the rider into the motorcycle, and the brakes. It can be seen very easily that each one of these also helps to raise the fun while riding. The riding fun belongs to the most important reasons for riding in the industrialised countries, where the motorcycle is used as a leisure time object by a large majority.

Accident Patterns - The most common accident patterns are described in an ISO standard /47/. This standard is based on data described in /3/. According to this data base, about 1/3 of all accidents is a fall of the motorcyclist. In nearly 2/3 of the cases a collision with another vehicle occurs, whereas this vehicle is usually a car. To update this data the Verband für Schadensversicherer e.V. examined the collision types defined in this standard for the latest data on motorcycle accidents in Germany /48/.

According to /48/ with a data basis of 528 accidents between a motorcycle and a car, it does not make sense to merely look at the number of accidents according to a certain configuration, but to also focus on the resulting injury severity. /45/ compared the often used MAIS_D measure with the average days of in-patient treatment but found only a very rough correlation for the 14 most frequent collision types.

A definition of collision types and the injuries resulting from it is necessary for a precise research on secondary safety measures. One reason, why safety devices like airbags and leg protectors have been discussed so controversially in the past, is that the crash patterns investigated were not exactly the same and thus lead to different results. Since an in-depth investigation of crash data was not available it was impossible to define one or the other crash test as most important to investigate. Little changes of the hit angle or the velocity of either the car or the motorcycle can have a very high influence on the actual crash pattern. Therefore ahead of every investigation dealing with secondary safety devices, an evaluation of the data presented by Sporner et al. is necessary. Together with the use of a motorcycle specific dummy the results of different scientists should be nearly the same. As research on this field usually failed to come up with proper acceptable solutions, the chance to investigate very precisely in a wide field is now there.

SOME OWN RESEARCH ACTIVITIES

Several accident causes and research results mentioned above point to the high importance of braking for the safety. With the following research results this importance will be underlined. The most important components of the entire system relevant for the motorcycle braking /49/ consisting of rider, motorcycle and environment, are considered.

Relevance of Motorcycle Braking

The highest possible reduction of kinetic energy in a pre-crash phase by full braking, whilst maintaining stability, is of central importance for primary as well as for secondary safety. An upright sitting position of rider and

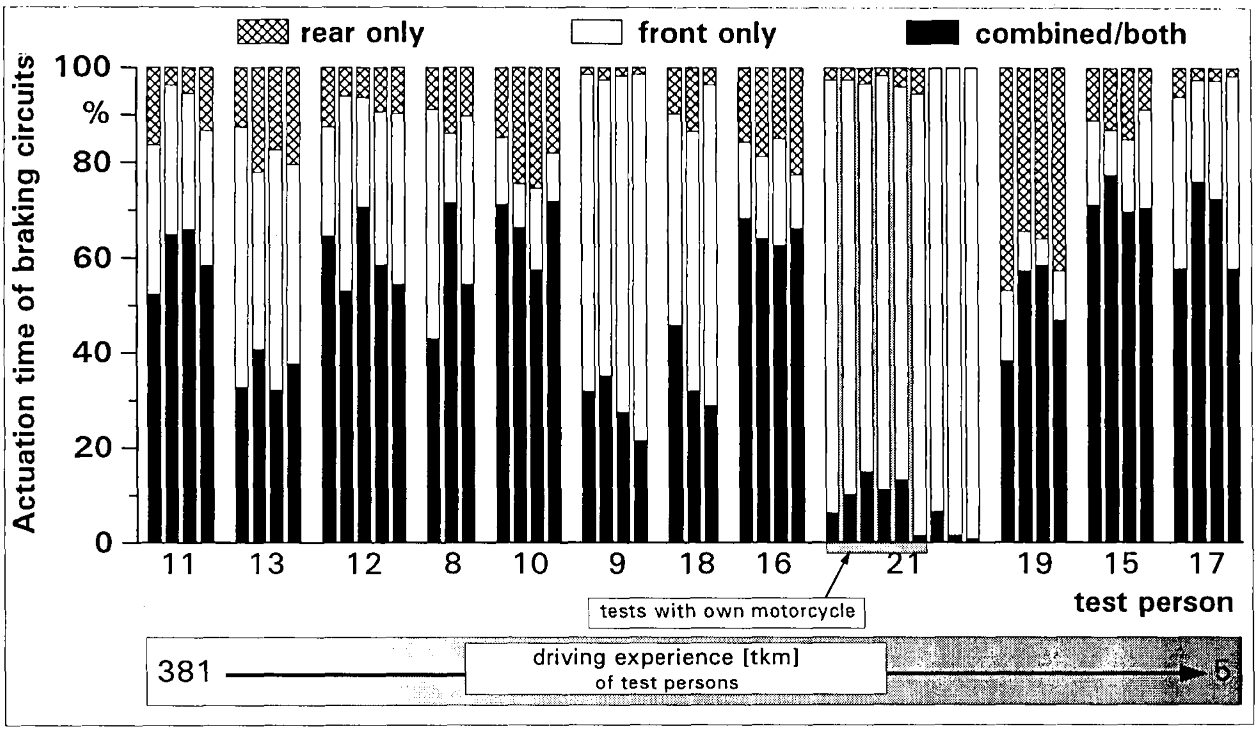

Figure 3. Test persons on public roads (with BMW R 1100 RS normally): percental actuation time of the braking circuits related to their complete braking time as function of the driving experience

motorcycle during a collision with a car provided this vehicle is not unnormally high by either shape or roof carriers enables the overflight of the rider. This reduces the consequences resulting from an accident. Even the level of protection supplied by motorcycle airbags, the introduction of which seems to be likely in the future, depends substantially on the position of the motorcycle and its rider. It is in particular the driving stability of the motorcycle/rider system which is not secured by today's standard motorcycle brakes (hand-lever actuated front wheel brake, foot pedal actuated rear wheel brake) in emergency braking situations. Various surveys on motorcycle accidents claimed operational errors in braking as a significant accident factor /50/. Riders' knowledge of the theory of braking is poor and needs improvement /5, 8/.

/51/ also contains hints for the existance of problems in practise too. In different practical single tests of the Motorcycle Operator Skill Test (MOST, performance test for measuring the driving skills, e.g. rapid stopping and evasive manouvers, at the end of a course) the highest ratios for failing are found in the field of emergency operations (stop braking straight ahead (41%), avoiding obstacle (68,4%), stop braking in curves (74,3%)). A strong reduction of the quota for failing in full braking straight ahead could be achieved by changing the course of practice. For the two other emergency operations only relatively little improvements could be achieved. As a consequence more practising of emergency stopping and evasive manoeuvers and all together more training of crash avoidance skills are needed.

Regarding the technical aspects in the past the problem of brakes dealt for example with the big difference of brake characteristics in wet and dry state of the disk and brake pad, and the possible deceleration including topics like fading /3, 4/. Modern brakes usually do not have these two problems any more. Nowadays, most brakes can yield an excellent deceleration relative to the actuation force. As one of the greatest progresses in safety, there is ABS available today /52, 53, 54/. Fortunately as one of the latest innovations an ABS-secured integrated brake system is offered by one motorcycle producer. But since these systems are not widely spread, important problems of motorcycle braking still exist and some problems even increased (e.g. dynamic front wheel overbraking /46, 49, 50/). The available technology (ABS and integrated brakes) needs to be spread.

Braking Task - Most motorcycles have an unregulated dual-circuit brake system without power braking with a separate front and rear hydraulic actuation (standard brake).

No other road vehicle leaves the rider with so much liberty as to the distribution of braking force for the front and rear wheel, (Figure 3.), /55/.

Even carrying out a so-called 'ideal' full braking under only slightly stressing conditions (straight ahead, even surface, dry road surfaces with a good grip, beginning of braking may be chosen freely), the rider must operate the hand and foot braking lever at the same time, whereas a degressive ratio above the deceleration of the two braking forces needs to be adjusted (Figure 4). From a certain deceleration on, the rear wheel braking force even needs to be reduced, while the front wheel braking force needs to be increased. This tendency grew in the last few years. To improve high speed stability as well, a static wheel load proportion of 1:1 is often realized. The lowering of motorcycle's center of gravity is limited (roll angle clearance). This leads to a more degressive ideal brake force distribution with a brake wheelie point at lower decelerations, (Figure 4). Nowadays it is possible that the friction potential offered by the tyre/road interaction can not be used to its full extent because of the danger of a brake forward roll. This is an important criterion for the ABS-design /52, 54/ and the dynamic tyre forces.

The operation of today's standard brake is highly demanding even for normal decelerations and needs experience. However, this experience is not available at the beginning of a "rider's career". Thus improvements of the standard brake make sense especially here e.g. for light motorcycles. Less experience /56/ coincides with the special risk behaviour of this age group /4/. The problem becomes even more severe, as it is always (up to age of 18) respectively often the only vehicle owned /6/. Hence, the motorcycle is more often used in all kinds of weather conditions. Conditions diverging from dry road surfaces aggravate the problem of braking.

Motorcycle Braking Dynamics

Because of its complexity the dynamics of motorcycle braking /50/ can not be described completely here. This is why only the most important issues will be described. The problem of brake force distribution has been previously discussed rider oriented.

A locked wheel can be regarded as one of the biggest problems riding a motorcycle. A locked wheel loses its cornering stability and deprives the gyro-stabilisation.

Even in straight ahead driving it is nearly impossible to prevent capsizing as a result of a front wheel lock; with rear wheel locking, it might be possible to master the motorcycle by steering (requires most delicate handling by the rider!), however, this is not stable, requires adjustment (therefore riders concentration) and the motorcycle is not steerable any more. With considerable lateral acceleration, the locking of one wheel is bound to lead to a fall. If the rider falls in front an obstacle, it results in an accident with an unpredictably high risk of injury. In addition, the precrash phase is then no longer controllable.

Required operational forces of modern front brakes often are so low, that dynamic overbraking (brake forces rises more steeply versus time than dynamic wheel load) of the front wheel can happen very easily in scaring situations. Some front wheel brakes are even so aggressive that this can even happen in normal driving situations.

Due to the single-track, braking in a curve - compared to straight ahead braking - poses a substantially more difficult problem in terms of driving dynamics. The balance between lateral force and weight force is a dynamic result and is extremely sensitive. If mass force vectors, acting on the centre of gravity of the complete system, do not point to the connecting line between the force centres of the contact patches of the front and rear wheel (gyro forces neglected),

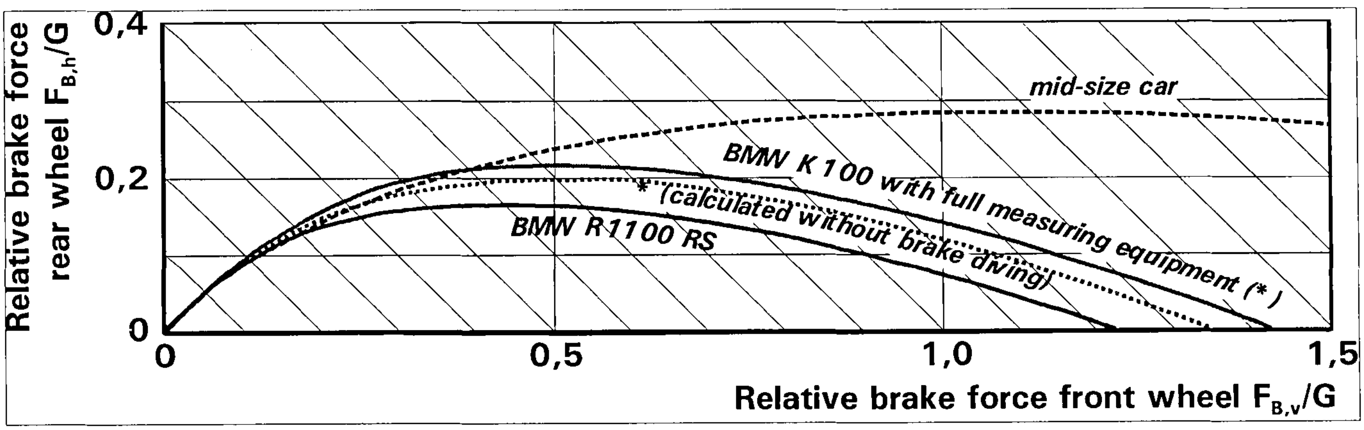

Figure 4. Experimental-calculated ideal brake force distribution: motorcycles and car compared

the emerging roll torque spontaneously alters the drive in the bend.

A braking system offering unrestricted bendworthiness is not available on the market today.

Motorcycles by principle never move ideally straight. The motorcycle is subject to a permanent interaction of - although only very small - steering movements and the resulting gyro, centrifugal acceleration and tyre forces. This stabilising mechanism, but also the lateral drainage slope of road surfaces, leads to a continuous lateral force on the tyres.

In /57/ it is recommended to use only the rear brakes in a bend. For this kind of advise a drastic increase of stopping distance can be expected especially for modern and more sporty motorcycles, the danger of a rear wheel lock is rather high and a crash is likely if the wheel is locked.

Furthermore the so-called brake steering torque is of great importance. Under roll angle the force center of the tyre contact patch moves sideways from the center plane of the motorcycle. Braking forces acting on the resulting lever arm on the steering axis create a steering moment. The brake steering moment adds to the steering moment to be applied by the rider at the handlebars. In case of an actuation of the front wheel brake, it can lead, depending ond tyre- and motorcycle design, to an evasive erection of the motorcycle, resulting in a strong course change. If an ABS is active, major dynamic effects are occurring additionally /49/.

In the past few years the controlling quality of ABS improved in the sense of attainable decelerations. The decelerations of the best modern available ABS can hardly be beaten even by experienced riders.

Modern ABS may even be helpful in stop braking while cornering. With the ABS used in the research described below full braking with ABS being active were carried out while cornering (curve radius R = 50 m, speed V= 45 km/h on dry and 40 km/h on wet road surface) without crash or significant course deviations.

Motorcyclists Braking Behaviour

For the examination of the entire interaction /49, 56/, test drives were conducted by the authors in real traffic with subjects who had not been instructed about the objectives of the tests. The test drives were mainly performed on a standard motorcycle (1100 cc) which was equipped with hidden measuring instruments. The subjects were given the opportunity to get used to riding the new motorcycle. To enable comparison, all test persons were asked to follow the same, given track /7/. On this track the friction coefficients have been measured with methods developed at the authors' department /58/. The track mostly had high tyre/road friction.

All in all, more than 100 conspicuous driving situations were identified and used for assessment. In most of these situations other road users were involved.

If both brake circuits were actuated, they normally were commonly used at the same time in the same direction, (Figures 5. and 6.). So the control can be called one-channeled with a distribution one in two. Test persons normally using both brakes have a mentionable braking time portion using only one brake circuit, too, (Figure 3.). These situations bear the danger of overbraking the wheel as soon as a scaring incident occurs.

Generally both brake circuits are needed for ideal braking. The combined actuation of the brakes especially important for low friction potential in situations of high deceleration leads to a overbraked rear wheel because of the one-channel control. If the rear wheel locks, both brakes are released, (Figure 6.), although this is not necessary at the front wheel. The result is a clear decrease of deceleration performance.

Even experienced riders tend to capsize during intended full braking conditions with braking task being known /56, 59/.

The stress of a driving situation is of major importance /16/. This is demonstrated for example in (Figure 7.). Test person 3 normally uses both brake circuits. In the driving situation depicted, the test person is approaching a police speed check. Although at legal driving speed(!), the subject brakes with a comparably high deceleration (still below the given potential) using only the front wheel brake. The brake pressure gradient indicates the subject was startled.

Adhesion Tyre/Road Surface

The interaction between the tyre and road surface represents the adhesion potential and therefore - disregarding aerodynamic drag - the deceleration potential. The results shown in this report were determined by the authors' departments motorcycle tyre measuring trailer /58, 60/ on real road surfaces.

As a consequence of the performance- and safety-oriented design of the motorcycle tyres, their level of adhesion on a dry clean road surface not submitted to traffic (asphalt and concrete) has in the meantime reached a coefficient of friction in circumferential direction of up to μ_l=1.2, (Figure 8.). Considering Figure 4., a premature reverse wheelie on high grip road surfaces is possible. Coefficients of friction of up to μ_l = 1.0 on wet road surfaces show that the forces transmitted on the test track which has a particularly good grip, are only minimally below the values obtained under dry conditions. The irregularities of the characteristics

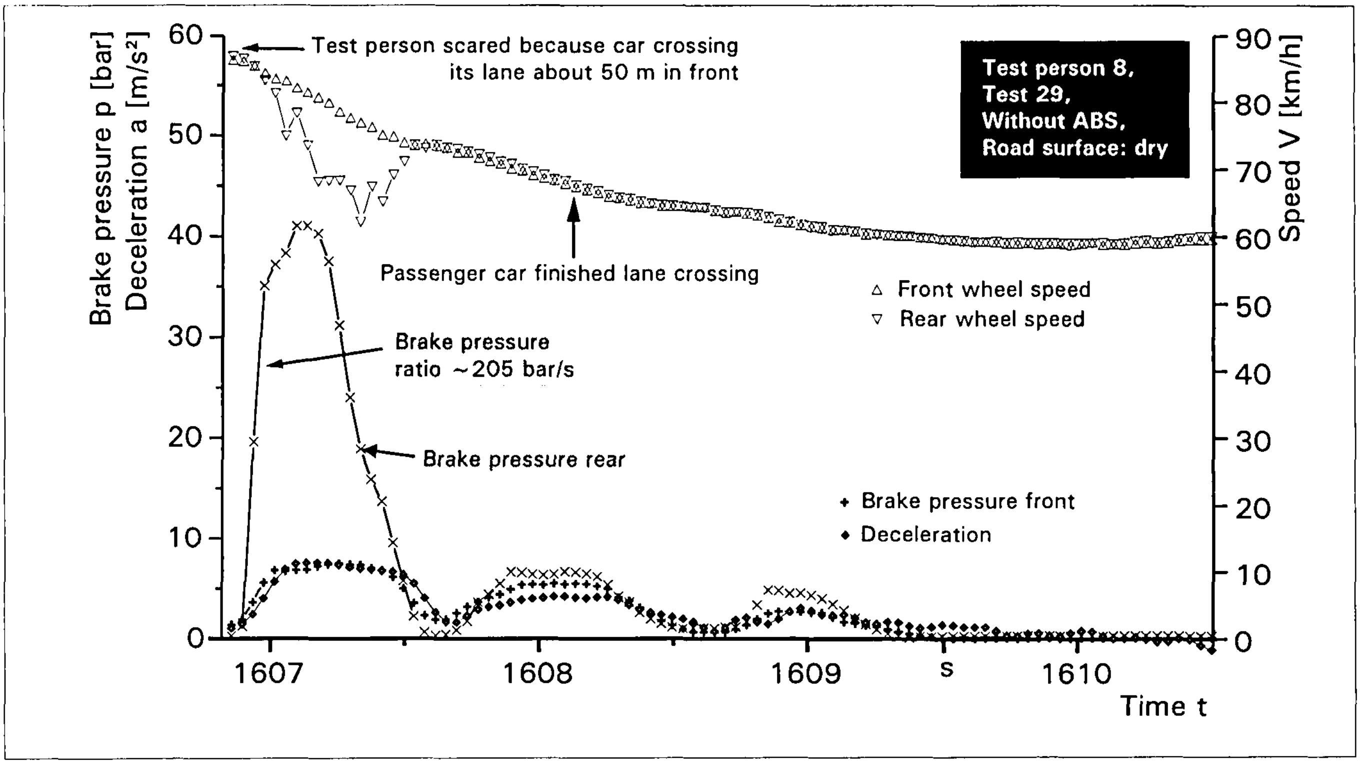

Figure 5. Real-world experiment: example for one-channel actuation of brake circuits

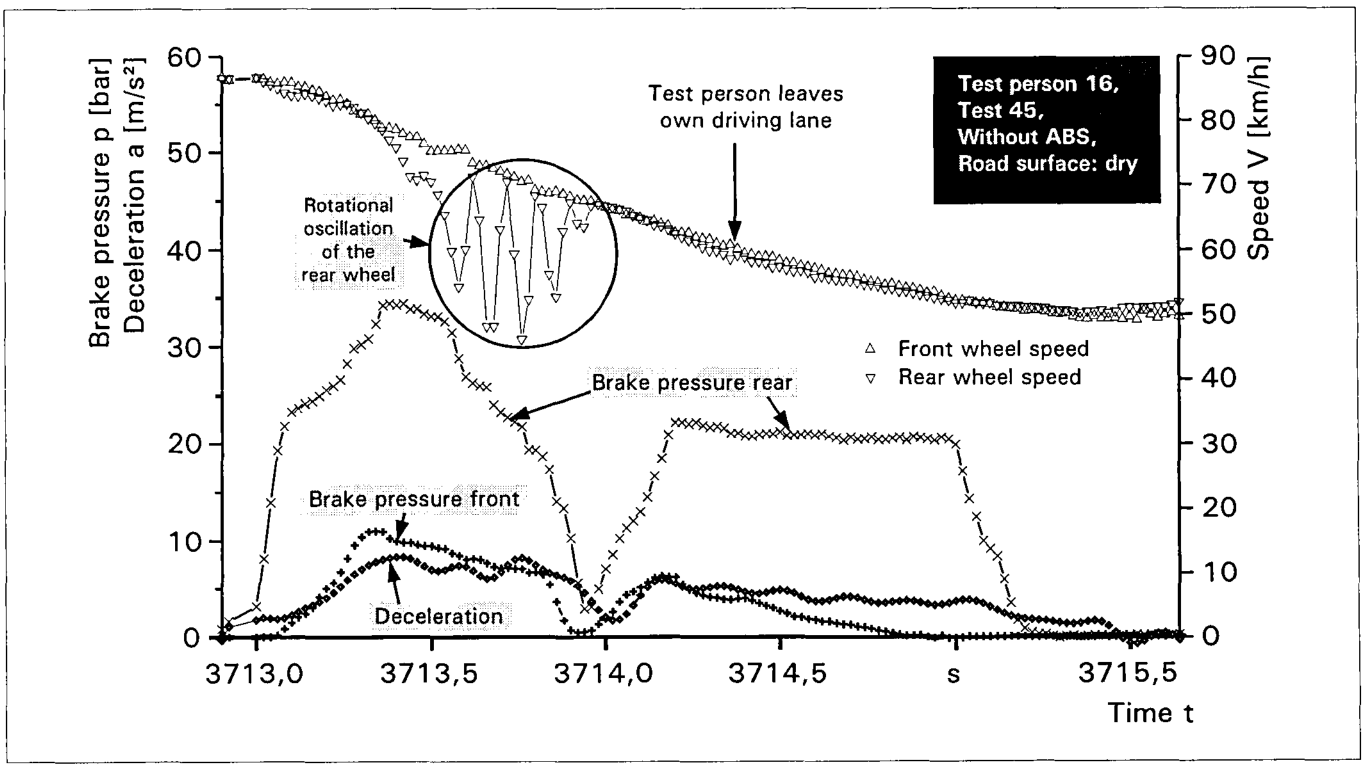

Figure 6. Real-world experiment: test person releasing both brakes because of locking rear wheel

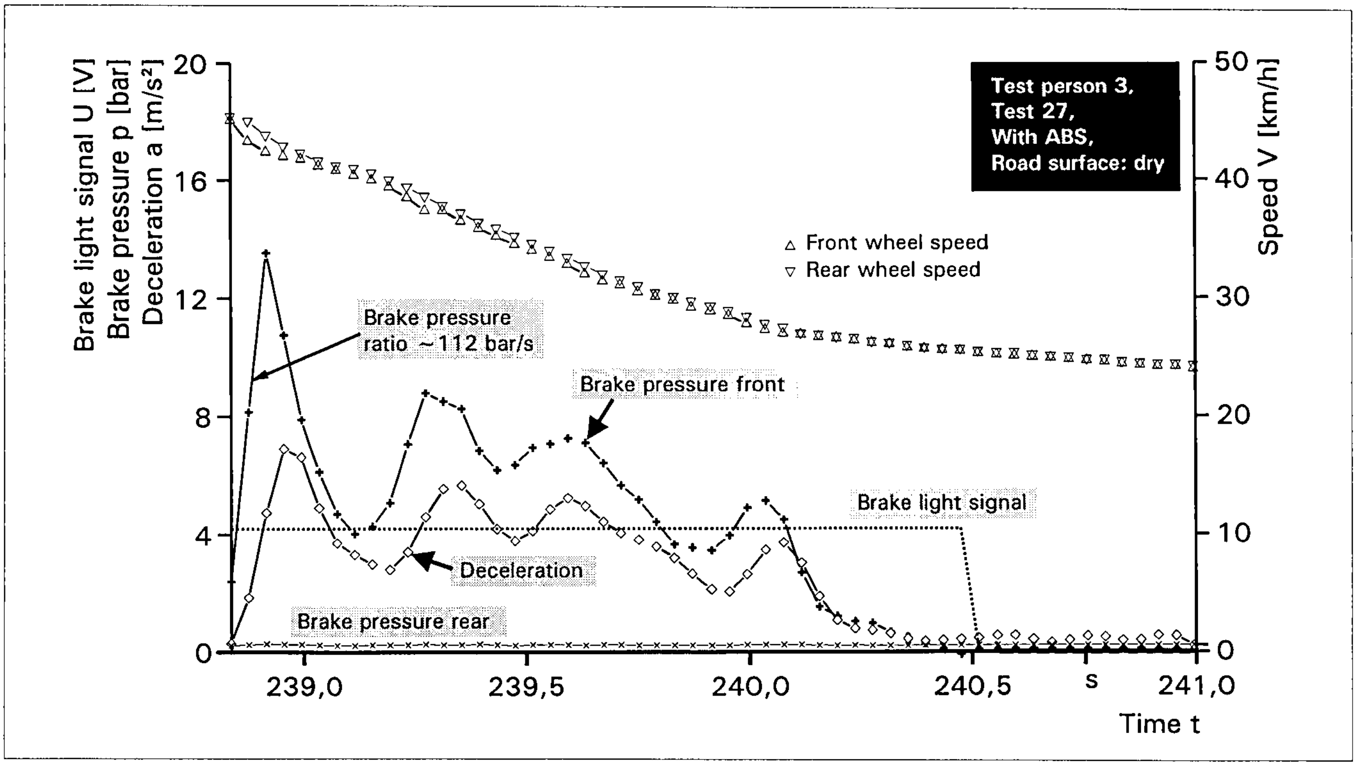

Figure 7. Real-world experiment: braking manoeuvre because of police speed check (speed limit: 50 km/h)

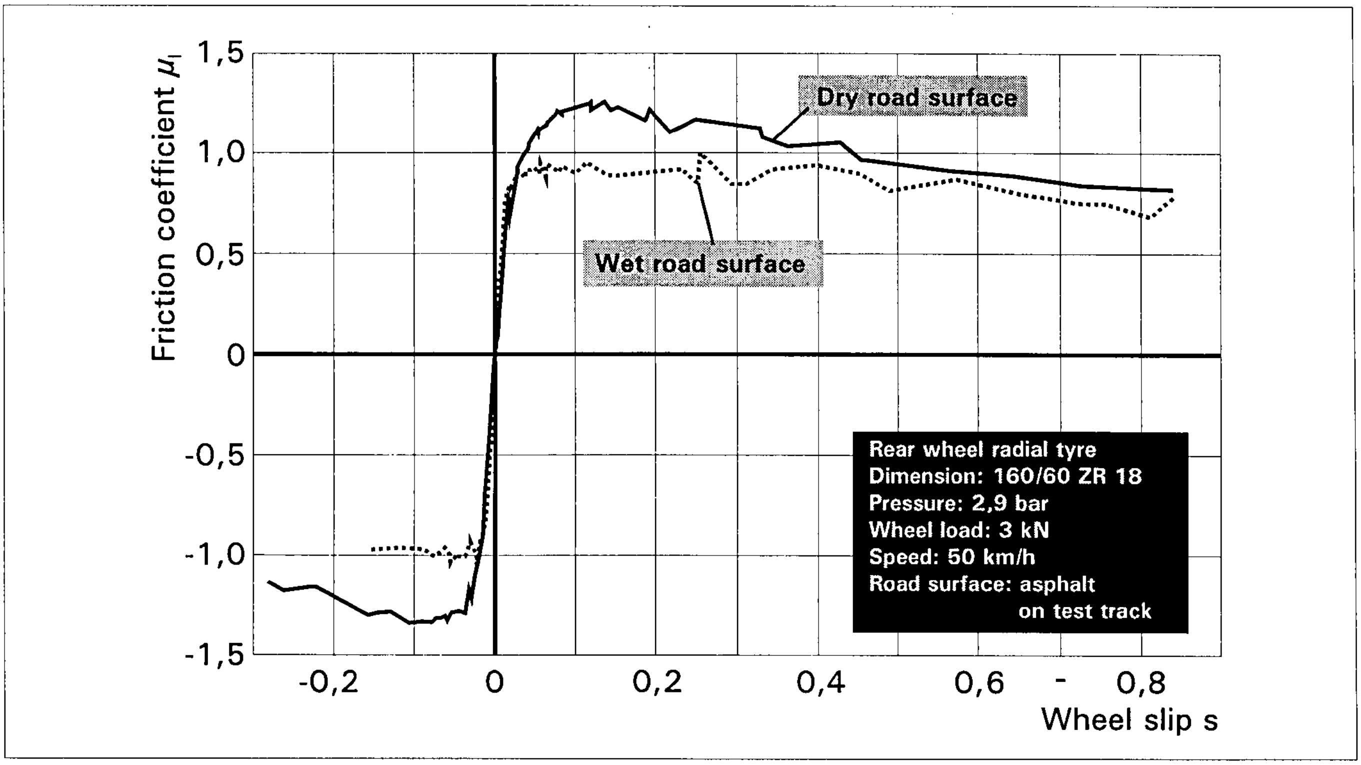

Figure 8. Circumferential force characteristics of a modern motorcycle tyre on dry and wet test track surface

are due to the discontinuous method of measuring, /60/ p. 16.

CONCLUSIONS AND PERSPECTIVES

Riding a motorcycle bears a comparatively high risk. In most accidents other traffic participants are involved. This is why accident avoidance and motorcycle secondary safety depend on them and their vehicles to a large extent.

The safety of today's motorcycles needs improvement. As secondary safety offers rather little potential (larger potential with large expenses or significant design changes which are hardly acceptable), primary safety is the main goal.

Protective clothing and helmets are effective, but protective clothing needs to be more widely spread. By deleting the formerly required second impact in the helmet test procedure ECE-R 22 a remarkable improvement of head protection became possible.

Airbags on motorcycles can increase safety very much, but the feasibility and effectiveness depend on actuation sensors, airbag design and accident configuration.

Human mistakes and driver behaviour are of great relevance for safety. Improved driver's education and continued instruction are helpful. Human performance and the great differences between real-life critical situations and exerci-sing situations restrict the possibilities.

Braking of motorcycles is particularly important for primary as well as secondary safety. It is not only the driving dynamics of the motorcycle, but also the operation of today's standard brakes (without fixed brake force distribution and brake power regulation) which result in the braking of a motorcycle being a rather demanding task, even in less stressing driving situations and driving straight on. In accident prone and highly stressing situations inappropriate if not even dangerous driver behaviour has to be expected with standard brake systems. Improvements as ABS and combined brake systems have to be spread and suitablility for braking in curves is re-quired.

A motorcycle brake system can only be regarded as being safe if it can cope with the abilities and performances of the majority of normal riders and not only performs well with expert riders /56/.

Regarding the standard brake system presently being used, there is an immense potential for improving brakes. ABS and integrated brake systems and combinations of both available today should urgently be spread. ABS can help to overcome the fear of a locked front wheel which is deeply embodied in the rider.

Important for the future of the motorcycle is the research and development of a brake system which can handle all driving situations. So the next step to be made is an ABS secured combined braking system suitable for braking in curves /50, 55, 61/.

In spite of some disadvantages /4/ combined braking systems and an ABS are urgent steps into the right direction. Assessing their advantages and disadvantages the advantages dominate significantly.

An electrically powered brake actuator poses interesting potentials for example. Another solution could be the implementation of brake boosting devices (in combination with ABS).

From the superior view the implementation of artifical intelligence to support the rider especially in critical driving situations is a future aspect /46/.

Because of motorcycle riders' sensitiveness to side slip angles of the rear wheel, a steered rear wheel can be a helpful measure for giving riders a feedback on the driving state. But also further improvements of driving stability and crash avoidance are safety related interesting aspects of steered rear wheels.

The man-machine-interface is of utmost importance for motorcycles and offers large potential for improvement of their safety. Future measures to prevent critical situations however must be derived from a total system approach which includes the environment of the motorcycle-man-system /46/.

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REFERENCES

/1/ Nurtsch, B. and D. Helm, "C1, Verkehrsmittel der Zukunft, Strukturauslegung eines Zweiradsicherheitsrahmens". In: 5. VDI-Fachtagung Motorrad, VDI-Berichte 1025, Düsseldorf, 1993

/2/ Brendicke, R. and E. Forke, "Institut für Zweiradsicherheit e.V. (ifz) Elements of its motorcycle safety work". In: Journal of International Association of Traffic and Safety Sciences, Vol. 19, No. 1 1995

/3/ European Experimental Vehicles Committee, "Report on Motorcycle safety".(EEVC, BASt, Cologne), 1994

/4/ N.N., "Motorcycle Safety - A Decade of Progress". Prepared by the Association des Constructeurs Européens de Motorcycles (ACEM) and the International Motorcycle Manufacturers Association (IMMA).

/5/ Hagstotz, W. and W. Ludsteck, "Motorcycle Braking - A 'Gap' between Technology and Rider? Investigations on Different Brake Systems and their Usefulness for the Rider". In: Journal of International Association of Traffic and Safety Sciences, Vol.19, No.1 1995

/6/ Schulz,U., "Freizeitmotivationen von Motorradfahrern und ihre Auswirkungen auf die Verkehrssicherheit". In: Zeitschrift für Verkehrssicherheit Jahrgang 39 (1993) Heft 2

/7/ Präckel, J., "Das Bremsverhalten von Motorradfahrern - ein Beitrag zur Mensch/Maschine-Schnittstelle". In: 6. VDI-Fachtagung Motorrad, VDI-Berichte 1159, Düsseldorf 1994, S. 67-102

/8/ Otte, D., E. Suren and H. Appel, "Lösungsansätze zur Verbesserung der Verletzungssituation des motorisierten Zweiradbenutzers". In: Passive Sicherheit für Zweiradfahrer, Reihe Forschungshefte Zweiradsicherheit Nr.5, Bochum 1987

/9/ Bayer, B., "Das Pendeln und Flattern von Krafträdern". Dissertation TH Darmstadt, Forschungshefte Zweiradsicherheit Nr. 4, Institut für Zweiradsicherheit e.V., Bochum, 1986

/10/ Schmieder, M., "Die Hochgeschwindigkeitsstabilität von Motorrädern - ein Mensch/Maschine-Problem". In: 4. VDI-Fachtagung Motorrad, Beilage zum VDI-Bericht 875, Düsseldorf, 1991

/11/ Otto, W.M., "Effect of Motorcycle Accessories on Stability". International Motorcycle Safety Conference, Washington D.C., Vol.4, 1980

/12/ Bayer, B. and A. Weidele, "Einflüsse von Betriebsparametern auf die aktive Sicherheit von Krafträdern". In: 100 Jahre Motorrad, VDI-Berichte 577, Düsseldorf, 1985

/13/ Verkehr. Fachserie 8, Reihe 7, Verkehrsunfälle, Herausgeber: Statistisches Bundesamt; Wiesbaden, 1993

/14/ Blaauw, G. and K. Poll, "Human Factors and Riding Motorcycle: Effects of Type of Motorcycle and Rider Experience". Proceedings of the International Motorcycle Safety Conference, Volume 2, Washington D.C., 1980

/15/ Spiegel, B., "Was hat der Begriff Mesokosmos auf einer Motorradtagung zu suchen?". In: 3. VDI-Fachtagung Motorrad, VDI-Berichte 779, Düsseldorf, 1989

/16/ Eberspächer, H., "Psychological Consideration on Brake Use Patterns of Motorcyclists". Proceedings of the 1991 International Motorcycle Conference

/17/ Cohen, A.S., "Blickverhalten und Informationsaufnahme von Kraftfahrern". Bericht zum Forschungsprojekt 8309/3 der Bundesanstalt für Straßenwesen. Herausgegeben in der Reihe Forschungsberichte der Bundesanstalt für Straßenwesen, Bereich Unfallforschung, Heft Nr.168, Bergisch Gladbach 1987

/18/ Kroj, G. and U. Stöcker, "Statistische Analyse der Unfall- und Bestandsentwicklung motorisierter Zweiräder". Forschungshefte Zweiradsicherheit Nr. 3, Institut für Zweiradsicherheit e.V., Bochum 1986

/19/ Brendicke, R. and H. Koch, "Schutzkleidung - Trageverhalten, Wissen und Einstellungen von Motorradfahrern". In: Aktive und passive Sicherheit von Krafträdern, VDI-Berichte 657, Düsseldorf, 1987

/20/ Eggers, R. and P.C. Compes, "Risk Tasking Behaviour of Motorcyclists: Strategical Aspects of Risk Analysis and Risk Control". In: Safety Environment Future, Forschungshefte Zweiradsicherheit Nr. 7, Bochum. 1991

/21/ Koch, H., "Motorradunfallforschung heute. Einführung des Herausgebers". Forschungshefte Zweiradsicherheit Nr. 3, Institut für Zweiradsicherheit e.V., Bochum 1986

/22/ Clayton, A.B. and M.R. Williams, "Motorcycle Training and Traffic Education in the United Kingdom". International Motorcycle Safety Conference, Washington D.C., Vol.1, 1980

/23/ Brendicke, R., "Attitudes of Motorcycle Riders Toward Risk Exposure - A Study of Various Age Groups." Safety Environment Future, Forschungshefte Zweiradsicherheit Nr. 7, Bochum, 1991

/24/ Falk, G., Ruhdorfer, H. and W. Stern, "ADAC-Motor-

rad-Training - Instruktoren-Handbuch". ADAC, München, 1991

/25/ Thomson, G.A., "Value of Headlight Use for Motorcyclists During Daylight". International Motorcycle Safety Conference, Washington D.C., Vol.3, 1980

/26/ Olson, P.L., Halstead-Nussloch, R., and M. Sivak, "Enhancing Motorcycle and Moped Conspicuity". International Motorcycle Safety Conference, Washington D.C., Vol.3, 1980

/27/ Tratner, A.A., "Review of Options Currently Available, and Suggestions for Future Research Directions for Increasing Motorcycle Conspicuity and Increasing Path-of Travel Illumination Effectiveness". International Motorcycle Safety Conference, Washington D.C., Vol.3, 1980

/28/ Stroud, P.G., Kirkby, C., and E.J. Fulton, "Motorcycle Conspicuity". International Motorcycle Safety Conference, Washington D.C., Vol.4, 1980

/29/ Olson, P., "Motorcycle Conspicuity revisited". Human Factors 1989

/30/ Tangorra, J. and A.R. George, "Wind Noise of Motorcycle Helmets". In: Safety Environment Future, Forschungshefte Zweiradsicherheit Nr. 7, Bochum, 1991

/31/ Tobler, U., "Ergonomics and Motorcycles". In: Safety Environment Future, Forschungshefte Zweiradsicherheit Nr. 7, Bochum, 1991

/32/ Appel, H., Otte, D. and J. Wüstenmann, "Epidemologie von Unfällen motorisierter Zweiradfahrer in der Bundesrepublik Deutschland- Sicherheitsaspekte". Forschungshefte Zweiradsicherheit Nr. 3, Institut für Zweiradsicherheit e.V., Bochum 1986

/33/ Langwieder, K., Sporner, A. and J. Polauke, "Stand der passiven Sicherheit für Motorradfahrer und mögliche Entwicklungstendenzen". In: Aktive und Passive Sicherheit von Krafträdern, VDI-Berichte 657, Düsseldorf, 1987

/34/ St. Laurent, A., Shewchenko, N., and J.A. Newman, "Design of a Motorcylist Anthropometric Test Device". Twelfth International Technical Conference on Experimental Safety Vehicles, Göteborg, Vol.2, 1989

/35/ Winiecki, T., "Human Engineering a Crash-Safe Motorcycle". Proceedings of the International Motorcycle Safety Conference, Volume 2, Washington, 1980

/36/ Grandel, J. and F.A. Berg, "Passive Sicherheit von Motorrädern - Entwicklung einer Systematik für ganzheitliche Bewertungen". In: 5. VDI-Fachtagung Motorrad, VDI-Berichte 1025, Düsseldorf, 1993

/37/ Rogers, N.M., "Evaluation of TRL designed leg protectors for a medium sized sport motorcycle". Fourteenth International Technical Conference on Enhanced Safety of Vehicles , München, Vol.2, 1994

/38/ Yettram, A.L., Happian-Smith, J., L.S.M.Mo., Macaulay, M.A. and B.P. Chinn, "Computer simulation of motorcycle crash tests". Fourteenth International Technical Conference on Enhanced Safety of Vehicles, München, Vol.2, 1994

/39/ Zellner, J.W., Newman, J.A. and N.M. Rogers, "Preliminray research into the feasibility of motorcycle airbag systems". Fourteenth International Technical Conference on Enhanced Safety of Vehicles, München, Vol.2, 1994

/40/ Ramet, M., Bouquet, R., Bouallegue, M., Bermond, F. and D. Desari, "The effect of airbag inflation on the cinematic and the lesions of motorcyclists". Fourteenth International Technical Conference on Enhanced Safety of Vehicles, München, Vol.2, 1994

/41/ Breuer B., et al., "Hochschularbeitsgemeinschaft Unicar" Schlußbericht. BMFT Studie 1983

/42/ Koch, H. and F. Schueler, "Reduction of Injury Severity Involving Guardrails by the Use of Additional W-Beams, Impact Attenuators and 'Sigma-Posts' as a Contribution to the Passive Safety of Motorcyclists". Eleventh International Technical Conference on Experimental Safety Vehicles, Washington D.C., 1987

/43/ Felten, G. and Ch. Leibeling, "Untersuchung der Stoßdämpfung von Motoradhelmen". In: Aktive und Passive Sicherheit von Krafträdern, VDI-Berichte 657, Düsseldorf, 1987

/44/ Weidele, A., "Gedanken zur Weiterentwicklung von Motorradfahrer-Schutzkleidung". In: Passive Sicherheit für Zweiradfahrer, Reihe Forschungshefte

Zweiradsicherheit Nr.5, Bochum 1987

/45/ Schmieder, M., "Die Bedeutung von Motorradfahrerschutzkleidung für die aktive und passive Sicherheit von Motorradfahrern". Bericht zum Forschungsprojekt 8718/2 der Bundesanstalt für Straßenwesen, herausgegeben in der Schriftenreihe Forschungsberichte der Bundesanstalt für Straßenwesen Heft Nr. 245, Bergisch Galdbach, 1991

/46/ Breuer, B., Bachmann, V., Präckel, J., Schmieder, M. and T. Tomita, "Approaches to enhance motorcycle safety". In: International Journal of International Association of Traffic and Safety Sciences, Vol. 19, No. 1 1995

/47/ Van Driessche, H., "Development of an ISO Standard for motorcycle research impact test procedure". Fourteenth International Technical Conference on Enhanced Safety of Vehicles, München, Vol.2, 1994

/48/ Sporner, A., Polauke, J. and H. van Driessche, "Collision parameters from real life car/motorcycle accidents. A basis for future standards". International Congress and Exposition Detroit, SAE Paper 950203, 1995

/49/ Präckel, J., Schmieder, M., Weidele, A., and B. Breuer, "Interaction of Rider, Brake System, Tyres and Road Concerning the Braking Safety of Motorcycles". In: Automobiltechnische Zeitschrift ATZ 98 (1996), Nr.1

/50/ Weidele, A., "Untersuchungen zum Bremsverhalten von Motorrädern unter besonderer Berücksichtigung der ABS-geregelten Kurvenbremsung". Dissertation TH Darmstadt 1993, VDI-Fortschritt-Bericht Reihe 12 Nr. 210

/51/ Thackray, R. and J. Prescott, "Field Test of the Motorcycle Rider Course". Proceedings of the International Motorcycle Safety Conference, Volume 1, Washington D.C., 1980

/52/ Cart, J. and J. Pickenhahn, "ABS and the Motor-Cycle". 4. Fachtagung Motorrad, VDI-Berichte 875, Düsseldorf, 1991

/53/ Hikichi, T., Tomari, T., Katoh, M. and M. Thiem, "Research on the Motorcycle Antilock Brake System. Part 3: Braking Effectiveness of an Electronically Controlled ABS on Road Surfaces with Different Levels". Safety Environment Future, Forschungshefte Zweiradsicherheit Nr. 7, Bochum. 1991

/54/ Tibken, M., "Das FAG ABS M3 für Motorräder, ein Beitrag zu mehr Sicherheit beim Motorradfahren". In: 5. VDI-Fachtagung Motorrad, VDI-Berichte 1025, Düsseldorf, 1993

/55/ Donne, G.L., "A Combined Anti-lock Brake System for Motorcycles". Twelfth International Technical Conference on Experimental Safety Vehicles, Göteborg, Vol.2, 1989

/56/ Segel, L., "Demands on Braking Performance and Directional Stability of Motorcycles". In: Sicherheit bei motorisierten Zweirädern, Verlag TÜV Rheinland GmbH, 1981

/57/ Sheppard, D., B.A.K. Hester, S. Gatfield and M. Martin, "Motorcyclists' Use of their Front Brakes". TRRL Transport-and-Road-Research-Laboratory Research-Report Nr. 20, 1985

/58/ Bachmann, T., Bielaczek, C. and B. Breuer, "Untersuchungen zum Reibwert Reifen/Fahrbahn und seiner Inanspruchnahme durch den Fahrer". In: Automobiltechnische Zeitschrift ATZ 97 (1995) Nr. 10

/59/ Post, W., Bayer, B. and B. Breuer, "Kombibremse Motorrad". Deutsche Kraftfahrtforschung und Straßenverkehrstechnik. Heft 289, VDI, Düsseldorf, 1984

/60/ Schmieder, M., Bley, D., Spickermann, M. and V. v. Zeddelmann, "Kraftschlußpotentiale moderner Motorradreifen unter Straßenbedingungen". Abschlußbericht zum Forschungsprojekt FP 1.9206 der Bundesanstalt für Straßenwesen, herausgegeben in der Schriftenreihe der Bundesanstalt für Straßenwesen, Unterreihe Fahrzeugtechnik, Heft F9, Bergisch Gladbach, 1994

/61/ Breuer, B., Präckel, J., Schmieder, M. and A. Weidele, "Motorcycle/Rider/Road - Complex and demanding interfaces. In: Small Engine Technology Conference, Pisa, Vol.1 1993, S. 31-39

EEVC TEST METHODS TO EVALUATE PEDESTRIAN PROTECTION AFFORDED BY PASSENGERS CARS

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ABSTRACT

In 1987 the European Experimental Vehicles Committee has set up Working Group 10 with the task to improve an existing proposal for an EC Directive with respect to pedestrian protection and to coordinate the necessary research. This Working Group finalized its activities in 1994.

This paper gives a general description and background information of the test methods developed by EEVC WG10 for assessing the protection afforded to pedestrians by the fronts of cars in an accident. The test methods are based on three sub-system tests, essentially to the bumper, bonnet leading edge and bonnet top surface. Each of the test conditions are generally based on a car to pedestrian impact velocity of 40 km/h but for the assessment of the leading edge of the bonnet, the test conditions are adjusted to compensate for the influence of vehicle shape. The acceptance levels for the tests are based on the characteristics of the weaker sections of the adult population including the aged, who have been shown to be the most susceptible to injury. The test methods are considered to be appropriate of children, but a separate child head impact test has been included to assess their particular requirements.

INTRODUCTION

In most European countries, unprotected road users like pedestrians account for a significant proportion of the road accident casualties. This was recognized by the European Experimental Vehicles Committee and several studies in this field were performed by Working Groups of EEVC [1,2,3]. Based on this research various recommendations for the front structure design of passenger cars were developed. Moreover, test methods and regulations have been proposed to assess pedestrian protection.

In the Spring of 1987 one of these proposals was discussed by the EEC ad-hoc working group 'Erga Safety' [4]. It was concluded that the basis of the proposal was promising however, additional research was needed to fill up some gaps. The European Experimental Vehicles Committee was asked to coordinate this research and at the end of 1987 EEVC Working Group 10 was set up.

The mandate of this group was 'to determine test methods and acceptance levels for assessing the protection afforded to pedestrians by the fronts of cars in an accident. The test methods should be based on sub-system tests, essentially to the bumper, bonnet leading edge and bonnet top surface. The bumper test should include the air dam; the bonnet leading edge test should include the headlight surround and the leading edge of the wings; the test to the bonnet top should include the scuttle, the lower edge of the windscreen frame and the top of the wings. Test methods should be considered that evaluate the performance of each part of the vehicle structure with respect to both child and adult pedestrians, at car to pedestrian impact speeds of 40 km/h. The different impact characteristics associated with changes in the general shape of the car front should be allowed for by variations in the test conditions (e.g. impact mass and velocity, direction of impact)'.

Work programme

EEVC WG10 started its activities in January 1988. Both automobile industry and research institutes were represented in the working group. A programme was set-up intended to develop the required test methods as described by the mandate.

The studies necessary to develop test methods have already been presented in a first report of EEVC WG10, presented to the 12th ESV Conference in 1989 [5]. These development studies included full scale dummy tests, cadaver tests, accident reconstructions, analysis of accident data and computer simulations. Furthermore the developed test proposals had to be tested against representative cars of current designs to determine the feasibility of the proposals. The compatibility with existing regulations, other safety features and basic operational requirements for cars was assessed. Figure 1 shows the work programme.

These studies were performed in 1989/1990 by a European consortium acting under contract to the European Commission and under the auspices of EEVC Working Group 10. The consortium consisted of BASt, INRETS, LAB/APR, TNO and TRL.

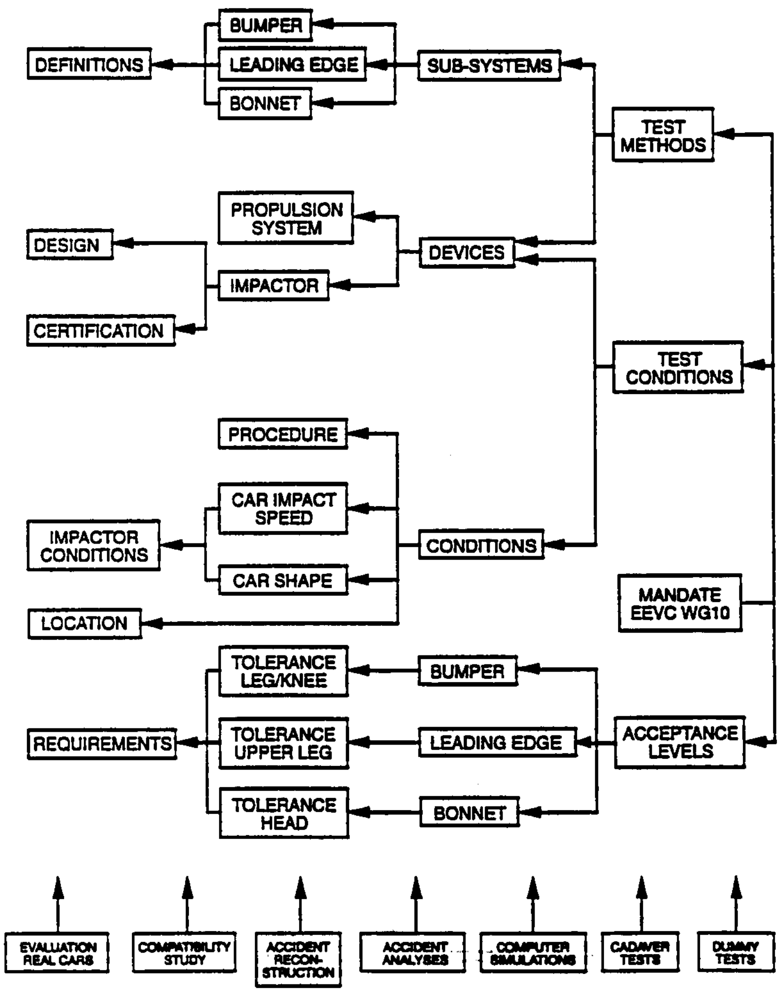


Figure 1. Mandate and work of EEVC Working Group 10.

The studies were completed in June 1991 and were summarized individually in technical reports [6-11]. The summary report [12] includes an Annex called "Frontal surfaces in the event of impact with a vulnerable road user - proposal for test methods". Based on this document, EEC/DGIII has drafted an extension to the existing Council Directive 74/483/EEC ("external projections") for inclusion of the EEVC sub-system test methods for pedestrian safety [13]. This work was also summarized in a second EEVC WG10 report, presented to the 13th ESV Conference in 1991 [14].

The EEVC Main Committee decided to extend the mandate of WG10 in order 'to consider what work would be necessary to support the results obtained from the EC study and to finalize the work programme'. WG10 restarted at the end of 1991 and since then the proposed test methods, including sub-system impactors, have been evaluated thoroughly.

The members and organisations involved in the WG10 activities during the period 1991/1994 are presented in Appendix I.

The third and final report of EEVC WG10 [15] focused especially on the changes and improvements with respect to the previous version of the proposed test methods, as described in [12] and [14]. The Annex "Frontal surfaces in the event of impact with a vulnerable road user - proposal for test methods" was up-dated. Also general background information was given and choices explained. The current paper summarizes this work. Activities performed by the former members of WG10 since the end of 1994, will be presented as well.

TEST METHODS

In this section changes and improvements with respect to the previous version of the proposed test methods, as described in [12] and [14], will be presented. Also general background information will be given and choices that were made will be explained.

General

Three sub-system tests are prescribed; legform to bumper, upper legform to bonnet leading edge and headform to bonnet top. The outer car structure representing these test areas is described in the test method. Attachments to these structures, for instance license plates, are also subject of these definitions and should be tested as such.

The bonnet top is divided in two areas; a forward area for a child headform impact and a rearward area (i.e. close to the windscreen) for an adult headform impact. Wrap around distances of 1000-1500 mm and 1500-2100 mm are defined for the boundaries of these two bonnet top test areas. The windscreen and A-pillars were not part of the mandate of WG10 and therefore not included as test area (the lower windscreen frame however is included).

The width of each test area is divided in 3 equal parts; a left and right outer part and a middle part. The side of the test area's is also defined by means of the 'corners' of the bumper and the leading-edge, and the 'side' of the bonnet top.

For vehicles with a special shape, exclusions are included in the test methods. For instance no headform test should be performed if the lower windscreen frame is located forward of the 1000 mm wrap around distance. No upper legform test needs to be performed if the determined kinetic energy of impact is 200 J or less, which can occur if the bonnet leading edge is located low and the bumper protrusion (i.e. bumper lead) is relatively large. If the bumper is located high and close to the bonnet leading edge, an upper legform to bumper test rather than to the bonnet leading edge is possible.

A minimum of three legform to bumper tests should be performed, one on each of the three bumper parts. A minimum of three upper legform to bonnet leading edge tests should be performed, one on each of the three bonnet leading edge parts. A minimum of nine tests should be performed with the child headform impactor, three tests each on the three forward bonnet top parts. A minimum of nine tests should be performed with the adult headform impactor, three tests each on the three rearward bonnet top parts. Table 1 summarizes the total number of tests per test area. The impact location should be on a 'position most likely to cause injury' in order to assess the injury risk for pedestrians. This position should be specified by the authorities after examining the vehicle and drawings supplied.

The tests should be performed on different types of the vehicle structure, which means that it is not necessary to perform a test on a similar (read: symmetrical) construction in another part of the test area, even though this would be a 'high-injury-risk' location (e.g. bumper attachment in left and in right outer part of bumper test area).

Furthermore, the distance between different tests in one test area should be equal or larger than the diameter of the impactor used. This means for instance that the distance between the impact location of the test on the left outer part of the bumper and the impact location of the test on the middle part of the bumper should be at least 132 mm (i.e. diameter of legform impactor).

The distance between the impact location and the side of the vehicle should be equal to or more than the half diameter of the impactor used, to avoid a glance-off impact. For tests to the windscreen lower frame, contact of the headform impactor with the glass is not allowed before impacting the vehicle structure.

The constraints indicated above could lead to fewer impacts than described in Table 1, for instance if the adult bonnet top area is very small.

The vehicle or sub-system of the vehicle should be positioned such that it represents an impact between the vehicle, loaded with two occupants, and a pedestrian at an impact speed of 40 km/h. Brake diving is not simulated, because the car may not be braking at impact and many modern suspension systems are designed to reduce or eliminate brake dive. The suspension should be set for a driving speed of 40 km/h in normal running conditions, specified by the manufacturer, especially for vehicles with an active suspension or a device for automatic levelling.

In the legform to bumper test the vehicle or sub-system may be raised to avoid contact of the legform with the ground (see Figure 2). Computer simulations showed that foot to ground friction appears to have only a minor influence on the loads generated in the leg during an impact. This shows that foot to ground friction forces may be omitted from a bumper sub-system test [14].

If the propulsion system used can not achieve the required impact angles necessary for the upper legform to bonnet leading edge test or for the headform to bonnet top test, the rear end of the vehicle may be raised to obtain

the correct impact angle. However, this should not influence the performance of the vehicle (for instance by translation or rotation of the engine, creating additional space between engine and bonnet).

Table 1.
Total number of tests per test area

TEST AREA	left outer part	middle part	right outer part	total
bumper	1	1	1	3
leading edge	1	1	1	3
bonnet top - child	3	3	3	9
bonnet top - adult	3	3	3	9
total	8	8	8	24

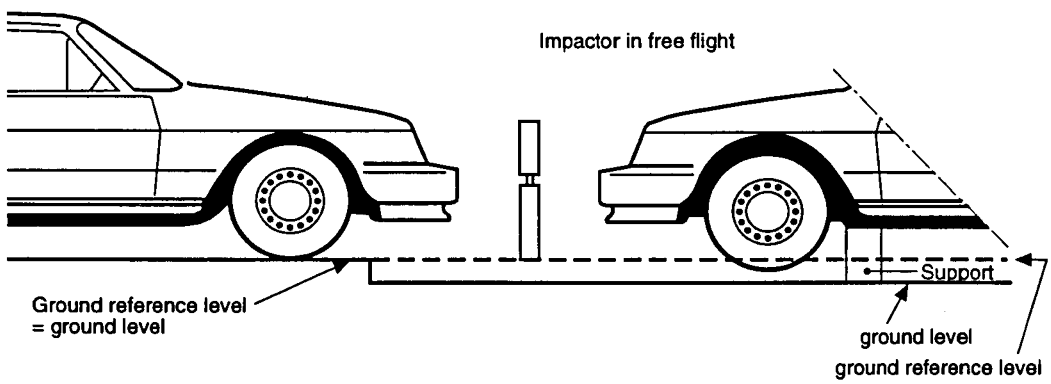


Figure 2. Legform to bumper test for complete vehicle in normal ride attitude (left) and for complete vehicle or subsystem mounted on supports (right).

It is possible that the vehicle to be assessed incorporates special devices designed to protect vulnerable road users, for instance a bonnet top which is lifted when the leading edge is impacted by the pedestrian. These (dynamic) systems should be active during the appropriate test. If they are activated in real accidents by a mechanism outside the considered test area (e.g. bonnet lifting is activated by sensor in bumper), they should be activated correctly during or before the test by an external trigger or manually. It is the responsibility of the applicant for approval to show that the device is activated (fast enough) in a real accident.

The type of propulsion system is not prescribed, however free flight impacts at 40 km/h with masses between 2.5 kg and 13.5 kg should be possible. The upper legform impactor should be mounted to the propulsion system by a torque limiting joint, to prevent damage to the system, and should be guided throughout the impact. This test requires impacts at 20 to 40 km/h at effective impactor masses (including guidance components) of 9.5 to 17.7 kg.

Legform to bumper test

The original impactor that has been developed by INRETS for the bumper sub-system test was chosen to represent an adult leg being impacted from the side. Accident studies have shown that in accidents at speeds up to 40 km/h, adults and particularly the aged, seem to be more at risk than children to leg injury that may result in permanent disability [14].

Development of test method and impactor - Since the extension of the WG10 mandate, a lot of effort has been spent in the evaluation and improvement of the legform impactor [16]. Computer model simulations showed good results of the leg-model when compared with a complete dummy-model, if the bumper impact occurs below the knee level. With impacts above the knee level the leg-model showed somewhat lower responses [17]. It is felt that the test procedure allows for evaluation of car bumpers at 500 mm above ground level or below (if the bumper is located at 600 mm from the ground level, the upper leg test procedure applies).

The legform impactor has been used by INRETS in several tests with different passengers cars. These tests did not show any important problems concerning durability and repeatability. Tests on the same car with different bumper heights showed the sensitivity of the test method and impactor design to this parameter which is directly related to the risk of knee injuries [16]. Large differences in knee bending angle and knee shearing displacement were also found when the bumper is impacted in the middle (far from the bumper attachment) or in front of the bumper fixation, which is a much stiffer area.

TRL [18] has evaluated the test procedure and concluded that the prescribed procedure was clear and easy to follow. It was stated that the number of tests required, combined with the selection of points most likely to cause injury, gives a reasonable coverage of the bumper. Coefficients of variation for a test series on a simulated vehicle were 4% for bending, 9% for shear and 4% for acceleration. It was concluded that the impactor design has a robust appearance. Several recommendations were given to further improve the impactor design and were included in the latest version.

BASt [19] performed tests according to the EEVC method, using a different propulsion system to INRETS. BASt concluded that the definitions and corresponding measurements on the car were simple. The durability of the impactor was good. A statement on repeatability of the test method could not be given, but is was found that it is not easy to keep inside the tolerances for impact height and vertical impact angle. However, BASt used a free flight distance of 1 m for the impactor, as described in earlier versions of the test method, while no minimum distance is prescribed in the latest version.

The dimensions, masses and moment of inertia specifications of the legform impactor have been improved and are based now on measurements from Robbins for a 50th percentile male [20]. A flesh-simulating foam has been selected ('Confor-foam') and in order to improve repeatability a cylindrical shape has been defined for this foam. The instrumentation has been improved; the angles between upper and lower leg are measured directly now, rather than by a non-linear cam mechanism. The knee protection criteria, which are bending angle and shearing displacement, are calculated from these measured angles. A calculation method has been defined by WG10.

A lot of effort has been spent in the optimization of the characteristics of the deformable elements to control the lateral bending and shearing motion of the knee joint. WG10 considered also an alternative TRL knee design, in which the shearing is controlled by a leaf spring. The specifications of the legform are also fulfilled by this second design. Evaluation of the prototype design has been performed by BASt [21] and TNO [22]. BASt concluded that the TRL legform impactor showed satisfactory results and meets the requirements of an acceptable test device. However, they observed oscillations in the system, that should be damped by improvements to the prototype. TNO concluded that the repeatability was good. Oscillations in the system were also found by TNO and were further analyzed using a MADYMO mathematical model of the legform. Improvements have been proposed.

Dynamic and static certification procedures have been developed for the legform impactor.

Impactor - The legform is 926 mm long and weighs 13.4 kg. It consists of two foam and skin covered rigid segments (see Figure 3) representing the lower leg (tibia and foot) and upper leg (femur) of an adult, connected by a simulated knee joint that will rotate and translate laterally. The motion of the knee joint is resisted by deformable elements, which are replaced after each test.

The legform is instrumented by angular transducers to measure the relative position of femur and tibia to each other. Additionally, an accelerometer is fitted to the non-impact side of the tibia, close to the knee joint (see Figure 3).

Test method - The impact velocity of the 13.4 kg legform impactor when striking the bumper in 'free flight' is equal to the vehicle/pedestrian impact speed (40 km/h or 11.1 m/s). The impact direction is parallel to the

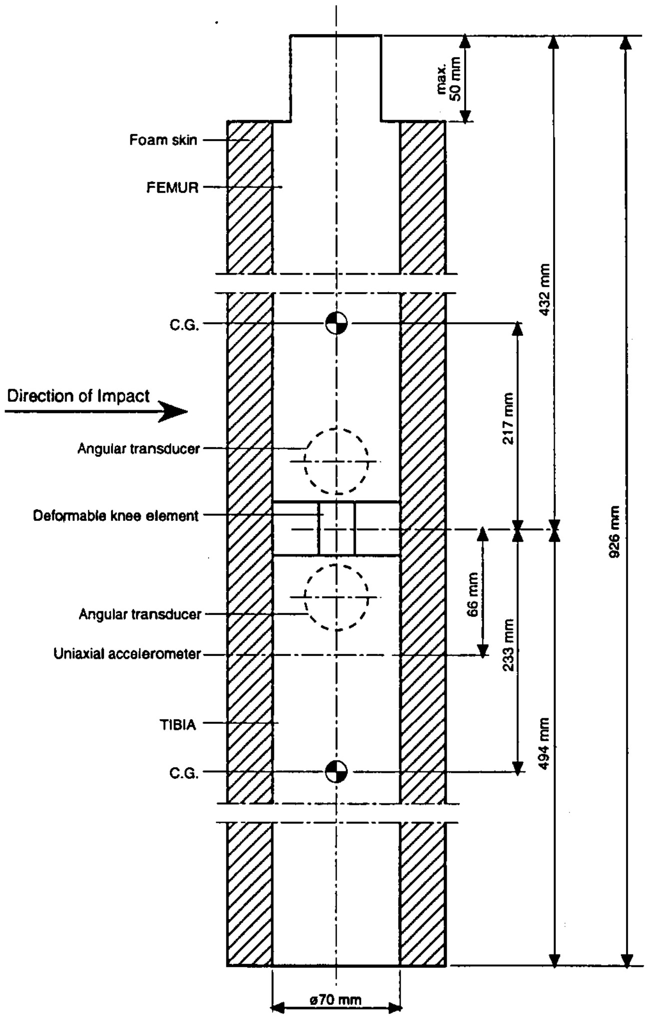


Figure 3. Legform impactor.

longitudinal vehicle axis, with the legform impactor vertical. Small tolerances to these directions are allowed. The impact position in the 'horizontal' direction is already described under 'general'. The impact position in the 'vertical' direction is prescribed by the dimensions of the legform impactor and by the bumper height; the bottom of the impactor is at ground level at the time of first contact with the bumper (see also Figure 2).

Acceptance levels - Soft tissue 'crush' injuries caused by flat bumpers were discussed within WG10. Based on an expert classification [23], it was decided to give first priority to avoidance of knee ligament rupture and bone fractures.

The proposed acceptance levels are 15 degrees of lateral knee bending rotation, 6 mm of lateral knee shearing displacement and 150 g lateral acceleration at the top of the tibia. The 150 g acceleration value is aimed to limit the contact force applied to the tibia. The bending angle is associated with the bending moment at knee level and assesses the risk for ruptures of the knee ligaments. The acceptance level is based on cadaver tests [24].

In the second report of WG10 [14] an angle of 5 degrees was mentioned as acceptance level for shear rotation, which was based on impact forces of 4 kN and lateral shear displacements of 5-6 mm in cadavers. According to autopsies made after these tests it was found that rupture of the anterior cruciate ligament (ACL) is the typical injury associated with shearing mechanisms. When pulled it can be considered that about 25-30 mm of the ligament is lengthened and with an elongation at rupture of 20% [25], this corresponds to a limit of 5-6 mm for shearing displacement.

Upper legform to bonnet leading edge test

Full-scale tests have shown that in a pedestrian accident the leading edge of the bonnet most frequently strikes the femur and pelvis of adults and the pelvis, abdomen or femur of children. Reports from European accident studies have shown that for accidents at speeds up to 40 km/h pelvic/femur fractures of AIS 3+ were more frequently to adults than to children. Child abdominal injury of AIS 3+ was rarely seen at speeds of 40 km/h or less [14]. As a consequence the impactor that has been developed by TRL for this sub-systems test represents a segment of an adult femur.

Development of test method and impactor - Since the extension of the WG10 mandate, some improvements have been included in the upper legform design. The strain gauges are covered to protect them against damage. A test programme has been performed to evaluate the temperature/time influence on the characteristics of the flesh simulating foam and to evaluate the durability of the foam [26]. It was concluded that the influence of the temperature is limited within the prescribed range for testing. Furthermore, it was concluded that the flesh deteriorates slightly and becomes slightly softer with repeated testing, increasing the measured forces and bending moments. Therefore it is recommended to use new flesh before each regulatory test.

In 1992, TRL evaluated the existing version of the test method and concluded that the test procedure , vehicle measurement and look-up methods proved easy to understand and use [27]. Some improvements, however, were proposed by TRL and accepted by WG10; a definition of the corner reference points and a minimum

impact distance from these points, and an additional requirement to cover repairs between tests.

BASt [19] performed tests according to the EEVC method. BASt concluded that the definitions and corresponding measurements on the car were simple. The durability of the impactor was good. The repeatability of the test method was considered good, with only small differences in test results (i.e. 2%) between two similar tests.

However, in 1995 BASt performed again a series of tests and found a 'hidden load path' from the impact point at the front to parts of the impactor behind the load cells.The foam seems stiff enough dynamically to transmit these forces. Historically, the problem was not observed in early prototypes so it probably arose from design changes to improve the attachment method and appearance of the foam. Based on these findings and their own reanalysis TRL has improved the upper legform by reducing the area of the foam sheets that cover the impactor, so that there are gaps between the foam and the support system behind the load cells and the revised design no longer exhibits this problem.

A static calibration procedure has been developed to assess the sensitivity of the strain gauges. The dynamic certification procedure has been improved to obtain a more representative impact speed and impactor responses.

Impactor - The upper legform consists of a 350 mm long tube mounted at either end through load cells to a support frame, which is in turn mounted through a torque limiting joint to a propulsion system (see Figure 4). Supplementary weights can be attached to the support frame (i.e. rear member) to meet the impact conditions of the car under test. Strain gauges are attached to the impactor tube to measure bending moments. The impactor is covered by foam and a skin at the front side. The mass is dependent upon the general shape of the car front (see 'Test method').

Test method - The impact conditions of the upper legform to bonnet leading edge test are dependent on the shape of the vehicle to be tested.

The bonnet leading edge height and the bumper lead are determined and based on these values the impact velocity (20-40 km/h), the impact angle ($10-47.4^0$) and the impact energy are determined (see Figures 5, 6 and 7). The impact mass (9.5-17.7 kg) is calculated from the impact velocity and energy (i.e. $2E/V^2$), and small adjustments are allowed to obtain standard increments of adjustable mass.

The impact direction is in the fore/aft vertical plane of the vehicle. Small tolerances to this direction are allowed. The impact position in the 'horizontal' direction of this guided impact is already described under 'General'. The centre of the impactor should be aligned with the bonnet leading edge (see Figure 8).

Acceptance levels - Based on pedestrian accident reconstructions and confirmed by available results from cadaver tests [8], acceptance levels are proposed by EEVC WG10: a total (instantaneous) force of 4 kN and a bending moment of 220 Nm (measured at one or more strain gauges).

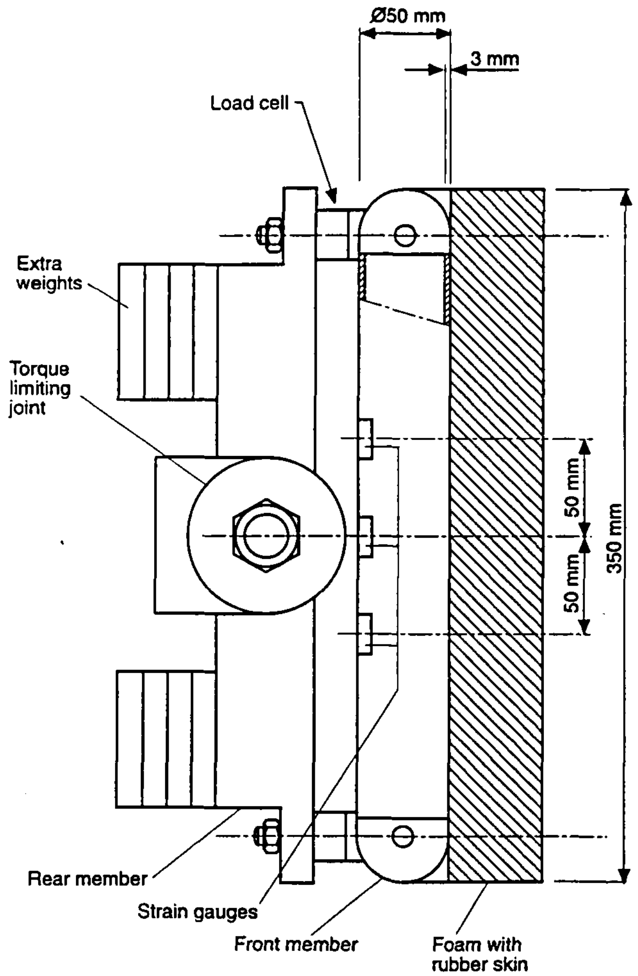
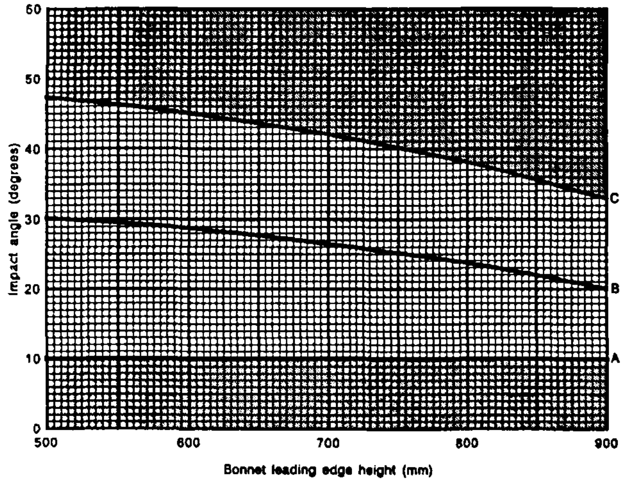


Figure 4. Upper legform impactor.



Key:-

A ≤ 0 mm bumper lead
B = 50 mm bumper lead
C ≥ 150 mm bumper lead

Figure 5. Impact angle of upper legform impactor with respect to vehicle shape.

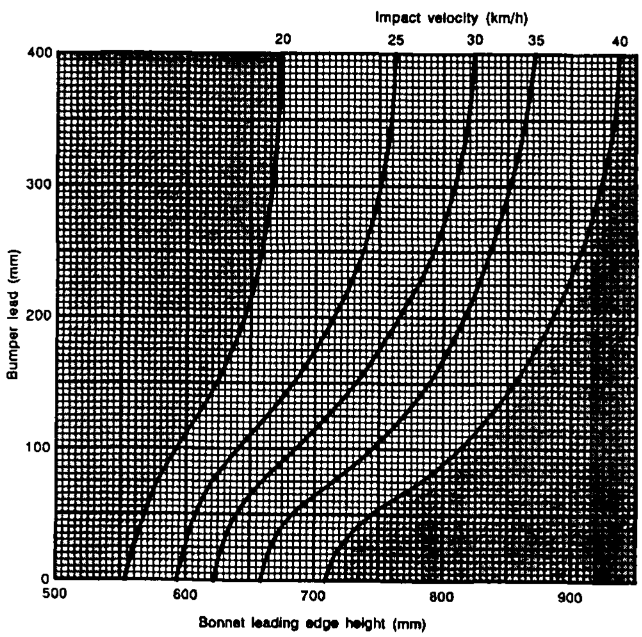
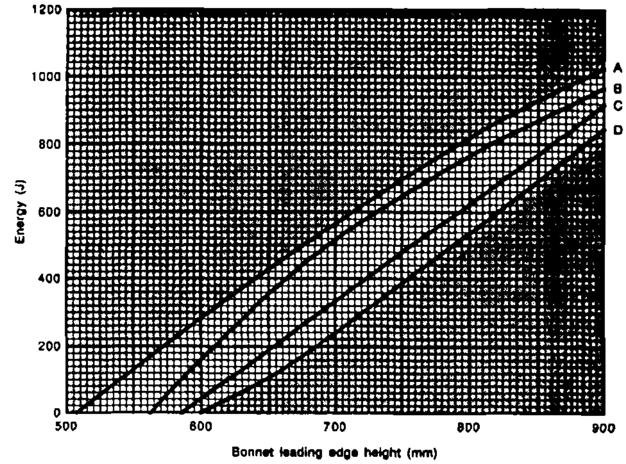


Figure 6. Velocity of upper legform impactor with respect to vehicle shape.



Key:-

A ≤ 0 mm bumper lead
B = 100 mm bumper lead
C = 225 mm bumper lead
D ≥ 350 mm bumper lead

Figure 7. Kinetic energy of upper legform impactor with respect to vehicle shape.

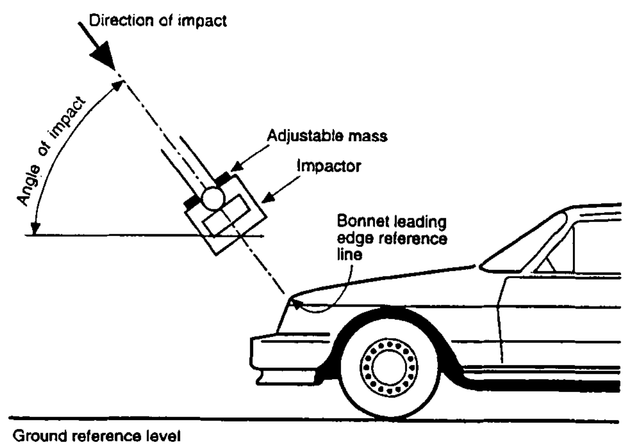


Figure 8. Upper legform to bonnet leading edge test.

Headform to bonnet tests

Accident data have shown that the head is the body region most frequently suffering from life threatening injuries in both child and adult pedestrian accidents [14]. As a consequence of these findings two assessments are included in this sub-systems test. One is based on an impactor representing a child headform to evaluate the forward section of the bonnet and wings and the second is based on an adult headform to assess the rear of the bonnet, wings and the scuttle.

Development of test method and impactors - Since the extension of the WG10 mandate, small changes were included in the design of both headforms. The centre of gravity of the headform and the accelerometer are now located more accurately in the centre of the sphere. Furthermore the (end of the) skin is connected to the sphere to avoid rotation of the sphere inside the skin during an impact. A test programme has been performed to evaluate the influence of temperature and humidity on the impact responses of the skin [19]. It was concluded that the temperature, within the prescribed range, has no influence on the headform responses. A 5-10% increase in headform acceleration could be seen when the skin was soaked for 4 hours in water. It was recommended to store the skin in a humidity-controlled room.

TRL has evaluated the test method and concluded that the procedures for identifying the test area were clear and easy to follow, the selection of test sites and the requirements for setting up and testing the car were also clear and easy to follow [28]. Only one point in the test procedure was found to require clarification; the difference between the centre of the dent on the bonnet and the line of free flight of the headform. Based on the TRL recommendation, WG10 defined the 'point of impact' as the 'point of first contact'. It was concluded that the repeatability of the impactors and test method was good.

The dynamic certification procedure has been improved, no different headform mass is required any more in the certification test. Moreover, the skin is certified now at several locations on the circumference.

Impactor - Both of the headforms developed by BASt are of spherical shape and made of a semi-rigid material, covered by a rubber skin (see Figures 9 and 10). An accelerometer is mounted in the centre of the sphere. The adult impactor has a diameter of 165 mm and weighs 4.8 kg. The child impactor has a diameter of 130 mm and weighs 2.5 kg.

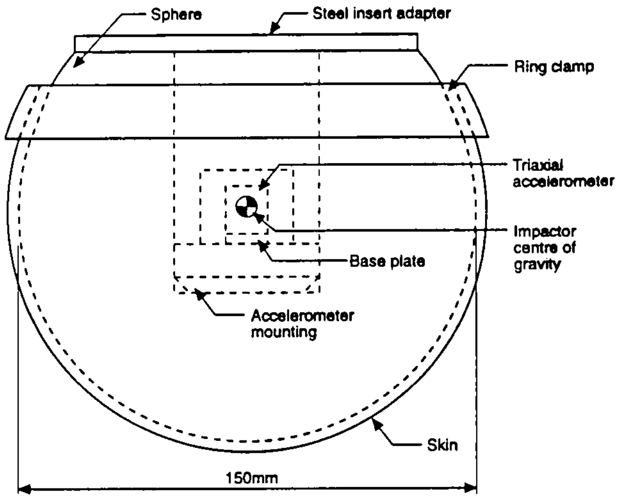


Figure 9. Adult headform impactor.

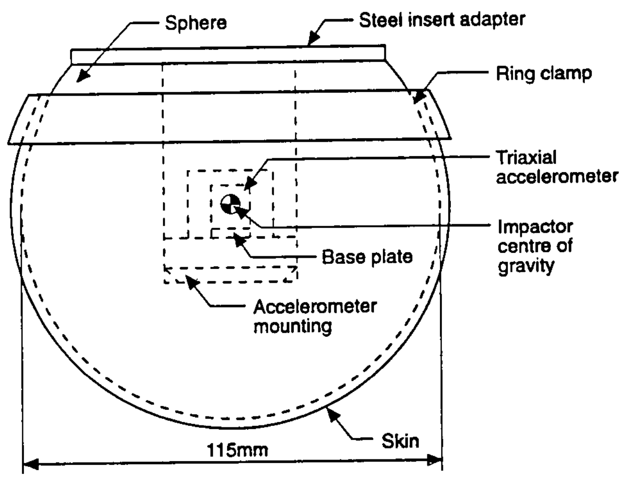


Figure 10. Child headform impactor.

Test method - It is known from cadaver tests and mathematical model simulations that the head to bonnet impact velocity can be up to 20% higher than the vehicle impact speed [14]. This would mean a headform impact velocity of 48 km/h for a simulated 40 km/h pedestrian accident. EEVC WG10 decided to describe an impact velocity of 40 km/h for both the child and the adult headform to bonnet tests, because:

headform impactor tests to a car body shell with the internal components removed have shown that it would be difficult to achieve a HIC value of less than 1000 from headform impact velocities of 45 km/h or greater;

there is a trend to design passenger cars with a less horizontal bonnet top, resulting in head impact velocities similar to the vehicle impact speed.

The direction of impact is rearward and downward, at an angle of 50 degrees to the horizontal for the child headform tests and at an angle of 65 degrees for the adult headform tests. The impact direction is in the fore/aft vertical plane of the vehicle. Small tolerances to these directions are allowed.

The impact point on the car is defined by the point of first contact between the circumference of the headform impactor and the bonnet top. For tests to the windscreen lower frame the headform impactor should not contact the windscreen glass before impacting the vehicle structure.

Acceptance levels - Rotational accelerations have been discussed by EEVC WG10, however, it was concluded that insufficient data is available to propose an acceptance level. Therefore only linear accelerations are measured and used; the proposed acceptance level is that the Head Performance Criterion, calculated from the resultant acceleration of the headform accelerometer time histories shall not exceed 1000.

PERFORMANCE OF CURRENT VEHICLES

The performance of current vehicles with respect to the proposed test methods has been evaluated also by WG10 in several programmes. This aspect was also included in the work programme (see Figure 1) in order to assess the feasibility of the test methods.

Tests performed by INRETS showed that lowering the bumper of a medium size mass-production car by 88 mm can decrease the bending angle and shearing displacement in the legform to bumper test by more than 50%. It is concluded that it is possible to optimise the design of car front ends in terms of shape and materials to improve the protection of pedestrians against leg injuries [16].

Leg-to-bumper tests performed by the BASt according to the EEVC test method on three different cars, showed that none of the cars passed all three requirements in all three bumper tests. However, every car showed in at least one test that one or two requirements can be fulfilled [19]. It should be remembered that these cars are not designed for pedestrian protection.

TRL performed three tests on the bonnet leading edge of four popular European cars [27]. For one of the three tests to each car a 'weak' test point was selected rather than the point most likely to cause injury. This was done to get a measure of the best performance achieved by current cars. All cars exceeded the proposed acceptance levels. All four cars had heavy under-bonnet reinforcement which was carried right to the bonnet leading edge. Relatively simple changes to the car/bonnet design, such as moving the reinforcement back from the leading edge, would probably be sufficient to pass the test [27].

Upper legform to bonnet leading edge tests on three different cars have been performed by the BASt. Large differences in test results were found between tests on different points of one car and between different cars. All requirements were passed in one test on one of the 3 cars [19].

In 1992 BASt performed a series of headform impactor tests on 9 (popular) cars [29]. Only the bonnet (i.e. the moving part) was used as test area and not the wings, scuttle, etc. All points which seemed to be dangerous were tested with no restriction to the number of tests in each sub-area (as described by the EEVC test method). In 42% of all tests with the adult headform, the HIC was less than 1000, and in 31% the HIC was between 1000 and 1500. For the child headform tests, only 14% resulted in a HIC value below 1000, while in 48% of these tests the result was between 1000 and 1500. Large differences between cars were found; from 83% below HIC 1000 for one car to 100% above HIC 1500 for another car. By means of double integration of the acceleration time histories, it was found that for obtaining a HIC $\leq$ 1000 in the child head impact test a minimum distance of 50 mm is required between the bonnet and a stiff under-bonnet surface, for the adult head impact test 70 mm is sufficient [30]. Theoretical studies showed that with even less distance to the substructure the requirement can be met [31].

TRL performed headform impacts on 4 cars according to the EEVC test method [32]. Since the adult test area was narrow on all cars and to reduce costs of testing, it was decided to reduce the number of adult headform tests. None of the tests resulted in HIC values below 1000, however, several test sites came close to passing the requirements, taking the non-linear effects of the HIC calculation into account. One car was close to passing at most test sites. Results of headform-to-bonnet tests on a 4x4 utility vehicle with an aluminium bonnet were discussed within WG10. In one out of four child headform tests and one out of four adult headform tests the requirement was fulfilled.

Several test programmes to current cars have shown that it is technically possible to fulfil the requirements proposed in the EEVC test method with new car designs. Several design guidelines have been developed, based on the experience gained in these programmes [33].

Bull-bars

TRL and BASt performed several tests on so-called bull-bars or crash-bars fitted to the front of off-road vehicles. Tests with the upper legform impactor [34, 35] and tests with the child headform impactor [35, 36] showed how pedestrian unfriendly these bent and welded steel tubes are.

Tests with the legform impactor showed, surprisingly, a decrease in bending angle and shearing displacement compared with the same off-road vehicle without a crash-bar. However, the tibia acceleration was increased indicating the higher stiffness of the crash-bar [35].

In Germany the percentage of off-road vehicles in the total number of cars is above 1% and approximately 62% are equipped with crash-bars. It is suggested that the proposed Directive should not only cover manufacturer mounted crash-bars, but be extended to cover also crash-bars fitted as after-market accessories [34].

COST BENEFIT STUDIES

Introduction of the EEVC pedestrian test methods as a Directive should reduce the large number of killed and seriously injured pedestrians in Europe. Indications for savings were already given in the previous reports of WG10 [12, 14].

Since then several members of EEVC WG10 have been involved in cost-benefit studies concerned with the proposed Directive, however these studies were not part of the mandate of WG10 and were not extensively discussed. Further details can be found in [37, 38, 39, 40].

CONCLUSIONS

EEVC Working Group 10 started its activities in 1988 with the task 'to determine test methods and acceptance levels for assessing the protection afforded to pedestrians by the fronts of cars in an accident. The test methods should be based on sub-system tests, essentially to the bumper, bonnet leading edge and bonnet top surface'. The studies necessary to develop test methods were already presented in a *first* report of EEVC WG10, published in 1989 [5]. The first results of the studies and the first version of the test methods was described in the *second* WG10 report, published in 1991 [14].

Since then the proposed test methods, including the sub-system impactors, have been evaluated thoroughly. Improvements have been included in the design of the impactors and in the test procedures. The procedures seem easy to follow and the test methods appear to be reproducible and sensitive to vehicle design changes. These developments are described in the *third* report of EEVC WG10 [15].

The headform and upper legform impactors are now available on a commercial basis. Prototype legform impactors have been available for some time and it is expected that a final version could be available in the summer of 1996.

Several test programmes to current cars have shown that it is technically possible to fulfil the requirements proposed in the EEVC test method with new car designs, however, a phased-in introduction of the requirements seems feasible. It is suggested that the proposed regulation to be extended to cover also crash-bars or bull-bars fitted as after-market accessories, since several test programmes have shown how pedestrian unfriendly these (steel) bars are.

The pedestrian protection methods discussed in this paper are only intended for the fronts of cars up to a wrap around distance of 2100 mm or to the base of the windscreen. However, other parts of cars are also responsible for severe or fatal pedestrian injuries: the A-pillar, windscreen and upper windscreen frame. Buses and coaches, heavy good vehicles and motorcycles are also involved in a considerable number of pedestrian accidents. Thus, further research is required in these area's.

ACKNOWLEDGMENTS

The work presented in this paper has been conducted by the (former) members of EEVC WG 10 (see Appendix 1).

REFERENCES

1. European Experimental Vehicles Committee:
Pedestrian injury accidents.
Presented to the 9th ESV Conference, Kyoto, November 1982.

2. European Experimental Vehicles Committee:
Cycle and light-powered two-wheeler accidents.
Presented at the 9th IRCOBI Conference, Delft, September 1984.

3. European Experimental Vehicles Committee:
Pedestrian injury protection by car design.
Presented to the 10th ESV Conference, Oxford, July 1985.

4. Commission of the European Communities:
Frontal surfaces in the event of impact with a vulnerable road user.
Ad-hoc Working Group ERGA Passive Safety, document ERGA S/60, Brussels.

5. European Experimental Vehicles Committee:
Study of test methods to evaluate pedestrian protection for cars.
EEVC Working Group 10 report, presented to the 12th ESV Conference, Gothenburg, May 1989.

6. Janssen, E.G., Nieboer, J.J.:
Protection of vulnerable road users in the event of collision with a passenger car, Part I - Computer simulations.
TNO Report No. 75405002/I under Contract No. ETD/89/7750/M1/28 to the European Commission, December 1990.

7. Janssen, E.G. et al.:
Protection of vulnerable road users in the event of collision with a passenger car, Part II - Sub-systems test method evaluation and compatibility study.
TNO Report No. 75405002/II under Contract No. ETD/89/7750/M1/28 to the European Commission, December 1990.

8. Lawrence, G.J.L. et al.:
Development of a bonnet leading edge sub-systems test to assess protection for pedestrians.
TRRL report under Contract No. ETD/89/7750/M1/28 to the European Commission, January 1991.

9. Glaeser, K.-P.:
Development of a Head Impact Test Procedure for Pedestrian Protection.
BASt report under Contract No. ETD/89/7750/M1/28 to the European Commission, June 1991.

10. Cesari, D., Alonzo, F.:
Assessment of Test Methods to evaluate the protection afforded to pedestrians by cars.
INRETS report under Contract No. ETD/89/7750/M1/28 to the European Commission, December 1990.

11. Brun-Cassan, F.:
Assessment of Test Methods to evaluate the protection afforded to pedestrians by cars - Compatibility.
APR report under Contract No. ETD/89/7750/M1/28 to the European Commission, July 1991.

12. Commission of the European Communities:
Summary of the work of the consortium developing test methods to evaluate the protection afforded to pedestrians by cars (including test proposals).
European Commission Study Contract No: ETD/89/7750/M1/28, July 1991.

13. Commission of the European Communities:
Draft proposal for a Council Directive adapting to technical progress Council Directive 74/483/EEC relating to the external projections of motor vehicles including their effect on pedestrians.
Document III/4025-92, Brussels, April 1992.

14. European Experimental Vehicles Committee:
Proposals for test methods to evaluate pedestrian protection for cars.
EEVC Working Group 10 report, presented to the 13th ESV Conference, Paris, November 1991.

15. European Experimental Vehicles Committee:
Proposals for methods to evaluate pedestrian protection for passenger cars.
EEVC Working Group 10 report, November 1994.

16. Cesari, D. et al.:
Optimization of pedestrian leg injury protection using a biofidelic human leg.
Presented at the 1994 International Conference on the Biomechanics of Impacts, Lyon, September 1994.

17. Cesari, D. et al.:
Subsystem test for pedestrian lower leg and knee protection.
Presented to the 13th ESV Conference, Paris, November 1991.

18. Lawrence, G.J.L., Hardy, B.J.:
Evaluation of the leg to bumper impactor proposed for the EEVC pedestrian impact test procedure.
TRL Unpublished Project Report PR/VE/66/93, S220C/VF, 1993.

19. Zellmer, H.:
Evaluierung des Prüfverfahrens der EEVC WG10 zur Bestimmung der Fußgängerverträglichkeit von Pkw-Frontflächen (Evaluation of the EEVC WG10 test methods to assess the protection afforded to pedestrians by the front of cars).
BASt report, July 1994.

20. Robbins, D.H.:
Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family.
Report no. UMTRI-83-53-2, Ann Arbor, 1983.

21. Faerber, E.:
Legform impact tests to evaluate the TRL legform impactor for the EEVC WG10 test procedure for car related pedestrian protection.
BASt report, Bergisch Gladbach, December 1995.

22. Saladin, A.:
Prototype TRL legform impactor evaluation and dynamic certification tests.
TNO report no. 96. OR.BV.011.1/AS, Delft, March 1996.

23. Cavallero, C.:
Inventory of possible injuries on the pedestrian lower-limb level - Personal communication to EEVC WG 10.
INRETS, Marseille, 1992.

24. Cesari, D. et al.:
Mechanisms producing lower extremity injuries in pedestrian accident situations.
Proceedings of the 33rd AAAM Conference, Baltimore, 1989.

25. Yang, J.:
Impact Biomechanics of the Lower Extremity in Traffic Accidents - Development and Validation of a Mathematical Model.
Chalmers University of Technology, Thesis, Gothenburg, March 1994.

26. Lawrence, G.J.L., Hardy, B.J.:
An improved certification method for the pedestrian upper legform impactor.
EEVC WG10 document, 13-9-1994.

27. Lawrence, G.J.L., Hardy, B.J.:
Report on tests using the draft directive for pedestrian protection on cars.
EEVC WG10 document, 25-11-1992.

28. Lawrence, G.J.L., Hardy, B.J.:
Evaluation of the head impactors proposed for the EEVC pedestrian impact test procedure.
TRL Unpublished Project Report PR/VE/34/93, S220C/VF, 1993.

29. Zellmer, H., Glaeser, K.-P.:
Performance of current cars in pedestrian accidents tested with the proposed EEVC head impactor.
BASt report, November 1992.

30. Zellmer, H., Glaeser, K.-P.:
The EEVC WG10 head impact test procedure in practical use.
Presented to the 14th ESV Conference, Munich, May 1994.

31. Okamoto, Y. et al.:
Concept of hood design for possible reduction in pedestrian head injury.
Presented to the 14th ESV Conference, Munich, May 1994.

32. Lawrence, G.J.L., Hardy, B.J.:
Evaluation of four cars using the EEVC pedestrian head impact test procedure.
TRL Unpublished Project Report PR/VE/76/94, S220C/VF, 1994.

33. Lawrence, G.J.L., Hardy, B.J.:
Final report on pedestrian protection test procedures and design.
TRL Unpublished Project Report PR/VE/81/94, S220C/VF, 1994.

34. Lawrence, G.J.L., Hardy, B.J.:
Vehicle crash bars - Assessment of pedestrian injury potential.
TRL Unpublished Working Paper WP/VS/225, S220C/VF, 1992.

35. Zellmer, H.:
Quantifizierung der Gefährdung von Fußgängern durch Frontschutzbügel an Geländefahrzeugen (Assessment of pedestrian protection afforded by crash-bars).
BASt report, Arbeitsprogramm-Nr.: 94 552, August 1994.

36. Zellmer, H.:
Test on crash bars for off-road vehicles with the EEVC WG10 child head form.
BASt report, June 1993.

37. Association des Constructeurs Europeens d'Automobiles:
Pedestrian Accidents in Europe - Developments and Challenges.
ACEA report, Brussels, September 1992, updated September 1993.

38. Lawrence, G.J.L et al.:
Costs and benefits of the EEVC pedestrian impact requirements.
TRL project report 19, S220C/VF, Crowthorne, 1993.

39. Bamberg, R., Zellmer, H.:
Nutzen durch fahrzeugseitigen Fußgängerschutz (Benefits from Vehicle-Pedestrian Protection Measures).
Berichte der BASt, Fahrzeugtechnik Heft F5, Bergisch Gladbach, April 1994.

40. Van Kampen, L.T.B.:
Cost-benefit study concerning car front impact requirements to increase the crash-safety of pedestrians and cyclists.
SWOV report no. R-94-31, Leidschendam, 1994.

APPENDIX I

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ENGINEERING FACTORS AFFECTING THE DESIGN OF MULTI-MODAL CHILD RESTRAINT SYSTEMS

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ABSTRACT

Over 50 years ago, child restraint devices were introduced in motor vehicles. With the advent of Federal Motor Vehicle Safety Standard No. 213 in 1971, child restraint devices, such as hook-type seats which were hooked over or under the vehicle seat back, were eliminated. The function of these early devices was to raise a child to better observe outside of the car and/or to prevent the child from falling on the floor of the automobile during a sharp turn or sudden stop. Since 1 1971, child restraints have been designed to provide safety protection to the child occupant of a motor vehicle. In 1985, child restraints were allowed to be certified for use in motor vehicles and aircraft. The emergence of new model vehicles equipped with passenger side air bags, along with new technologies of vehicle seats and belts, raised some questions about the potential negative effect on the effectiveness of child restraint systems in motor vehicles. Similarly, the effectiveness of child restraint systems may be hampered by technological and design considerations associated with other vehicles' environments such as aircraft and school buses.

This paper discusses some of the critical factors affecting the design of MULTI-MODAL use of child restraint systems (CRS). The paper summarizes the results of a research effort conducted by the National Highway Traffic Safety Administration (NHTSA) to determine the effects of available space for head and knee movement of the child occupant, belt anchor point locations, belt angle and routing on the dynamic performance of surrogate child occupant of various child restraints placed in motor vehicle and aircraft seats. Findings of this testing indicate that the current fleet of motor vehicles has adequate average available space for head and knee displacement. On the other hand, the testing indicates that some belt anchor point locations and belt routing configurations result in excessive displacement of the head and high potential for head injury of the child occupant when restrained in some motor vehicles and aircraft seats. This paper emphasizes the importance of incorporating into the design process the interfacing of child restraints with the passenger compartment environments. Alternative courses of action are presented for providing safety protection for children traveling in motor vehicles and aircraft.

INTRODUCTION

Devices for restraining children in cars were introduced over 50 years ago. These devices were hooked over or under the back of the seat of the vehicle. These "hook-type" devices had two functions: i) one to provide the child with a better observation platform and ii) to prevent the child from ending at the floor of the vehicle during sharp turns or sudden stops. These child restraint devices did not provide safety benefits for the child during a crash. It was not until the mid-1960s, when occupant safety in automobiles was receiving national attention, that the safety benefit of these child seats was questioned. To address this matter, General Motors and Ford developed seats for use by infants and toddlers with the goal of preventing children fatalities and injuries. These seats were designed to manage crash energy and to provide occupant protection.

Along with the development of the new child restraints by GM and Ford, Federal Motor Vehicle Safety Standards (FMVSS) were instituted to require a minimum safety performance of motor vehicles and equipments such as child restraint systems. In March 1970, FMVSS No. 213, "Child Restraint Systems" was published in the Federal Register and became effective on April 1, 1971. Among the requirements of this standard were that: i) securement of the child restraint system on a vehicle seat be accomplished using the vehicle lap belt system only, and ii) restraining of the child be accomplished by the child restraint only. The standard required that the child restraint system distribute the crash forces over the thorax and pelvis of the child and that the restraint withstand a static load of 1000 and 500 pounds for forward- and rear-facing child restraint systems, respectively. The immediate effect of this standard was the elimination of the hook-type of child restraint devices. As a result of the static strength requirements of the standard, the design of child restraint systems evolved to meet the requirements. However, in 30 miles per hour (mph) dynamic testing these restraints were allowing excessive forward head excursion of the child surrogates occupying the restraint.

To remedy the excessive forward displacement of the child's head that may result in the collision of the child's head with the interior of the vehicle, the National Highway Traffic Safety Administration (NHTSA) proposed in 1974 a standard that was based on dynamic testing of child restraint systems. The proposal included the use of anthropomorphic dummies in three tests: i) 30 mph frontal impact allowing a 24" head forward excursion, ii) 20 mph side and rear impacts allowing a 19" head sideways excursion, and iii) 3g load inversion test. This proposal was criticized as being too stringent and would result in the elimination of all untethered child restraint systems from the market, which in turn would negatively affect child safety protection. Because of these reasons and the fact that the test dummies were not developed at that time, the proposal was abandoned and replaced by a May 1978 proposal. The 1978 proposal eliminated the side impact, rear impact and inversion tests previously proposed. The previously proposed 24" forward head excursion requirement was extended to 30" so toddler child restraints that use a shield for thorax protection were not eliminated. Further, testing of toddler child restraints was required only with a three-year-old dummy. Testing with a six-year-old dummy was eliminated from the proposal because the dummy was not developed. In December 1979, NHTSA published a rule in the Federal Register which became effective on January 1981. A 32" head excursion requirement in the rule replaced the 30" proposed in the 1978 proposal. This excursion was extended to avoid the elimination of untethered and shield types of child restraint systems that could not satisfy the 30" head excursion. Child restraint systems, such as the Ford "Tot-Guard" which had an excellent safety record and had been in use for ten years was among those seats that did not meet the proposed 30" head excursion. In summary, the 1979 dynamic standard was modeled to accommodate most of the reasonably well designed child restraint systems at that time.

In 1985, FMVSS No. 213 was amended to provide for certification of child restraint systems for use in aircraft. A rollover inversion test subjected the system, consisting of a three-year-old child surrogate restrained in a child restraint secured in a seat representing the aircraft environment, to separate rotational motions to ensure child containment.

The following discusses the design process and the effects of critical engineering factors on the design of MULTI-MODAL child restraint systems. Emphasis of the discussion is on engineering and safety-related factors associated with the motor vehicle and aircraft environments in which children travel.

DESIGN PROCESS

In gross terms, the process of designing a child restraint system is similar to the design process of other products. In designing a product, engineers generally follow a process consisting of six elements: identification of needs, problem definition, formulation of alternatives, analysis of alternatives, decision of selected alternative(s), specification of selected alternative(s) and communication of the product specification to the public and to the stage of fabrication or construction of the designed alternative(s). As shown in Figure 1, these elements are not sequential, on the contrary they are iterative at any point in the process. Further, many elements of the process are not necessarily solely engineering or technical in nature. For example, a need may be identified or a problem may be defined by owners of child restraints that experience improper fitting or restraining of a specific child restraint system model using a vehicle or aircraft seat/belt configuration.

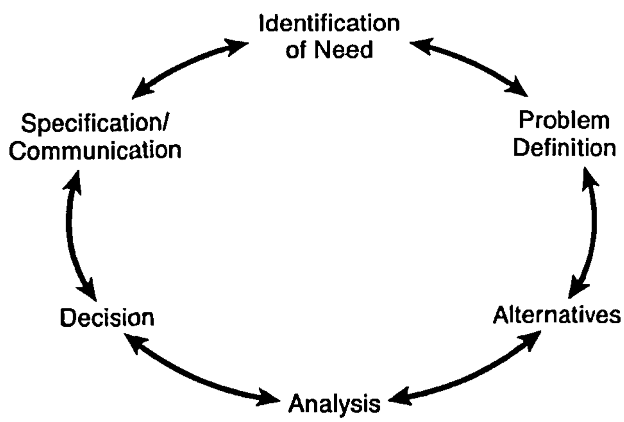

Figure 1. Design Process

Designing a child restraint system for use in various transportation modes presents the engineer with challenging and, in some instances, conflicting factors. Many of these factors are technological and/or societal in nature, and evolve with time. Among the important factors that affect the environment of a child occupant are the seat and belt systems of the vehicle. Various vehicle makes or models have different types of belts, configurations, retractors and anchorage point locations, as well as different types and configurations of air bag systems. Many of these factors are also different from and among various types of aircraft and school buses. An example of societal factors affecting the design of child restraints is the Federal Head Start Program that uses school buses to transport infants and toddlers to day care facilities. This implies designing a

child restraint to be compatible with a school bus and provide adequate child occupant protection during a crash. It is recognized that some of the above listed factors between and among the various modes may be conflicting and therefore it may be difficult to optimize a child restraint's design for several occupant protection environments.

The remainder of this paper focuses on the problem definition and formulation of alternatives to deal with the compatibility of child restraints in motor vehicles and aircraft.

CHILD RESTRAINTS AND MOTOR VEHICLES

The degree of compatibility and misuse of child restraint systems and motor vehicles are important determinants of the level of effectiveness of the child restraints in providing child occupant protection during a crash. Even though a child restraint performs adequately during compliance testing, if it is not used properly in or is incompatible with a motor vehicle, its effectiveness in a real crash may be compromised. To determine the degree of compatibility of child restraints and motor vehicles, NHTSA conducted a research effort at the agency's Vehicle Research and Test Center (VRTC) to survey and assess late model vehicle interior environment. This assessment compared the dimensions and anchor point locations and path of seat belt geometry of vehicles to the specifications of FMVSS No. 213 to determine if they are representative of today's fleet.*(1)(2)

The vehicle interior assessment showed in general the available space for the travel of the child's head and knee during a crash is adequate. Specifically, the assessment indicated that:

- The amount of head room in the front seat (at mid-track position) is slightly higher than the current excursion criterion specified in FMVSS No. 213. However, the mean values of the head and knee available space in the rear seat of vehicles (with the front seat at mid-track position) are less than the head and knee excursion criteria of the standard.
- New model vehicles are equipped with lap and shoulder belt systems in the front and rear outboard seating positions.
- Using a 3- and 6-year-old dummies in belt-positioning booster seats, the vehicle lap/shoulder belt fit survey identified a range of anchorage point locations for the shoulder portion of the vehicle belt system.
- The seat backs of late model vehicles are on the average 25° off the vertical and the seat base angle is 15° off the horizontal when compared with the FMVSS No. 213 test seat assembly that is representative of the 1970 vehicle seats.
- Seat cushions of the late model vehicles are stiffer than the ones of the test bench seat.
- The seat back of the test bench seat assembly is flexible as compared to the rigid seat back of the rear seat of vehicles -- where children are recommended to be placed when being transported in motor vehicles.

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* Numbers in parentheses indicate references at end of text.

The research however showed that the performance of the child restraint is sensitive to the location of anchor points and routing of the vehicle belt system. The authors recognize that an optimum compatibility is not easy to achieve for all child restraints and occupant environments, especially because the vehicle belt anchorage points locations and routing are also required to be optimized for adult passengers.

It is noted that the incompatibility of child restraints and motor vehicles has been a concern of the child safety community for a very long time. The Society of Automotive Engineers (SAE) recognized this problem more than a decade ago and in 1994 published the Recommended Practice J1819 - Securing Restraint Systems in Motor Vehicles. This Practice serves as a set of voluntary guidelines for child restraint and motor vehicle manufacturers to use in designing better compatibility between motor vehicles and child restraints. It is too early to determine what effect these guidelines have made in trying to achieve the objective of compatibility of child restraints and motor vehicles. In measuring the effectiveness of the Practice, it should be noted that the Practice was based on child restraint systems manufactured in 1983 and 1984 and many changes have occurred since then in both motor vehicle occupant compartment and child restraint technologies.

Other approaches are being sought to address the problem of incompatibility between child restraints and motor vehicles. The international safety community has devised a system of attachment of child restraints to motor vehicle seats which is independent of the adult vehicle belt system. The objective of this independence is to enable motor vehicle manufacturers to attempt to optimize their designs for fit and performance of restraint systems as a result of a narrower range of occupant weights/height and age. An example of such an approach is the International Standards Organization (ISO) child restraint and universal attachment system ISOFIX which will use attachment points that are dedicated for child restraints. Unfortunately, the merit of this approach is that it is a long-term solution to the problem of incompatibility of add-on child restraint systems and motor vehicles. In the short-term, aggressive implementation of the SAE J1819 design guidelines may alleviate many of the incompatibilities between new model vehicles and child restraints.

CHILD RESTRAINTS AND AIRCRAFT

In addition to the variance in the characteristics of motor vehicle passenger compartments, a child restraint designer is faced with a set of characteristics of the aircraft occupant compartment. Specifically, aircraft seats not only are generally different from motor vehicle seats but also are different among themselves in terms of seat belt anchor points location and routing geometry. Because these parameters are variant, and in some instances conflicting, compromises are made by the designers of child restraints resulting in a compatibility that is not present for all passenger compartments and across the modes.

Federal Aviation Administration Testing

The Federal Aviation Administration (FAA) identified several child restraint systems that are currently certified for use in aircraft as being incompatible with the aircraft passenger occupant environment. In 1994, the FAA's Civil Aeromedical Institute (CAMI) conducted a series of sled tests to evaluate the performance of various types of restraints in aircraft seats.[3] The tests were conducted using a 44 ft/sec velocity and a triangular deceleration-time profile with a 16g peak. The FAA uses this horizontal crash test pulse (FAR 25.562) to certify aircraft seats.

A total of six different types of restraining a child in an aircraft were tested: booster seats, rear-facing, forward-facing, harness system, lap held or "belly belt" restraints, and aircraft lap belts. Four child dummies were used in the testing: I)CRABI-6-months, ii) SA103C-3-year, iii) SA106C-6-year and iv) a 24-month-old, with a pressure measuring abdominal insert, identified as CAMIX. The aircraft seats used were representative of the 9g peak deceleration style that is currently in use in the aircraft fleet. Three different configurations of aircraft seats were tested: i) single row, with the seat back locked and unlocked; ii) double row, with the dummy/CRS in the aft row; and iii) double row, with the dummy/CRS in the front and adult occupant in the aft row. Figure 2 shows a double row of aircraft seats environment. The double row tests were conducted with the seat pitch at 32" from cushion reference point (CRP) of the aft row to the CRP of the front row - this represents the average spacing found in the majority of commercial aircraft. The child restraints were tested with the aircraft seat lap belts in their standard attachment location. A small number were tested with a

modified attachment location.

CAMI summarized the results of the dynamic testing program of the child restraints as follows:

- Because booster seats generally do not have an integral back, a child may be exposed to potential abdominal injury from an aft row occupant loading the aircraft seat back and child.
- Rear-facing infant seats were relatively simple to install and performed satisfactorily.
- Forward-facing convertible seats were generally difficult to properly and snugly install, either due to the routing of the lap belt through the CRS or lack of space between aircraft seats. The 3-year-old dummy in the aft row contacted the back of the front row seat in 75% of the tests.
- Lap belt geometry of the aircraft seat prohibited snug attachment of the harness system. The harness system also resulted in unacceptable forward excursion of the dummy (off of the front edge of the aircraft seat cushion).
- The lap held CRS, or "belly belt", was not an acceptable means of restraining the dummy.
- Acceptable results were observed when the 3 year old dummy was restrained with the lap belt of the aircraft seat. Only marginally acceptable results were observed for the 24-month-old dummy when restrained by the lap belt.

NHTSA Testing

At its Vehicle Research and Test Center, NHTSA conducted a joint effort with FAA to devise an appropriate testing effort to ensure proper performance of child restraint systems in aircraft. This program emphasized the forward-facing child restraint configurations which did not perform satisfactorily in the FAA testing program. The series of tests used the FMVSS No. 213 test fixture and acceleration crash pulse peaking at 24g and representing a 30 mph velocity change. The following child restraints were evaluated:

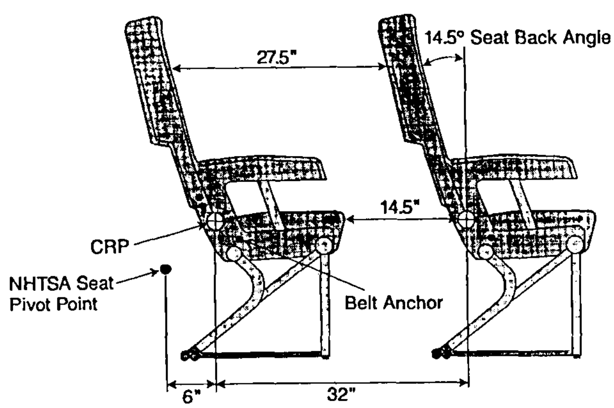

Figure 2. Aircraft Occupant Environment
Source: Referenced CAMI report

- Kolcraft AutoMate convertible, forward-facing
- Century Breverra toddler, forward-facing
- Cosco Touriva convertible, forward-facing
- Century 3000 STE convertible, forward-facing
- Evenflo Champion convertible, forward-facing
- Kolcraft Traveler 700 convertible, forward-facing
- Travel Vest Harness system, forward-facing
- Kolcraft Rock N Ride infant, rear-facing
- Fisher-Price infant, rear-facing
- Evenflo Joyride infant, rear-facing

The rear-facing seats were tested using the 9-month-old-TNO dummy. The SA103C-3-year-old dummy was used to test the forward-facing child restraints and travel harness system. Both 9g and the newer 16g aircraft seats were used in these tests. Two rows of aircraft seats were positioned at a 32" pitch from CRP of the aft row to the CRP of the front row -- the same set-up used in the FAA testing program (Figure 2).

Tests Conducted with 9G Aircraft Seats - Initial tests were conducted using a representative 9g aircraft seat because the majority of seats in the fleet at this time are the 9g model. Four tests were conducted in the baseline 9g seats. The first test in the baseline seat resulted in structural damage to the aluminum tubing along the row of seats below the rear of the seat cushion. The aluminum tubing was replaced with a sturdier tubing to extend the life of the seats for testing. After the tests were completed with the reinforced seats, tests were conducted with a different row of baseline seats. No structural damage to this row of seats was observed. All tests conducted with the baseline aircraft seats were a double row configuration, with the seat back break over feature unlocked (enabled) in the aft row and locked (disabled) in the front row. Aircraft seats generally have a feature that enables the seat back to break over and fold onto the cushion for ease in maintenance and aircraft seat reconfiguration. The seat back is designed to allow break over with a moderate force of about 30 to 50 pounds.

All of the child restraints were tested on the reinforced aircraft seats using the standard lap belt anchorage locations. Three of the forward-facing CRS were also tested in a single row aircraft seat to evaluate the amount of head and knee excursion without interference from a front row seat.

i) Effects of Modifying the Belt Routing Geometry:

The first set of tests used the same aircraft seat belt system anchor point locations (standard) as the ones used in the FAA testing. In the simulated aircraft environment of two rows of aircraft seats, the first row had the seat break over feature "disabled" while the second row had it "enabled". To determine the effect of the location of the anchor points and routing geometry of the aircraft seat belt system, another set of tests was similarly performed. The lap belt anchor point locations were modified by repositioning the anchorages 4.5" rearward and 4.8" up from the standard anchorage locations. To further determine the effect of the belt geometry routing, tests were performed on a harness system and toddler seat.

Table 1 shows that the head injury criteria (HIC) and the chest acceleration measurements for the 3-year-old dummy occupying forward-facing child restraint systems are very sensitive to the location of the anchor point of the aircraft belt system. Decreasing the angle of the belt relative to the child restraint, either by means of repositioning the location of the anchorages or wrapping the belt around the armrest, resulted in substantial improvements of the measurements of the occupant's head and chest injury criteria. In fact, HIC measurements were substantially reduced from critical levels of about 1500 to values (about 700) that are much lower than the threshold of head injury. It is noted that similar improvements were observed in the case of the travel vest harness/3-year-old child occupant as a result of wrapping the belt around the armrest of the aircraft seat. In fact, in this case the dummy's injury criteria measurements and kinematics improved (no submarining was observed). Without the belt wrapped around the armrest, the dummy submarined and came to rest almost under the front row aircraft seat.

ii) Effect of Disabling Second Row Aircraft Seat: A Century 3000 STE convertible seat was tested twice with the 3-year-old child dummy occupying the second row aircraft seat and not allowing the first row seat to break over (disabled). The HIC and chest injury measurements of the dummy increased from 898 to 1285 and from 48.5g to 56g, respectively, as a result of allowing the second row aircraft seat to break over during one of the tests.

Tests Conducted with 16G Aircraft Seats - Aircraft seats are in the process of being replaced by the newer 16g aircraft seat when new aircraft are built or the 9g seats have been retired from existing aircraft. Tests similar to the ones performed using the 9g aircraft seats were performed. These tests used the same crash pulse, configuration of aircraft seats and child surrogate as the ones used in testing with the 9g aircraft seats. In addition to testing the 16g seats with a standard location of seat belt anchor points, tests were performed to determine the effect of an adult dummy in the second row of aircraft seat, loading a 3-year-old child surrogate in a child restraint located in the first row of aircraft seat.

i) Results of Injury Measurements with Standard Anchors: This set of tests used the 16g aircraft seats with a standard belt system anchor point location. Table 2 summarizes the HIC and the chest acceleration measurement of the 3-year-old dummy occupying forward-facing child restraint systems. As shown in Table 2, the HIC measured exceeded the threshold allowed in FMVSS No. 213. It is noted that, in the case of the travel vest harness without the belt wrapped around the aircraft seat armrest, the HIC measurement of the 3-year-old child surrogate was 2183.

ii) Effect of Adult Rear Loading of Child Restraint: Two tests were performed in a configuration of a 3-year-old child dummy/child restraint in a front row aircraft seat and a 95th percentile Hybrid II male dummy occupying the second row aircraft seat. The front row seat was allowed to break over. Injury criteria measurements were determined for the cases of the second row aircraft seat not allowed to break over. Table 3 shows that loading the child restraint/dummy did not result in significantly higher injury criteria measurements. The high HIC value (1119) for the Cosco Touriva "no front seat" configuration was primarily due to the dummy's head impacting the flip-over tray of the child restraint.

TABLE 1
Effect of Modified Anchor Point Location on Injury Criteria (9G Seats)

Forward-Facing Child Restraint	Head Injury Criteria (HIC)	3 ms Chest Acceleration Clip (G)
Kolcraft Automate		
•Standard Anchor Points	1878 (1136)	54.0 (46.9)
•Modified Anchor Points	685	40.2
Cosco Touriva		
•Standard Anchor Points	1535	41.7
•Modified Anchor Points	737	37.8
Century Breverra		
•Standard Anchor Points Without Belt Wrapped Around Armrest	1542	47.2
•Standard Anchor Points With Belt Wrapped Around Armrest	762	37.5
•With Modified Anchor Points	624	39.2

TABLE 2
Results of Tests With Standard Anchor Point Location on Injury Criteria (16G Seats)

Forward-Facing Child Restraint	Head Injury Criteria (HIC)	3 ms Chest Acceleration Clip (G)
Kilcraft Automate	1401	52.1
Cosco Touriva	1146	41.9
Toddler Century Breverra	1555	63.4
Travel Vest Harness Without Belt Wrapped Around Armrest	2183	51.9

TABLE 3
Effect of Adult Loading in Rear Row Seat on Injury Criteria

Forward-Facing Child Restraint	Head Injury Criteria (HIC)	3 ms Chest Acceleration Clip (G)
Century Breverra (Toddler)		
•No Front Row Seats	290	35.9
•CRS in Enabled Front Seat and Adult in Disabled Second Row	324	32.5
Cosco Touriva (Convertible)		
•No Front Seat	119	40.6
•CRS in Enabled Front Seat and Adult in Disabled Second Row	964	37.3

Analysis of Testing

Based on the findings of the FAA and NHTSA research programs, it is evident that some of the currently certified forward-facing child restraint systems are not compatible with the aircraft environment. This incompatibility is twofold:i) the child restraints are too wide to fit in the aircraft seat, which has a 15" base width, and ii) they do not provide adequate safety protection for the child occupant's head during a crash. The child's head is allowed to be displaced excessively without sufficient resistance in a the longitudinal direction of a simulated frontal crash. This is the case regardless of whether the crash pulse is the one specified in FMVSS No. 213 or the milder FAR 25.562 pulse that is used by FAA to in certifying aircraft seats. Figure 3 shows the belt routing geometry of the aircraft belt -- whether it is a 9g or 16g seat -- when restraining a forward-facing child restraint system. The belt does not provide any resistance capability to a horizontal and longitudinal motion that results from a decelerating crash pulse. The sketch shows that the aircraft belt being almost in a vertical position is incapable of providing a horizontal tensile resisting force; and therefore allows the child restraint/child dummy to translate forward until the angle of the belt with the aircraft seat decreases enough to produce a horizontal resisting component to the horizontal forward motion. The fact that the horizontal distance between two rows of aircraft seats (pitch) is on the average only about 27.5" results in the head of the child dummy contacting the back of the front row aircraft seat. This impact against a relatively rigid surface is the major contributing factor to the high HIC values that were observed during the crash testing in the aircraft environment.

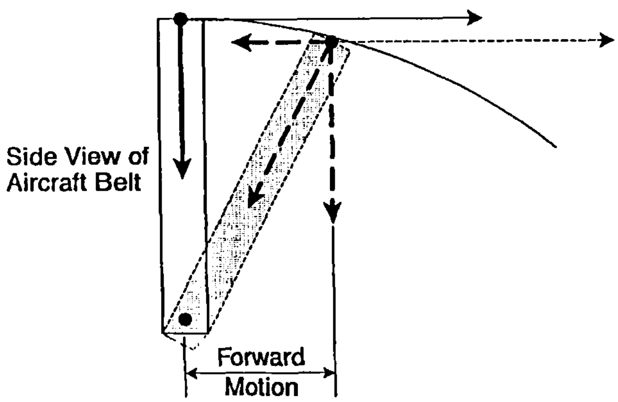

Figure 3. Effect of Anchor Point Location

SUMMARY AND CONCLUSIONS

Based upon the results of the series of tests conducted during the NHTSA and FAA research programs, the following conclusions were made. Data from the sled tests using FMVSS No. 213 procedures and pulse, performed with the 3-year-old child surrogate in forward-facing convertible and toddler child restraint systems, indicate that:

- the HIC measurements were substantially higher than the 1000 threshold specified in FMVSS No. 213. On the other hand, the 3 ms chest clips (chest acceleration) measurements were below the specified threshold of 60g,
- the HIC and chest acceleration measurements were substantially higher than the thresholds specified in FMVSS No. 213 when the break over feature of the aircraft seat was disabled,
- when the anchor point locations or belt routing geometry were modified HIC and chest acceleration measurements substantially decreased below the specified thresholds, and
- when loading from behind a front row aircraft seat/child restraint with an adult surrogate, the injury criteria measurements were substantially reduced as long as the child dummy's head does not impact a rigid surface.

Based on these findings, it is clear that today's child restraint problems are not limited to passing the FMVSS No. 213 requirements. The interface of these systems with the diversity of environments of the various transportation modes in which these restraints are designed to be used is a major problem. That is to say, child restraints should be designed to be compatible with the vehicle's passenger compartment. This compatibility should not be limited to the "fit", but should also address safety protection based on where the child restraint is to be used. Because of the diverse seating/belt systems and passenger compartment characteristics of motor vehicles (passenger cars, multipurpose passenger vehicles, trucks and buses) and aircraft, it is critical that envelops be defined in terms of the variances between and among the modes as practicable. Alternate and flexible restraining or standardized attachment methods of child restraints to vehicle seats could alleviate the difficulties in trying to satisfy the wide range of vehicle characteristics currently affecting fit and installation.

REFERENCES

Howe, J. Gavin, Chambers, Fletcher and Sullivan, Lisa K., "Assessment of Vehicle Interior Dimensions and Lap/Shoulder Belt Fit", NHTSA Final Report, DOT HS 808 003, October 1992

Howe, J. Gavin, and Sullivan, Lisa K., "Evaluation of Belt Positioning Booster Seats and Lap/Shoulder Belt Test Procedure", NHTSA Final Report, DOT HS 808 005, October 1992

Gowdy, Van and DeWeese, Richard, "The Performance of Child Restraint Devices in Transport Airplane Passenger Seats", FAA Final Report DOT/FAA/AM-94/19, September 1994

CHILD RESTRAINT EVALUATION PROGRAM

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ABSTRACT

During crash sled tests in 1993, some of the new child restraint systems (CRS's) sold in Australia did not appear to offer the same levels of protection as the existing products in the marketplace.

There has also been a significant increase in the number of consumer complaints made to the Roads and Traffic Authority of NSW (RTA) about CRS/motor vehicle compatibility, difficult installations and usage problems.

The Roads and Traffic Authority, the NRMA Ltd and the Australian Consumers' Association (ACA) conducted the first stage of an ongoing joint program to provide consumers with information which will enable them to make an informed choice when purchasing a CRS. This should allow market forces to bring about consumer driven improvements to CRS design.

CRS's were examined for their:-

- Performance in crash tests which were more rigorous than the Australian Standards tests.
- Ease of installation and ease of use.
- Compatibility with a representative range of popular motor vehicles.

Twenty-two CRS's were evaluated. These included dedicated rearward facing infant restraints, dedicated forward facing child seats, convertibles (CRS's which convert from rearward facing infant restraints to forward facing child seats), booster seats, (with back and sides) and booster cushions (backless).

At the conclusion of the program, the results were presented in a national subscription consumer magazine with advice to consumers as to what to buy. Wider consumer access was arranged through a brochure in which a CRS was given a *Preferred Buy* rating if it performed well in all the crash tests and scored well for ease of correct installation and for ease of use.

INTRODUCTION

When purchasing a CRS, it should be reasonable to expect that it will be easy to install, easy to use, and offer a high level of crash protection under most crash conditions. All CRS's sold in Australia carry the Australian Standards Mark, indicating that they have undergone independent testing, during which they have demonstrated compliance with the minimum performance requirements of Australian Standard (AS) 1754-1991 (1).

A year long study conducted in NSW in 1993 (2) found that children in correctly installed and properly used Australian child restraints had survived, without serious injury, crashes of far greater severity than those simulated for the purpose of determining compliance with AS 1754. There were also a number of cases reported of children being seriously injured in improperly used CRS's.

In summary, as of 1993, Australian child restraints seemed to be offering very good protection, even in severe crashes. Also, up until 1993, the Australian market for child restraints had been dominated by locally developed systems, specifically designed to the rigorous performance requirements of the Australian Standard. However, since 1993, adapted imported child restraints have significantly increased their market share.

This might have gone unremarked, except that during the conduct of a number of laboratory research programmes involving sled tests, some of these adapted child restraints did not appear to offer the same level of performance, as the existing child restraints. Some of the adapted restraints exhibited undesirable performance characteristics not previously observed in tests on existing products. Simultaneously, there was a significant increase in the number of consumer complaints about the compatibility, and ease of use of these adapted restraints in motor vehicles.

This triggered a suspicion that some of these adapted CRS's might not offer the same level of protection as the existing products. If this was the case, then there was the potential of a significant degradation in the level of protection offered by CRS's in Australia.

The adapted products were all based on existing CRS's sold in the US and European markets, where the standards for CRS's are considerably less demanding than the Australian Standard. In modifying them to pass the Australian Standard, it was possible that they may not offer as high a level of protection as those CRS's originally designed to the Australian Standard.

To test this hypothesis, an objective set of crash tests, and ease of fitment and use assessments was devised so as to conduct scientific comparisons of performance of the various products. The CRS's were tested for their:

- Performance in crash tests which were more rigorous than the Australian Standard tests.
- Ease of installation and use.
- Compatibility with a representative range of popular motor vehicles in Australia.

To be included in the Program, a CRS had to be on

sale in Australia at the commencement of the Program. Twenty-two CRS's met this criteria.

The CRS's included four (4)dedicated rearward facing infant restraints, four (4) dedicated forward facing child seats, six (6) convertibles (child restraints which convert from rearward facing infant restraints to forward facing child seats), five (5) booster seats and three (3) booster cushions.

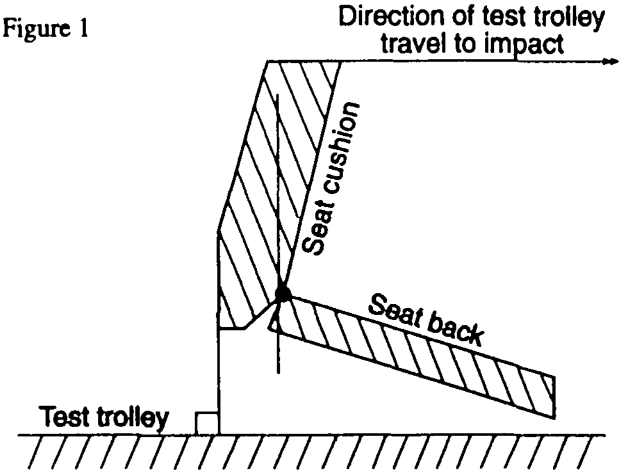
By coincidence, similar programs were carried out at about the same time, in Germany (1992, 1993 and 1995), Sweden (1994) and the US (1994). The Australian program appears to have been the most comprehensive in range of testing, and the most rigorous in test procedures. A comparison of the respective test conditions and test dummies is provided in Tables 1 and 2 respectively.

METHODOLOGY

Crash Testing

The test conditions, which were simulated using a horizontal crash simulator, were either in accordance with, or in excess of Australian Standard (AS) 3629.1-1991 (3). Each CRS was tested twice in the frontal and sideways directions and once rearwards, except for the booster cushions, which were not tested in the rearward direction. The infant restraints, were also tested under conditions which simulated a specific roll-over condition. This is referred to in the context of the Program as an inverted test. The orientation of the test seat for this test is shown in Figure 1.

Figure 1



One frontal test was conducted with the deceleration and velocity change as near as practicable to the minimum requirements (24gx49km/h) of AS 3629.1. The other test aimed for deceleration, as near as practicable, to the maximum acceleration (34g) allowed by AS 3629.1, and a velocity change of 56 km/h. This latter set of conditions was chosen to match the assessment of adult restraint in the Australian New Car Assessment Program. 34g is at the low end of the range

Table 1 Comparison of Australian, U.S., German and Swedish Test Conditions.

Country	*Frontal Impact 90°*	*Side Impact 45°*	*Side Impact*	*Rear Impact (Simulation of Rollover Configuration)*	*Inverted Impact*
Australia	24g x 49 km/h and 34g x 56km/h	14g x 32km/h	14g x 32km/h	14g x 32km/h	8g x 16km/h
U.S.	49km/h	N.A.	N.A.	N.A.	N.A.
Germany	33g x 50km/h	N.A.	N.A.	N.A.	N.A.
Sweden	56km/h	40km/h	N.A.	35km/h	N.A.

Table 2 Test Dummies, Australian, U.S., German and Swedish Programs

Country	*Rearward Facing Infant CRS's*	*Forward Facing Seats*	*Booster Seats and Cushions*
Australia	9kg - Frontal & Side Impact 4kg - Rearward & Inverted Impacts	22kg - Frontal & Rearward Impacts 15kg - Side Impacts	22kg or 32kg* - Frontal Impacts 15kg - Side Impacts
U.S.	9kg (Frontal Impact only)	15kg (Frontal Impact only)	22kg (Frontal Impact only)
Germany	15kg	15kg (Frontal Impact only)	22kg (Frontal Impact only)
Sweden	15kg - Frontal, Side & Rear Impacts	N.A.	N.A.

* The choice of test dummy depended on the maximum occupant mass specified by the manufacturer for the CRS.

of rear floor pan accelerations recorded in the full frontal NCAP testing.

The inverted testing was conducted with the deceleration and a velocity change as near as practicable to the minimum requirements (8gx16km/h) of AS 3629.1.

Side and rearward testing was also conducted in accordance with AS 3629.1 (14gx32km/h), except for the addition of a simulated door adjacent to the test seat for the sideways tests (Figure 2). A simulated door was decided upon for reasons of repeatability of test conditions and cost.

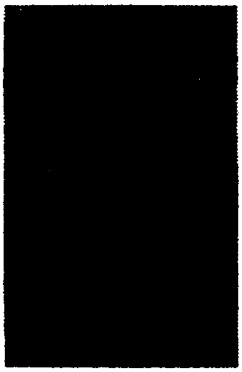


Figure 2

The door structure attempted to replicate a simplified rear door of a large Australian family sedan, in shape and size. To ensure its durability, the structure was fabricated mostly from thin wall tubing. A new inner door skin was used in each test. The skin was formed from 0.7mm sheet metal, (designated G2-ZF100), to replicate the section of inner door skin immediately below the glass. The door 'glass' was cut from 6mm thick Polycarbonate sheet.

Test Equipment, Instrumentation and Cinematography - The test seat complied with the requirements of AS 3629.1. It is similar to that specified in ECE Regulation 44.

Measurements were made of the sled acceleration, and where appropriate, the tensile forces in the top tether strap, the adult seat belt and selected harness straps in the CRS.

Each test was filmed using high speed cinematography. The number of cameras used and their locations varied according to the CRS being tested and the orientation of the test

Each CRS was restrained by an emergency locking retractor (ELR) seat belt and the top tether strap supplied with the CRS.

The seat belt and top tether strap anchorage geometries for the front, rear and inverted tests were in accordance with AS 3629.1. For the side impact tests, the test geometry approximated the child restraint anchorage (CRA) and seat belt anchorage geometries tor the rear outboard seating positions of a VR model Holden (GM) Commodore sedan.

Test Dummies - A TARU Theresa (4kg) and TNO P3/4 (9kg), P3 (15kg), P6 (22kg), and P10 (32kg) anthropometric dummies were used for the tests. Where appropriate, instrumentation was fitted to measure resultant head acceleration.

Ease of Installation and Use

The consumer trial was divided into two phases. The first phase assessed ease and correctness of installation of restraints into cars. The second phase assessed ease and correctness of securing infants and children into the restraint harness. Trialling was conducted on dedicated forward facing, dedicated rearward facing and convertible child restraints.

1. The installation trial design was balanced repeated measures, in which each triallist, recruited by research assistants, installed all the restraints being tested, in sequence, in a large late model sedan. The order of restraints for each triallist was different. Triallists may have had experience installing child restraints for their own children, but were not accepted if they routinely installed restraints for others. 18 females and 2 males participated in the installation trial.

2. The securing trial design was between subjects, in which each subject pair (adult and child) completed a single trial. Parents, or adults accompanying children, secured the child in the restraint which was currently being tested and was already installed. Initially, triallists were recruited at public functions such as regional fairs/shows etc by the research assistants and assigned to restraints in the sequence of their recruitment. However, the difficulty of obtaining triallists with small infants led to the recruitment of triallists at baby health centres and early childhood centres.

Installation Trial Procedure

All parts of the trial were observed by a research assistant who scored each part of the trial for correctness and time elapsed.

Triallists were asked to first read instructions and then adjust positions of shoulder straps from lowest to highest position within five minutes and rate the restraint for ease of use.

The triallist then attempted to install the restraint into the left rear seat of a large late model sedan car within ten minutes. After each installation the triallist scored the following for each restraint:

- Ease of reading and understanding the instructions.
- Placing the restraint in the car.
- Routing the seat belt.
- Using the "gated buckle" if one was necessary. Some

CRS's are supplied with a "gated buckle" as standard equipment. It is used for retractable lap sash seat belts to hold the two webbing straps together. Its purpose is to reduce the adverse effect retractors have on holding the CRS securely.

- Adjusting and attaching the tether strap.

Securing Trial Procedure

The securing phase of the trial was conducted at a number of public events over a period of some weeks using restraints already installed in large late model sedan cars. Restraints were rotated so that each restraint was trialed at two or more locations. Before each trial the harness buckle and/or tether strap was fastened and any slack removed from the harness straps.

Parents with children or infants were recruited by research assistants who first weighed and measured the overall length of the children. The triallists read the instructions for the restraint, and then attempted to secure the child in the restraint. The triallists could refer to instructions throughout the trial and ask for assistance if necessary. Any assistance was recorded along with correctness and elapsed time.

For a rearward facing restraint the trial commenced with the tether strap fastened. The triallists were asked to place the child in the restraint and then remove the child. If the restraint was a rearward facing type with a carry handle, the child was secured in the restraint on the table adjacent to the car, and the restraint was then installed in the car with the child in place.

After securing and removing the child, the triallists scored the following:

- Ease of reading and understanding the instructions.
- Ease of adjusting the harness.
- Ease of putting the child into the restraint and the harness.
- Ease of using a buckle and harness straps or tether (as appropriate).
- Ease of releasing the child from the restraint (rear facing).
- Ease of placing the bassinette in the car (if removable).

CRS/Vehicle Compatibility

Vehicles and Seating Positions - Testing of all restraints was carried out in two positions in six different models of vehicle. Each vehicle was one of the top four selling models in six different passenger vehicle categories. The vehicles were labelled Vehicle 1 to Vehicle 6. Descriptions of the vehicles are included in Appendix 1.

The restraints were tested in the left rear position, which is the kerbside seating position recommended for child restraint installation, and the centre rear position which is usually fitted with a lap only seat belt. Because Vehicle 3 did not have a CRA for the centre rear (CR) position, the right rear position was tested instead. In Vehicle 5, the centre rear position of the middle row of seats and the right rear position of the third row of seats were tested.

Procedure - A procedure was developed for the assessment of the dedicated rearward facing infant restraints, the dedicated forward facing child seats and the convertibles. This procedure was modified for the assessment of the booster seats and cushions.

Dummies Used for Assessment - The following dummies were used for the compatibility assessments:

- TNO P3/4 test dummy (9kg) – used for testing of the rearward facing restraints.
- TNO P3 test dummy (15kg) – used for testing of the forward facing restraints and booster cushions.
- TNO P6 test dummy (22kg) – used for testing of the booster seats and cushions.
- TNO P10 test dummy (32kg) – used for testing of the booster seats and cushions.

Equipment and Methods - Recline angle measurements were taken for rearward facing CRS's using a calibrated digital level placed on the inclined surface being measured.

The length of rearward facing restraints was measured using a measuring tape and steel rule. The measuring tape was aligned along the top surface of the seat cushion, with the zero point approximately located at the intersection between a tangent to surface of the seat back cushion and the surface of the base of the seat. The steel rule was held vertically and aligned with the rear extremity of the child seat.

Top tether extension straps from the one manufacturer were used when necessary.

Assessment of front seat comfort was performed by the Project Officer who was 1.84 metres tall and of slight build.

PERFORMANCE CRITERIA - CRASH TESTING

Each CRS was assessed for:-

- Retention of the CRS.
- Retention of the test dummy.
- Separation of load bearing components.
- Fragmentation of rigid components.

These criteria were taken from AS 1754-1991

Other assessments were made for:-

- Crash energy management in the rearward facing infant restraints and the convertibles in infant restraint mode, in frontal and side impact testing.
- Crash energy management in the forward facing seats and the convertibles in forward facing mode, in side impact testing.
- Distribution of crash forces in the rearward facing

infant restraints and the convertibles in infant restraint mode, in frontal testing.

- Head displacement in the rearward facing infant restraints and the convertibles in infant restraint mode, in frontal, side, rear and inverted testing.
- Head displacement in the forward facing seats and the convertibles in forward facing mode, in frontal testing.
- Head displacement and crash energy management in boosters in side impact testing.

Table 3 provides a quick reference to these protocols.

Field studies in Australia have shown that children do not appear to be as well protected in CRS's in side impact crashes as in frontal crashes.

Some Australian infant restraints have a tendency to rebound rearwards during frontal, rearward and inverted crash testing. This can allow the test dummy's head to contact the seat back or the test rig.

Restraint design should place a high priority on the minimisation of excursion of the upper torso in order to prevent these head strikes occurring. Therefore, an infant CRS was excluded from the final assessment process if, during frontal, rearward or inverted testing, it permitted the dummy's head to contact any part of the test rig or to pass outside the hatched area shown in Figure 3. Convertibles which did not comply with this criteria in the rearward facing mode, carried the head strike penalty in their overall ranking in both operating modes.

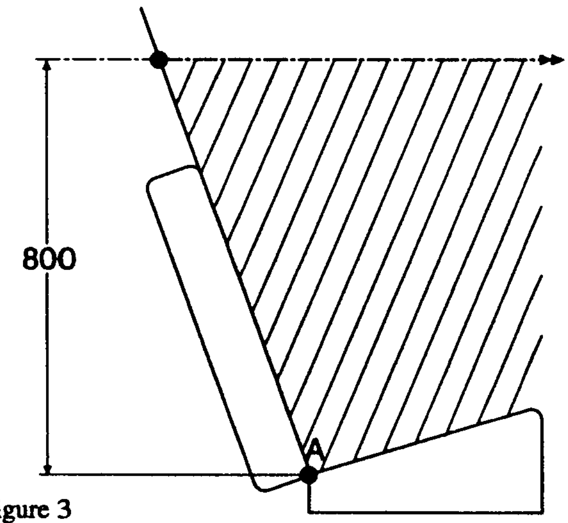


Figure 3

Similarly, forward facing seats which permitted a head strike outside the CRS in the 90° sideways test carried the penalty in their overall ranking. A convertible in forward facing mode which did not comply with this criteria carried the penalty in its assessment as an infant restraint.

CRS's in general, have so-called "side wings". One of their functions should be to provide adequate side impact protection, by retaining the occupants head, and attenuating energy. Thus, as part of the program, observations were made for head contact with the test rig in the side impact tests.

Measurements were made to examine crash energy management. This was a measure of the CRS's capacity to attenuate head impact energy. Because of the unknown usefullness of head acceleration without reference to time as a performance measure, "Head Injury Criteria 36" (HIC 36) was adopted for this purpose. Although the lack of good head injury tolerance data for children, does not allow the use of HIC 36 for predicting the risk of brain injury in children, it does provide a standardised way of combining direction, intensity and duration of forces on the head to allow performance comparisons.

Head displacement was measured for the forward facing CRS's, in frontal impacts.

Table 3 Assessment Protocols

Assessment Protocol	*Rearward Facing Infant Restraints*	*CRS Type Forward Facing Seat*	*Booster Seats and Cushion*
Head Accel + HIC 36	•	•	•
Head Strike with Seat Back/Test Rig	•		
Head Strike with Door Structure 45- 90° Side Impact	•	•	•
Head Strike with Door Structure 45° Side Impact	•	•	•
Head Excursion		•	
Dummy Retention	•	•	•
CRS Retention	•	•	•
Breakage of Load Bearing Components	•	•	•
Webbing Loads	•	•	
Load Distribution - Frontal Impacts	•		

SUMMARY OF RESULTS

Crash Testing

There were no dummy ejections during the 142 test program and no CRS completely separated from the test rig, although there was one case of top tether breakage.

Infant Restraints - Of the ten infant CRS's tested, seven permitted the dummy's head to make contact with the test rig in one or more tests.

In the frontal tests, only one of the CRS's, a dedicated infant restraint, was able to demonstrate good control over rotation in rebound, in both tests. By contrast, one of the other dedicated infant restraints rebounded in such a way as to allow the dummy's head to strike the seat back. The dummy's head just missed the seat belt upper anchorage mount, which was positioned immediately behind the test seat.

The HIC values for the frontal tests ranged between 470 and 940 at 24g and between 592 and 1476 at 34g. Of the five CRS's which performed best in the 24g test, four also performed best in the 34g test. One CRS did best or next to best in both tests, while another returned the second highest HIC at 24g and the highest HIC at 34g.

The crash forces in these tests were adequately distributed over the back of the dummy's torso.

The 90° side impact tests resulted in four CRS's which allowed a head strike on the door structure. HIC values ranged from 505 to 1828. Significantly, the 1828 HIC value was produced in a test which did not produce a head strike outside the CRS.

No restraint allowed head contact with the door structure in the 45° test. There was, however, one CRS which allowed the dummy's head to come clear of the restraint during rebound and to contact the section of top tether nearest the door structure. It then rolled along the top tether and in so doing it rotated almost 180° in a plane normal to the dummy's neck. The CRS then rebounded into the back of the test seat, allowing the dummy's head to also contact the seat back.

During the rear impact testing, four CRS's rotated rearward sufficiently to allow the dummy's head to strike the seat back. The same four CRS's also allowed similar head strikes to occur when tested in the inverted mode.

Forward Facing Seats - The only major component failure occurred when the top tether broke away from the back of a forward facing CRS when it was tested at 34g.

Head excursions for the forward facing CRS's during frontal testing ranged from 731mm to 906mm at 24g, and from 783mm to 931mm at 34g. Head accelerations were also measured in these tests. However, if the head struck the dummy's legs the head accelerations were not ranked.

Only one forward facing CRS, a convertible, was not able to prevent the dummy's head striking the door structure when tested sideways at 90°. This was the same convertible which allowed a head strike when tested under the same conditions, as an infant restraint. The HIC values from these tests ranged from 762 to 1992.

A head strike against the door structure was recorded in each of the 45° tests.

Booster Seats and Cushions - During the frontal tests on the boosters, the only booster manufactured from soft plastic foam allowed significant levels of submarining.

A head strike against the door structure was recorded in each of the 45° and 90° tests. The 90° head strikes resulted in HIC values ranging from 704 to 4939.The 4939 value was recorded by a backless booster. The two remaining backless devices also performed poorly, with HIC values of 3418 and 3436.

Ease of Installation and Use

Forward Facing CRS's - Three of the forward facing CRS's performed well for ease of use and correctness in both installation and securing. One CRS performed particularly well. This CRS, a dedicated forward facing model, emerged as better than average in the installation phase, in both ease and correctness, and in correctness of securing. It ranked well in every test.

Rearward Facing CRS's - Two dedicated rearward facing restraints performed very well compared to most of the convertibles in rearward facing mode in the installation phase, but were not outstanding in the securing phase, scoring lower than two of the convertibles.

Convertibles - Among the convertibles, one tended to perform well in both modes, and was the top performer in the securing phase in rearward facing mode. Another two performed well as forward facing CRS's, for ease of use and correctness in both installation and securing. However, in common with most of the other convertibles, neither performed as well in the rearward facing mode. Their scores were in the average range.

In contrast, three other convertibles performed poorly in almost every comparison. One did not perform well in any phase of the trial, and another hardly fared better. The other device did the best of them, but only managed to stay in the average range.

The remaining convertible, despite having one or two very good results (e.g. correctness of securing in the rearward facing mode), tended to go from low average to below average range. A great deal of this was due to its adjusters and complicated harness adjustment.

CRS/Vehicle Compatibility - One of the main findings from this part of the overall study related to the size of the convertible CRS's. Four of the six convertibles tested would not fit into the outboard positions of the smaller vehicles and one of the large

vehicles, without rendering the front seats unusable by an adult. Some vehicles cannot fit all CRS's.

A number of other significant compatibility problems were identified in the study; these included:

- Two convertible CRS's in the rear facing mode could not be installed properly without the use of two top tether extension straps.
- Adverse interaction was found between the recline mechanism release handle on some CRS's and the vehicle seat back. This resulted in inadvertent release of the recline mechanism.
- The centre rear lap belt was too short to pass around one of the convertible CRS's assessed, in two out of the six vehicles used in the study.
- The minimum top tether length was found to be relatively long on some child restraints. This was a problem where one CRA in one of the vehicles was located very close to the seat back.
- Some boosters allowed the sash belt to cut into the neck of the 15kg P3 dummy in some of the vehicles tested. This problem did not occur with the boosters that incorporated sash guides.

More detailed information and data from the program described in this paper are available from the authors.

DISCUSSION

Crash Testing

The seat in which the top tether broke originated in the US. It had been modified to include a top tether, to comply with the Australian Standard. A fourth set of shoulder strap slots had also been added following consumer complaints that the original top slots were too low for children at the top end of the mass range. The failure occurred when the seat shell broke between the top tether mounting and the top shoulder strap slots.

The maximum force recorded in the top tether before the breakage occurred was lower than the maximum top tether strap force recorded for the same device in the lower velocity (49km/h) test. Also head excursion for the two tests was of the same order. This was the only CRS the crash test performance of which did not appear to significantly exceed the requirements of the Australian Standard. This suggests only marginal performance in terms of compliance with the Australian Standard frontal test.

Overseas Consumer Programs - In sharp contrast, the US and European child restraint consumer programs produced CRS failures which, if repeated in real world crashes, could expose the occupant to serious injury.

One outcome from the US program was the voluntary recall of one CRS and a petition to the National Highway Traffic Safety Administration (NHTSA) to recall another. The recalled CRS is a two piece infant restraint, one part of which contains the child. This then snaps into the second part which is secured in the vehicle. There have been reports of the two parts separating in real world crashes.

These outcomes imply a greater factor of safety in Australian CRS's than in their US and European counterparts. This may be because all child restraints currently sold in Australia require independent Standards Australia certification prior to each batch being sold, as opposed to the 'self certification' for their US and European counterparts.

Head Impact - When examined for head retention and crash energy management, many of the CRS's performed poorly. Only one dedicated infant restraint, four dedicated forward facing child seats and two convertibles were able to prevent the dummy's head striking part of the test rig. One of the convertibles was, however, the CRS in which the top tether broke. As a consequence, it was excluded from being considered for a *Preferred Buy* rating.

Side Impact - Of concern here is the number of CRS's which allowed a head strike with the door structure in the 90° side impacts. Two factors which contributed to this result were poor lateral stability and the absence of sufficiently well defined side wing structures.

Although some of the remaining CRS's returned relatively low HIC values for this test, it is believed that the overall results would have been better had there been less aggressive internal surfaces presented to the dummy's head. There would have been further likely gains had the internal surfaces of these CRS's been lined with appropriate energy attenuating material. These CRS's produced HIC values exceeding 1000 in more than 50 percent of the tests and a top HIC of 1992. Although these HIC values cannot be related to injury potential, they do indicate heavy head impacts.

Lateral stability is being addressed through research on the CAUSFIX, ISOFIX and other anchorage systems. Clearly, however, more needs to be done to reduce the risk of head strikes outside the CRS. Similarly, a need exists for better head impact energy management when the head is contained within the CRS.

Overall, some of the results would support the perception that some manufactures are perhaps paying too little attention to research and development beyond the Standard's requirements.

Ease of Installation and Use

There were sufficient differences in the difficulty, assistance required, time taken and correctness of use of CRS's to suggest that, when used by first time users, some restraints are more likely to be installed incorrectly, or some children may be inadequately secured. These

differences are due to the design of the products and their instructions. Users learning incorrect methods and techniques may repeat them.

Better design of some products and their instructions for use should lessen incorrect use. This may in turn lead to a reduction in injuries or in severity of injuries.

CRS Vehicle Compatibility – from the Vehicle Perspective

Of the six vehicles used in this study, all vehicles, except one, displayed problems that affected the fitting of at least one model of child restraint.

Earlier compatibility studies (4,5) found improvements have occurred in the location of CRA's in vehicles. However, one of the vehicles in this current study, had a centre rear anchorage point on the parcel shelf, which was very close to the vehicle seat back. Tensioning of the top tether was impossible with two models of child restraint in this position. In each case the minimum top tether adjustment was too long.

Fitting of some of the larger rearward facing convertible seats into the left-rear and right-rear positions of three of the vehicles tested required the front seats to be moved so far forward that they would not comfortably fit a front adult occupant. Two of the three vehicles were the smaller of the tested vehicles. The third vehicle was a large off-road vehicle where this problem would not be expected.

It was generally more difficult to install restraints in the smaller vehicles than the larger vehicles which had more headroom, more occupant space and larger doorways. This was particularly the case with restraints which had to be manoeuvred into position with the child already in the restraint. It was also evident in the smaller vehicles, that the top tether on the rearward facing restraints had to be loosened in order to place the child in the restraint. In one of the smaller vehicles in this study, the anchorage points were mounted on the rear wall of the cargo area. The anchorage points were therefore an average arm's length away from the back seat. In this situation, shorter people may find it necessary to open the hatch door to attach the top tether. This would be a particular problem in the case with restraints where the top tether has to be repeatedly connected and disconnected each time the child is transported to and from the car. A similar problem existed with one of the larger vehicles where the centre CRA was located on the floor pan behind a third row of seats. In this situation connection of the top tether strap usually required opening the rear door, if the extension strap slipped between the rear seats.

The lap belt supplied in the centre rear position of two of the vehicles in this study was not long enough to pass around one model of restraint.

With one of the vehicles in this study, the use of a 600mm top tether extension strap resulted in the top tether attachment clip sitting on top of the seat back in such a way as to depress the retention spring. There is a chance that in a crash the top tether may inadvertently release. In a further vehicle in this study, a protrusion obstructed the installation of a restraint design, so that the restraint back did not sit squarely against the seat back.

From the vehicles inspected in this study, it was also evident that when CRA's are located in a vehicles cargo area, they can adversely affect the use of this space. The public should be made aware that the top tether of an installed child restraint, can be adversely affected by moving load in a cargo area of a vehicle, during a crash.

Booster seats and cushions are designed to improve the fit of adult seat belts on children by moving the sash strap away from the neck and improving the pelvic/abdominal fit of the lap belt. The main problem with fitting a small child in an adult belt without a booster, is that the sash often ends up across the childs face or neck. There is a fear that this may injure the child in the crash.

Lack of support behind a childs neck can increase the severity of injury in a rear end collision. The position of eye height above the seat back is an indication of lack of support. All of the booster models, except for two, were recommended for use by children up to 32 kilograms (mostly when used in conjunction with an approved adult lap-sash seat belt).

In vehicles without head restraints, the eye height of the 32kg P10 dummy would be positioned at least 35mm above the booster seat back or the vehicle seat back. Three of the boosters in this study, had a relatively high base height and positioned the eye height of the P6 dummy above the seat back of some of the vehicles tested without headrests. Some of the booster seats had backs which extended above the eye line of the P6 dummy. However, there is no guarantee that the booster seat back will offer any support during a rear end collision. There may be a need to educate the public in regard to the relationship between eye height and boosters and to have a requirement that boosters incorporate head restraint.

A general observation from this study was that seat belt geometry affects the performance of the child restraint. There is a significant degree of variability in the geometry of the anchorage point positions of lap sash seat belts and seat shape between different types of vehicles. No configuration stood out as best or worst. One configuration gave relatively poor stability and correctness of installation for some restraints, but not for others. Seat belt geometry is largely dependent on the individual manufacturer's design, limited only by parameters set out in the appropriate design rules.

Publication of Results

At the conclusion of the program, the results were presented in a national subscription consumer magazine with advice to consumers as to what to buy. Wider consumer access was arranged through a brochure which gave CRS's a *Preferred Buy* rating if they performed well in all the crash tests and scored well for ease of correct installation and for ease of use.

Preferred Buy ratings were awarded to only one infant restraint and three child seats. Two of the seats and the infant restraint are from the one manufacturer and have been in production for more than ten years.

Although none of the boosters met all the crash test requirements - they all permitted a head strike in the 90° side impact test - all but the backless boosters and the one soft foam booster seat were given a *Preferred Buy* rating because of the lack of a suitable alternative device.

Only one of the convertibles was able to comply with the Program's crash test criteria. It did not, however, perform as well as the dedicated '*Preferred Buy* 'infant restraint and child seats. It also performed poorly in the ease of installation and ease of use evaluations. Consequently, it was not given a *Preferred Buy* rating. Instead, advice was given to consumers that, if they needed to buy a convertible, this one performed better than the others in the crash tests.

A dedicated forward facing seat, of similar construction, from the same manufacturer did not gain a *preferred buy* rating for the same reasons.

<u>**Consumer Reaction**</u> - Some sections of the community questioned the value of the Program, arguing that it could seriously undermine consumer confidence in the Australian Standards Mark. It was also argued that the outcomes from local field studies showed that CRS's were performing well in real world high speed frontal crashes. It is significant, however, that the field studies involved CRS's that had been in production in Australia for many years. Nothing is yet known of the real world crash performance of the newer model CRS's. It cannot be assumed that they would all perform equally in these circumstances.

The Authors were conscious from the outset of the need to maintain consumer confidence in the Australian Standard. To minimise the risk of such an eventuality, the brochure emphasised the need for parents and carers to remain confident in the overall protection offered by CRS's bearing the Standards Mark.

Some unfortunate media coverage did result in consumer dissatisfaction with products which did not gain *preferred buy* status. The usual reference points for consumers reported an increase in phone calls from concerned consumers seeking clarification. Also, some retailers reported that customers who had purchased non preferred restraints sought to return them. Some of the distributors of non preferred products reported reduced sales and retail outlet orders for their products.

Confusion and consumer concern about their existing child restraints is probably undesirable, particularly if it has any possibility of no child restraint being used.

Overseas programs reported similar reactions, so clearly this is a universal problem which can only be mitigated (probably not avoided) by careful, caring handling by the media.

In summary, there does not appear to have been any longer term loss of public confidence in the Standard as a consequence of this Program.

What is apparent is that purchasers of CRS's were interested in and used the information contained in the brochure when selecting a CRS. This is being reflected in the pattern of child restraint sales. Within a short period of time following the release of the results, one manufacturer reported a significant drop in sales of one of its 'non preferred' products. It is likely that sales of other products not given a *Preferred Buy* rating have been similarly affected. Conversely, there has been a report of an increase in market share for the infant restraint given a *Preferred Buy* rating. This CRS is used extensively in infant restraint rental schemes throughout Australia. There have been reports from NSW restraint rental operators of significant increases in the number of rentals since the publication of the results.

This would appear timely, since it was reported that the continued production of this CRS was under threat because of the popularity of convertibles. A similar report has been received from the manufacturer of two of the other three dedicated infant restraints involved in the program.

Convertible restraints have become popular with consumers because of their perceived convenience. However, their use may result in a significant degradation in overall safety.

One way in which child restraint manufacturers are seeking to remedy problems with convertibles is to limit the recline angle in rearward facing mode. However, there have been reports of young infants being seated so upright in some convertibles that their heads are continually falling forward onto their chests. This has the potential for increased head injury in frontal crashes. It also increases the risk of the infant's head coming clear of the device in side impacts where this might not otherwise occur.

The incompatibility of these CRS's with a proportion of the car population means that there will always be a need for dedicated infant restraints. There is a concern, however, that with a further decline in popularity of dedicated infant restraints, fewer resources will be spent on developing this type of CRS.

It is hoped that the program described in this paper will result in either significant improvements in

convertible performance or a shift in popularity back to dedicated infant restraints.

Program Justification

Evidence of the need for consumer information on child restraints is the popularity of the brochure. This was far higher than anticipated. Within a matter of weeks of its release, the distribution agency reported that its stocks had been exhausted. The second edition of the brochure is now in print.

Child restraint manufacturers have reacted differently to the Program's outcomes. Some have been critical, while others have appeared indifferent. More important, however, is that two of the five manufacturers whose products were evaluated have taken remedial action to correct limitations the program detected in their products.

Most notable is the case of one of the convertibles. This was remodelled and given a make and model name change. It was then retested by the manufacturer (in the laboratory in which the Program was conducted), albeit in only one of the two configurations in which the CRS was unable to comply with the Program's crash test criteria. The results from these tests combined with results selectively chosen from the evaluation program were then reproduced in promotional material.

The other case involves a booster seat. This has been remodelled to give it deeper sidewings.

Future Stages of the Program

Stage 2 of the Program is about to commence. Twelve new products are to be assessed. The intention is for the Program to be ongoing. However, the introduction of new CRS's beyond Stage 2 will determine the timing of subsequent stages.

CONCLUSIONS

It is evident from the work reported here, that all but one of CRS's involved in the Program exceed by a considerable margin the crash test performance requirements of the Australian Standard. In spite of this, significant differences are apparent in the crash performance of Australian CRS's, as evidenced by their varying performances when examined against criteria not currently included in the Standard.

Not withstanding developments with the CAUSFIX, ISOFIX and other anchorage concepts, it is evident that their is potential for manufacturers, particularly those modifying imported products, to test beyond the minimum requirements of the Standard, so that their products do not offer degraded performance compared to existing restraints with proven field performance, particularly in regard to side impact protection.

When used by first time users, some restraints are more likely to be installed incorrectly, or some children may be inadequately secured. These differences are due to the design of the products and their instructions. Better design of some products and their instructions for use should lessen incorrect use. This may in turn lead to a reduction in injuries or in severity of injuries.

It is evident that motor vehicle size is a determining factor in the selection of an infant restraint systems in Australia. Most, if not all, small cars will not accommodate a convertible CRS, and in some larger vehicles, it is necessary to compromise the safety of the front passenger seat occupant by having to have the seat in its foremost position.

It is clearly very important that information from consumer programs of this type emphasises the need for consumers to remain confident in the Standards Mark, although quite clearly, the program aims to empower consumers to purchase those restraints with above average performance.

The rate at which the first print run of the brochure was consumed is a clear indication that consumers will seek out information which will enable them to make an informed choice when buying a CRS.

Reports from manufacturers and others about fluctuations in sales and rental numbers of CRS's, following the program, indicate the influence the outcomes from such programs can have on the buying decisions of consumers. It is also apparent that these outcomes can influence manufacturers to make changes beyond the minimum requirements of the Standard, to improve their products.

REFERENCES

1. Henderson M.
   Children in Car Crashes: an in-depth study of car crashes in which child occupants were injured
   Child Accident Prevention Foundation, NSW Division, June 1994.
2. Standards Australia
   AS 1754-1991
   Child Restraints for Passenger Cars and Derivatives.
3. Standards Australia
   AS 3629.1-1991
   Methods of Testing Child restraints.
4. Booth, M .
   Compatibility Between Vehicles and Child Restraints. Discussion Paper. Unpublished. NRMA (Sydney), 1986.
5. Booth, M.
   A Review of Compatibility Between Vehicles and Child Restraints. Paper presented to the Road Traffic Safety Seminar, Wellington, New Zealand 1988. Seminar Papers Volume 1, 1988.

APPENDIX 1

Description of Vehicles Used to Assess Compatibility

Vehicle 1 - 1992 large family sedan with 3 CRA's located along the parcel shelf.

Vehicle 2 - 1993 large family station wagon with 3 CRA's located in the floor behind the back seat, under the carpet .

Vehicle 3 - 1992 small hatch type vehicle with 2 CRA's located in the floor of the hatch area.

Vehicle 4 - 1993 medium sized hatch type vehicle (4cyl) with 3 CRA's located in the rear vertical panel.

Vehicle 5 - 1993 8 seater people mover with 2 CRA's located in the floor behind the middle row of seats and 2 CRA's located behind the back row of seats.

Vehicle 6 - 1994 long-wheel base 4-wheel drive with 2 outboard CRA's located in the roof and 1 centre CRA in the floor.

PEDESTRIAN SAFETY

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Paper Number 96-S7-W-20

ABSTRACT

In recent years, there have been many advances in vehicle design which have increased safety for occupants. Few of these improvements are relevant to pedestrian safety. Yet one in five fatalities on Australian roads is a pedestrian. This study reviews pedestrian behaviour, crash site characteristics and vehicle behaviour in fatal pedestrian crashes using data collected from coronial investigations into fatal road crashes in Australia. The paper considers the possible impact of improved vehicle design on pedestrian safety.

BACKGROUND

Australia, along with other developed nations, has experienced significant reductions in its road toll in the last twenty five years. The number of people killed has decreased by 47% from 3,798 in 1970 to 2,017 in 1995. Significant features in reducing the road toll include continuing improvements in vehicle design, an improved road network and police enforcement of seat belt wearing, random breath testing and speed limits.

The 47% decrease in fatalities from 1970-95 is even more impressive in view of growth in the population and the number of registered vehicles over the period. The population rose by 40% from 13 million in 1970 to 18 million in 1995 and the number of registered vehicles rose by 120%, from 5 million in 1970 to 11 million.

In 1995, 401 pedestrians were killed on Australian roads, and a further 3,000 suffered injuries requiring admission to hospital. Pedestrian fatalities represented 20% of all those killed (2,017) on the road in 1995. Pedestrian fatalities in that year increased by 8.1% over the previous year, which was the largest increase recorded by any road user group.

The cost of road trauma in Australia has been estimated at approximately $A6.1 billion per annum. Pedestrian crashes cost the Australian community nearly $A1.0 billion each year.

DATA SOURCE

The Federal Office of Road Safety collects national statistics on road trauma in Australia. Many of these statistics are collected from police accident reports. The Federal Office of Road Safety also collects copies of documents used by coroners investigating fatal crashes including autopsy findings, toxicology reports, vehicle inspection reports, police accident data and eye-witness accounts. This information is coded by a professional team including coders with medical training.

Strict data quality guidelines are observed. The resulting database contains over three hundred variables relating to the crash environment, people involved and the vehicle. It is the most extensive file of fatal crash data available in Australia.

The time involved in conducting coronial investigations, especially those which recommend the laying of criminal charges, is considerable. The most recent year where full data is available for analysis is 1992 and this was used to derive the statistics reported herein.

In 1992, there were 350 pedestrian fatalities. Coronial reports were available for 344 fatalities (ie 98.3% of cases) resulting from 338 crashes. The vast majority of crashes (323) involved a single pedestrian fatality, three crashes had a double fatality and one crash resulted in four pedestrian deaths. Eleven pedestrian fatalities were excluded from the analysis because ten of these involved a motorcycle and one a bicycle.

PEDESTRIAN BEHAVIOUR

Demographics

There were 232 male pedestrian and 100 female pedestrian deaths in 1992. The ratio of male to female involvement is fairly typical of fatalities involving all road users. Table 1 has details of pedestrian fatalities by age and sex.

Table 1
Pedestrian Fatalities by Age and Sex

	Male	Female	Total
0-16 yrs	33 (14%)	16 (16%)	49 (15%)
17-25	47 (20%)	11 (11%)	58 (17%)
26-59	66 (29%)	24 (24%)	90 (27%)
60-75	47 (20%)	31 (31%)	78 (23%)
over 75	39 (17%)	18 (18%)	57 (17%)

It is interesting that children make up a minority of pedestrian deaths accounting for approximately 15%, and, in fact, children under six years account for only 4% of the total.

The elderly are far more at risk with 40% of all pedestrian fatalities over the age of 60 years. In comparison, those over 60 years comprise less than 20% of all road deaths.

Injuries Sustained

In 30% of fatal pedestrian crashes, the death of the pedestrian is instantaneous, a further 16% die before they reach hospital and 53% die in hospital. On rare occasions, an individual dies after release from hospital.

The time of death does not vary by sex. However, for those aged from 17 to 59 years, death is instantaneous in 44% of cases while the majority of the young and old tend to die in hospital (over 70%). This is somewhat counter-intuitive as the more physically robust group has the greater rate of instantaneous death.

Over two thirds of pedestrians suffered serious head injuries while 47% had serious chest injuries (these are not mutually exclusive). The younger age groups tended to have even higher rates of severe head injury. The coroner does not always specify a particular body region when describing cause of death. This information is available for two thirds of the cases. Head injury and multiple injuries were the major causes of death recorded by the coroner.

Pedestrian Involvement

On the basis of evidence gathered by coroners, it is possible to attribute causal responsibility, or fault, for individual crashes. Pedestrians were predominantly at fault in fatal crashes. Overall, 74% of pedestrians involved in fatal crashes were primarily responsible for the crash and a further 8% were partially responsible. Male pedestrians (79% fully at fault) tended to be more often at fault than females (62%).

Nearly 50% of pedestrians killed entered the road from the side nearest the direction in which the vehicle involved was travelling. About 10% of these emerged from between parked vehicles. 19% entered the road from the side furthermost from the vehicle involved and 17% were on the carriageway.

Alcohol use by pedestrians is a factor in nearly 30% of pedestrian fatalities as evidenced in Table 2.

Table 2
Pedestrian Fatalities by Blood Alcohol Content

	Male		Female		Total	
Not tested	31	(13%)	23	(23%)	54	(16%)
less than .05	86	(37%)	49	(49%)	135	(41%)
over .05	84	(36%)	13	(13%)	97	(29%)
unknown	31	(13%)	15	(15%)	46	(14%)

Fatally injured female pedestrians are less likely to be tested for blood alcohol content (BAC) than male pedestrians. Where test results are known, over 50% of male fatalities involve blood alcohol levels in excess of .05 gm/litre. Similarly elevated blood alcohol levels occur in 21% of female fatalities where BAC was measured. Alcohol use is certainly one of the factors in the relatively high "at fault" finding against pedestrians. The main destination of pedestrians involved in fatal crashes was either home or a recreational activity.

When adjusted for missing data and the fact that the elderly and very young are unlikely to have consumed alcohol, it is estimated that one in three pedestrian fatalities involve a pedestrian with a BAC in excess of .05.

This is comparable to the level of alcohol involvement in all fatal crashes (where the driver has an elevated BAC). In Australia, the problem of the drinking pedestrian in pedestrian crashes is of similar dimension to that of the drinking driver in single and multiple vehicle crashes.

CRASH SITE CHARACTERISTICS

Pedestrian crashes are not particularly concentrated by either time or place. Nearly 50% of fatal crashes occur on the weekend and 50% are at night. Approximately 60% of crashes occur in State capital cities and 25% in other towns. The remaining 15% of crashes occur in rural areas. Nearly 75% of fatal pedestrian crashes occurred mid-block and 90% happened in fine weather.

Nearly two thirds of pedestrian crashes occurred on roads where the speed limit is 60 kilometres per hour (kph) or less. 60 kph is the general urban speed limit in Australia. Nevertheless, nearly one in six pedestrian crashes occurred on roads with speed limits of 100 kph or greater.

Normal residential streets accounted for 26% of pedestrian crashes and urban arterial roads for 45%. Highways, both State and Federal, accounted for 22% of crashes.

VEHICLE BEHAVIOUR

Driver Characteristics

As is evident from the high rate of pedestrian responsibility for fatal crashes, the level of responsibility that can be attributed to the driver is relatively low. Drivers were fully responsible for 15% of fatal crashes and partially responsible for another 8%. There were no differences in responsibility that could be attributed to sex or age. It might be noted that 77% of drivers involved in fatal pedestrian crashes were male; however, this is exactly the same rate of involvement as in all fatal crashes.

Drivers were likely to be driving to or from work when involved in fatal crashes and 41% were within five kilometres of home.

The rate of involvement of drivers with elevated BAC's was low as outlined in Table 3.

Table 3
Drivers Involved in Pedestrian Fatalities by BAC

	Male	Female	Total
Not tested	24 (10%)	9 (13%)	39 12%)
less than .05	156 (68%)	48 (70%)	204 (65%)
over .05	14 (6%)	1 (1%)	15 (5%)
unknown	37 (16%)	11 (16%)	56 (18%)

Only one in twenty drivers involved in a fatal pedestrian crash had a BAC greater than .05. This is far lower than the overall involvement of drinking drivers in fatal crashes.

Exceeding the speed limit or driving at speeds "excessive for the conditions" was identified as a factor in 7% of fatal pedestrian crashes. This factor was equally prevalent for male and female drivers.

It should be noted that marginal speed infringements are unlikely to be detected by the police or through the coronial process. The impact speed of the vehicle in a pedestrian crash is a critical determinant of the level of injury sustained. Even small reductions in impact speed can contribute to a significant decrease in the overall level of trauma suffered by pedestrians.

Vehicle Characteristics

The type of vehicle involved in pedestrian fatalities is given in Table 4. Cars comprise nearly two thirds of the vehicles involved in fatal pedestrian crashes, while trucks are involved in one in six crashes. The rate of involvement in pedestrian fatalities is higher for trucks at 5.2 deaths than for cars at 2.5 deaths per 10,000 registered vehicles.

Table 4
Vehicles Involved in Fatal Pedestrian Crashes

	Frequency	Percentage
Car	194	64%
Van, utility, 4WD	43	14%
Bus	7	2%
Rigid truck	36	12%
Articulated truck	16	5%
Other	7	3%

<u>Point of Impact</u> - The majority of pedestrian fatalities (84%) involve the pedestrian being struck by the front of the vehicle. About 35% of pedestrians are struck by the front left of the vehicle, which is the side nearest the kerb in Australia. About 25% are struck by the centre of the front and 25% by right front, which is nearest the centre of the road.

The only exception to this is where an articulated truck is involved. About two thirds of these crashes involve an impact somewhere other than the front of the vehicle.

The majority of pedestrians (94%) do not strike the undercarriage of the vehicle. They are thrown over or to the side of the vehicle on impact.

The point of impact is not related to the type or extent of injuries received *in fatal crashes*, the speed of the vehicle, the propensity to brake or swerve or driver responsibility for the crash.

Bull bars were involved in 12% of fatal pedestrian crashes. However, the proportion of missing data for this variable is 55% of the total cases. It is probable that bull bars are involved in up to 20% of pedestrian fatalities.

<u>Braking and swerving</u> - The coroners' records contain details of whether the vehicle braked or swerved prior to the crash. This information is summarised in Table 5. A substantial number of vehicles neither braked nor swerved (42%).

This is probably indicative that the driver had little or no time to react rather than lack of attention on behalf of the driver. The relatively low proportion of drivers found at fault on the basis of coronial evidence supports the interpretation that it is action on part of the pedestrian which is crucial.

Table 5
Braking and Swerving Prior to Crash

	Frequency	Percentage
Braked only	63	20%
Swerved only	13	4%
Braked & swerved	68	22%
No brake or swerve	131	42%
Unknown	38	12%

It is interesting that approximately the same proportion of drivers "braked only" as "braked and swerved" possibly reflecting the traffic conditions at the time of the crash.

DISCUSSION

When considering the implications of the data reported in this paper for vehicle design, the primary considerations are:

1. Pedestrians are deemed responsible for the crash in which they die in 74% of cases.
2. Pedestrians with elevated BAC's are involved in 30% of fatalities.
3. 40% of pedestrian fatalities were over the age of 60 years.
4. In 42% of cases, drivers were unable to brake or to swerve.
5. 30% of pedestrians died instantaneously.
6. Two thirds of pedestrians received severe injuries to the head.
7. The pedestrian was struck by the front of the vehicle in 84% of cases.
8. The involvement of bull bars may be as high as 20%.

It is true that pedestrians to a large degree are responsible for their own fate. They are at fault in the crash in 74% of cases and they have elevated BAC's in 30%. Apparently, their movements in crossing the road or walking along it are such that in 42% of cases drivers had no time to brake or to swerve.

These figures in themselves are a persuasive argument for continuing attempts to change pedestrian behaviour and to study in more detail the involvement of alcohol in pedestrian crashes. Nevertheless, behaviour change on a large scale, while not impossible to achieve, is a difficult and time consuming task. There may be greater road safety benefits to be derived from changing the other variables in the pedestrian crash equation, ie the environment and the vehicle.

Pedestrian safety will benefit by planned reductions in speed limits and through greater enforcement of existing limits. In Australia, there has been considerable recent discussion of the introduction of a general urban speed limit of 50kph to replace the existing limit of 60kph. As noted earlier, the extent of injury and indeed the probability of death is a function of the impact speed of the vehicle.

There are also aspects of vehicle design that can influence the likelihood of survival in a pedestrian crash. These aspects can either assist in avoiding crashes or reduce the impact of crashes once they occur.

Avoidance - Braking and swerving are obviously critical strategies when attempting to avoid or ameliorate a pedestrian collision. Approximately half of all drivers attempted to brake or swerve or both when confronted with a likely pedestrian collision. Continuing improvements in these areas will contribute to improved pedestrian safety. The gradual replacement of the current fleet with more recent model vehicles should incrementally enhance pedestrian safety and reduce the proportion of fatal outcomes in at least 50% of such crashes.

Pedestrians may also be able to avoid potential collision if vehicles are made more visible. A number of countries are investigating the benefits of "lights on" legislation for all vehicles.

Harm Reduction - Finally, a significant majority of fatal pedestrian crashes involve the pedestrian striking the front of the vehicle, being thrown over or to the side of the vehicle and dying from head or multiple injuries.

Design changes to the front of the vehicle which reduced the severity of impact between the pedestrian, especially the head of the pedestrian, and the body of the vehicle could assist in reducing the number of fatal outcomes in such crashes.

The role of bull bars and their recent proliferation in Australia is no doubt significant in the consideration of pedestrian-friendly aspects of vehicle design.

Design changes which effect a reduction in harm potential have the ability to reduce the level of road trauma across the entire spectrum of pedestrian crashes regardless of their cause or circumstance.

The Federal Office of Road Safety has initiated a research program to assess the potential benefits from pedestrian-friendly vehicle design.

Technical Session 8

Side Impact and Upper Interior Head Protection

Chairperson: Richard Lowne, United Kingdom

HEAD AND NECK INJURY IN SIDE IMPACTS

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Paper Number 96-S8-O-01

ABSTRACT

This paper discusses the injuries that result from side impact crashes in Australia, and identifies the high incidence and cost to the community of head and neck injury. The limitations of injury risk measurement are discussed, as well as the need to achieve protection for the whole community. It cautions that strategies concerned with only one performance measure (such as government regulation or NCAP test) can lead to ineffective protection for the community. It proposes the use of a biomechanical injury cost model in the development of occupant protection to achieve the maximum benefit to the Australian community, in terms of minimisation of injury and cost to the community.

INTRODUCTION

Road safety in Australia has traditionally been measured in terms of fatality reduction. This has been a valuable focus, encouraging the legislation for compulsory seat belt wearing, which has been of great benefit to our community. It is now more appropriate to consider in addition, the cost to individuals and the community of long term and irrecoverable injury. The measure of community cost, including hospitalisation costs, rehabilitation costs and lost earnings, and provides a broader perspective than cost benefit decisions made on crash fatalities alone. This type of analysis helps focus attention on the relative importance of injury as a leading health risk in our community, and allows a systematic priority setting for safety development.

Side impact crashes are more hazardous for the vehicle occupants than are frontal crashes, because of the limited structure for energy absorption. Fatal side impacts frequently involve high collision speed and extensive damage to the struck vehicle. The biggest risk with side impact is head injury. Only a minor proportion of injuries are related to contact with the door (8). An examination of the causes of side impacts indicates that driver error is responsible for most accidents at intersections. Typically, younger drivers don't stop, and older drivers pull out into the path of approaching traffic. The impacting vehicle usually has right of way.

Head Injury

There is a growing awareness of the incidence of non-fatal brain injuries and their impact on the individual, the family unit and the community. It is becoming evident that brain injury is a major social issue. The long term consequences and the personal cost of a brain injury are very evident to the victim and to those close by. The community cost is progressively becoming evident. Figure 1 shows data from the Westmead Hospital in Sydney (1).

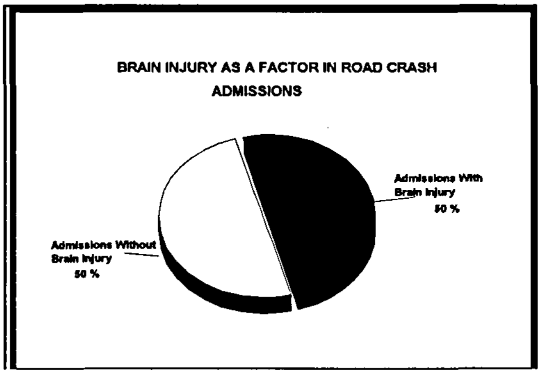

Figure 1. Proportion of Admissions With Brain Injury

There has been a dramatic increase in brain injury in the last decade, not as a result of increased accidents, but because of increased survival. This has resulted from the use of ambulances with life support systems, helicopter ambulances and the use of cat scans to identify haemorrhaging and location of blood clots. Seven million head injuries occur annually in the United States. No Australia wide data is available, but at least 3000 people each year in Victoria are identified as having suffered non-fatal, irrecoverable head injuries. Around 60% of all compensation costs are as a result of head injury.

Neck Injury

Mass data from the USA shows that a significant proportion of side impact fatalities are due to neck injury, Figure 2 (2).

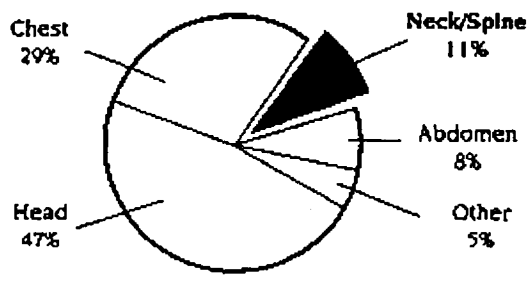

Figure 2: Fatal Injury

The vast majority of neck injury is chronic pain and muscle damage, causing discomfort and debilitation, as shown in Figure 3.

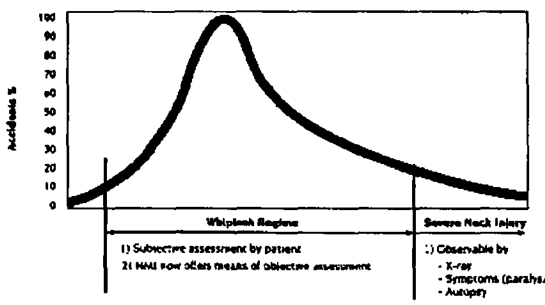

Figure 3: Neck Injury Type

These are potentially the injuries not documented by hospitals or accident research groups in Australia. It is now recognised that neck injuries have a significant cost, to both the individual and to society apart from the pain and suffering. Figure 4 shows the severity of neck injuries resulting from crashes.

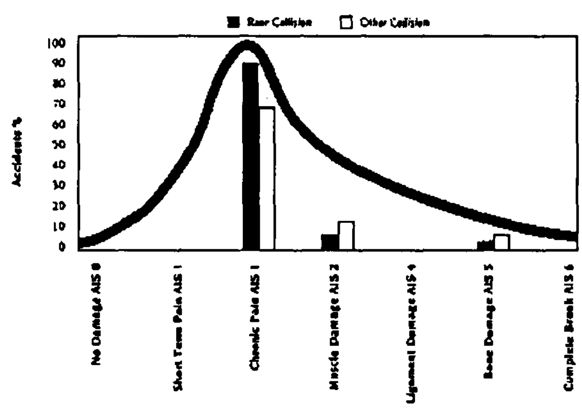

Figure 4. Neck Injury Severity

Current understanding of human injury indicates that body deformations are the causal factor of chest and abdominal injury. Long term and irrecoverable injuries of the neck are also expected to be the result of soft tissue injury. A predictor of soft tissue injury severity is the Viscous Criterion, a measure developed by Dr David C. Viano and Dr Ian V. Lau of General Motors Research and Development Center. Two important components are required to accurately assess neck injury risk in a crash. The first is the use of a crash test dummy that responds in a biofidelic, or human-like way, both in global kinematics, and in response to localised loading. The second is the ability to measure the viscous response of local regions of the dummy body in order to evaluate the injury risk to internal organs and tissues.

Measurement of Head and Neck Injury Risk

Three dummies are used for assessment of injury risk - SID, EuroSID, and the latest and most biofidelic dummy, BioSID. The SID dummy was the first side impact dummy developed, and has relatively poor biofidelity. The SID dummy can't measure head or neck injury risk. Not only is the biofidelity of the SID dummy inadequate in terms of head, neck and thoracic response, the lack of arm does not result in appropriate representation of the interaction between the occupant's arm and the impacting structure. Loading due to local hard spots such as an arm rest or window regulator which represent an injury risk to a human occupant, are enveloped by the soft side of the SID dummy, and do not register an injury risk. Interaction between side impact airbags and the occupant arm are not represented. Strategies which use load paths to couple the dummy to the side structure early in the collision can reduce the dummy-measured acceleration by increasing the time over which the change in velocity will occur. However this will result in increased energy being transferred to the human occupant, with resulting increased injury viscous ad skeletal injury risk. It is thus important to reduce deflection and viscous response in the development of protection.

The EuroSID dummy is a significant improvement on SID, as it can measure head and neck loads. Its kinematics are questionable, due to the unrepresentative shoulder configuration, as the shoulder is a major load path in a side impact crash. It also behaves unrepresentatively if loaded other than along the shoulder axis, making it unsuitable for evaluating the majority of side crash types.

The development of side impact protection utilising either of these test dummies will not provide the best protection for people involved in side impact crashes in Australia. Neither adequately addresses head and neck injury. In Australia, 50% of all fatalities caused by side

collision result from head and neck injury, and irrecoverable head and neck injury is a major concern for our community.

The BioSID represents the best available dummy at this time. Holden safety development utilises BioSID dummies to ensure reduced injury risk is realised in field crashes. Recent research indicates that the lateral response of the Hybrid III neck is a good representation of the human neck response (3).

Computer Modelling

There are currently two methods of simulating dummy kinematics in a vehicle crash. The dummy can be modelled using lumped masses or by finite elements. Lumped mass modelling provides an efficient analysis technique which allows rapid evaluation of a large number of parameters, and is very suited to optimising restraint systems for frontal collision. However, when the crash involves coupling of the dummy with gross deformation of the vehicle structure, as occurs in side impact collisions, it is currently necessary to use an explicit finite element code. Representing the dummy using finite element methods gives excellent results, but greatly increases execution time, making system optimisation more difficult.

Models of the SID dummy have been developed in the USA, and there are models of the EuroSID dummy in Europe, but until recently no models of the BioSID dummy existed. Lumped mass and finite element models of the BioSID have been developed by Holden. (4). These will be used in conjunction with BioSID dummies in the development of occupant protection for side impact crashes.

Side Impact Protection

Side impact protection must address the needs of all members of the community, and this requires that protection is most effective for the crashes that occur most frequently, and for the members of the community most frequently involved in side impact crashes. The number of injuries experienced by the community is a product of the injury probability and exposure frequency at that crash severity. The frequency of side impact crashes against change in velocity, V, in the USA and the associated injury risk is shown Figure 4 (5).

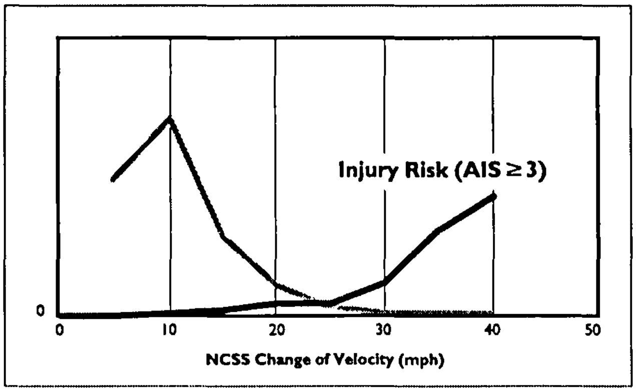

Figure 5: Side Impact Exposure and Injury Risk

As with frontal collisions and NCAP testing, the choice of a single performance target to indicate safety performance inadequate, and potentially misleading approach. Development of side impact protection that delivers the best benefit to the community needs to recognise both exposure frequency and severity, as well as the range of fragility of the community of passengers involved in side impact crashes in the Australian environment.

The inappropriateness of using a single measure is demonstrated by the following example developed by Heulke.

"It is important that frequent exposure conditions have low injury probabilities. For example, a design which halved injury probability in side impact for ΔV's greater than 27 mph would actually increase the number of injured occupants (AIS >=3) if the design added a 1% increase probability for ΔV's less than 13 mph." (6)

The change in injury risk is illustrated in Figure 6, and the resulting change in injury is illustrated in Figure 7.

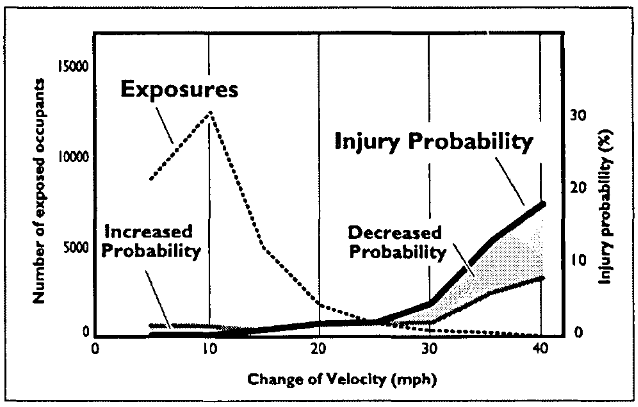

Figure 6. Injury Risk Change

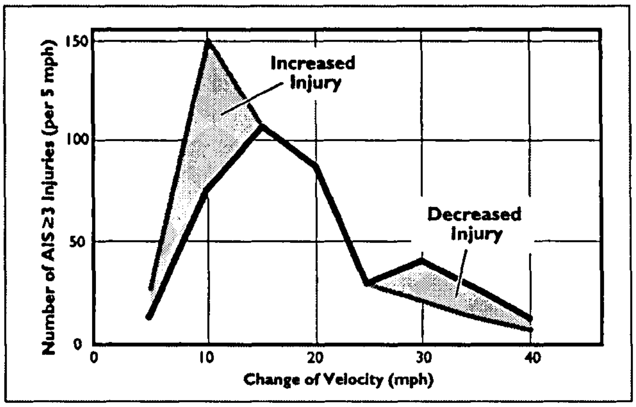

Figure 7. Injury Risk Change

"Injury is distributed across a wide range of car crash severities, indicating that both injury risk and exposure frequency are important concepts. Only when both exposure frequency and injury risk, which considers the range of tolerance , are used in the analysis of test data does the distribution of perceived injury appear similar to that of car crashes. Exposure frequency is a function of exposure severity and must be estimated from crash data. Injury probability functions which recognise the range of tolerance provide a more useful means to infer injury risk than does the use of a single tolerance value. It is essential that frequent exposure situations have low probability of injury." (6)

Biochemical Injury Cost Model

Current technology for frontal crash protection cannot provide one design solution for restraint systems that provides the optimum protection for every size and fragility of passenger in all seating positions, involved in every type and speed of crash. Equally, current technology for side impact crash protection cannot provide one design which provides the optimum protection for every occupant in every collision.

The Weighted Injury Criteria, WIC, developed by Viano and Arepally (7) for frontal impact, has been utilised in the development of restraint systems for minimal societal harm in frontal collisions (8). The same methodology could be applied to a Side Impact Weighted Injury Criteria, in order to optimise occupant protection.

The Abbreviated Injury Scale (AIS) was developed by the Association for the Advancement of Automotive Medicine (9) to provide a method for describing the severity of injuries. In the development of vehicle safety systems, the AIS is used to predict the injury risk associated with a test dummy response. The AIS has also been used to categorise the cost to the community of injuries to various parts of the body for a range of injury severity. A comprehensive analysis exists for the USA, as a result of the work of Miller in 1991 (10) and in Australia by Steedman and Bryan in 1988 (11). The evaluation of a design strategy in terms of cost benefit to the community is a potentially powerful tool that could recognise the crash risks in terms of the varying exposure and crash severity, and varying fragility of the driving community in terms of age, size and sex.

A Biomechanical Injury Cost Model would ensure that the design characteristics chosen result in benefit to the community, in terms of reduced risk of fatality and reduced societal harm. Before a cost model can be utilised for side impact protection decisions, a level of confidence must exist in the correlation between AIS and measured dummy responses in the areas of injury risk of priority in side impact crashes; head injury, neck injury and thoracic injury. Newman, Tylko and Miller have proposed probability distributions for head and thoracic injury (12). Unfortunately, there is currently no established neck injury probability distribution, and so this major source of injury resulting from side impact crashes cannot be appropriately accounted for when balancing vehicle protection characteristics. Use of available neck injury test data to expand the existing discrete injury criteria into probability of injury curves is a desirable first step. A further requirement is to establish the costs of the range of neck injuries experienced in car crashes in Australia. A comprehensive analysis exists for the USA, as a result of the work of Miller. Improved estimates are required for Australia, based on local hospital and treatment costs and ancillary costs (lost income, value for pain and suffering, legal costs), for fatal and non-fatal injuries, as it is to be expected that a significant difference exists between Australian costs and the costs in the USA.

A biomechanical injury cost model for side impact is needed to ensure that the design characteristics of the injury protection system implemented result in benefit to the community, in terms of reduced risk of fatality and reduced Societal Harm. The economic consequences of design changes can thereby be evaluated, and an optimisation process can be utilised to balance the design characteristics between the various demands of collision types and speeds, and occupant exposure and fragility.

Side Impact Protection Optimisation

The process of optimising side impact protection for maximum community benefit is expected to be a more difficult process than that for frontal protection. In a frontal crash, the vehicle impact and the occupants are decoupled, allowing the structure to be optimised initially

(13), and then the restraint system to be optimised to the crash pulse developed (14). However, in a side impact crash, the close coupling of the vehicle and the occupants makes the optimisation process more complex. A more severe structural impact such as a pole crash represents a relatively much more severe impact to the occupants than does a front pole impact.

An injury cost model will be more sensitive to design changes than evaluating against a single measure such as government regulation or an NCAP target, and will result in significantly more benefit to the community.

Conclusions

Head and neck injury resulting from car crashes is potentially a more serious problem than is currently recognised in Australia. Our past focus on road fatality reduction has overlooked the societal harm of long term and irrecoverable brain and neck injury. The development of side impact protection which reduces the risk of brain and neck injury requires an understanding of the risks of injury in Australia, the use of biofidelic test dummies and computer modelling techniques which allow the optimisation of injury risk reduction strategies. Designs can then be developed which result in reduced risk and cost, and hence maximum benefit to the community.

References

1. "Social Cost of Transport Accidents in Australia". Report by the Bureau of Transport and Communications Economics.

2. "Preliminary Regulatory Impact Analysis - Side Impact FMVSS 214", Report by NHTSA Office of Regulatory Analysis, Plans and Policies, January 1988.

3. Seeman, M.R., Muzzy, W.H., Lustick, L.S., "Comparison of Human and Hybrid III Head and Neck Dynamic Response", 30th Stapp Conference, SAE No. 861892, October 1986.

4. Fountain, M., Altamore, P., and Skarakis, J., "Mathematical Modelling of the BioSID Dummy", 38th Stapp Conference, SAE No 942226, Nov 1994.

5. Rouhana, S.W. and Foster, M.E. "Lateral Impact: An Analysis of the Statistics in the NCSS". SAE Paper No. 851727, 29th Stapp Car Crash Conference, 1975, Society of Automotive Engineers Inc, Warrendale, PA.

6. Heulke, D.F., "Near Side Passenger Car Impacts - CDC, AIS & Body Areas Injured", SAE Paper No. 900374, SAE International Congress, Detroit, MI, 1990.

7. Viano, D.C. and Arepally, S. "Assessing the Safety Performance of Occupant Restraint Systems". SAE Paper No. 902328, Society of Automotive Engineers Inc, Warrendale, PA, 1990.

8. Hou, J., Tomas, J., and Sparke, L.J. " Optimisation of Driver -Side Airbag and Restraint System by Occupant Dynamics Simulation" SAE Paper No. 952703, 39th Stapp Car Crash Conference, 1995, Society of Automotive Engineers Inc, Warrendale, PA.

9. "The Abbreviated Injury Scale: 1990 Revision". Association for the Advancement of Automotive Medicine, 1990

10. Miller, T.R., "Motor Vehicle Injury Costs by Body Region and Severity", 35th Annual Proceedings of the AAAM, 421-427, 1991

11. Steadman L. and Bryan R.J., "Cost of Road Accidents in Australia", Occasional Paper 91, Bureau of Transport and Communications Economics, Australian Government Printing Service, Canberra, 1988.

12. Newman, J.A., Tylko, S., Miller, T., "Toward a Comprehensive Biomechanical Injury Cost Model", 36th Annual Proceedings of the AAAM, 271-287, 1992

13. Sparke, L.J., "Optimisation of Crash Pulse Through Frontal Structure Design". Paper Number 96-S4-W-21, 15th International Conference on Enhanced Safety of Vehicles, 1996.

14. Hou, J., Tomas, J., and Sparke, L.J. " Optimisation of Driver -Side Airbag and Restraint System by Occupant Dynamics Simulation" SAE Paper No. 952703, 39th Stapp Car Crash Conference, 1995, Society of Automotive Engineers Inc, Warrendale, PA.

RESEARCH CONCERNING VEHICLE OCCUPANT PROTECTION FOR LATERAL COLLISION

-Accident Analysis of Lateral Collision and Vehicle Characteristics in Japanese Market-

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Paper Number 96-S8-O-02

ABSTRACT

Lateral collision in automobile accidents are recognized as a serious accidents because very little space is available on the side of the vehicle, to absorb the energy of the impact. Test procedures for evaluating the capabilities of a vehicle for protecting the occupants in lateral collision have been applied in the United States since 1993, and are expected to be applied in Europe in 1998. In Japan, in the report of the Council for Transport Technology presented in 1992 on this subject, lateral collision occupant protection was adopted as a middle term study item and studies are in progress for finding an appropriate test procedure to be adopted in Japan.

This paper reports the results of analyses of lateral collision accidents in Japan, and also outlines the results studies of test conditions for a lateral collision testing procedure to be introduced into Japan.

Samples of lateral collision accidents were taken from traffic accident data of the National Police Agency for 1993 and from the data file of the Ministry of Transport for accidents from 1973 to 1992. Analysis of lateral collision accidents was implemented with respect to (1)frequency of accidents, (2)types of vehicles involved in the accidents, (3)distribution of impact velocities, (4)distribution of impact direction, (5)deformation of the collided vehicles, (6)location of occupant injury and the object damage and (7)seating location of the occupants in the vehicle, etc.

The results of the analysis of lateral collisions were compared with the test conditions for the lateral collision test procedures introduced in the US and Europe, specifically, for impact configuration, impact velocity, impact point, and the like. The conditions of the lateral collision testing procedures to be introduced into Japan were studied based on the results of this comparison. In addition, the effects of injury reduction expected when the test procedures would be introduced was estimated for lateral collision accidents in Japan.

INTRODUCTION

Research of test methods for evaluating the performance of vehicle occupant protective measures for lateral collisions has been centered around the United States, Europe, and Japan. In the US it has been decided that, in addition to the static tests which have been used up to the present, actual vehicle collision tests are necessary. In 1990 the new Federal Motor Vehicle Safety Standard 214 (FMVSS214) was enacted and its stepwise application to passenger vehicles has been commenced. October 1998 is the target date for applying this standard in Europe. In both the European and US test methods a Moving Deformable Barrier (MDB) is impacted against the side surface of the vehicle and the results are evaluated according to the injuries value sustained

by a dummy which is loaded into the vehicle for lateral collision test. In Japan, the protection of the vehicle occupants for lateral collisions was proposed as an middle-term study item in a recommendation in a Council for Transport Technology. The introduction of such evaluation test methods conforming to realities in Japan is being expedited. This studies are being made to devise test methods from a full understanding of accident analysis.

This report was undertaken in cooperation with the Japanese Ministry of Transport (MOT) and the Japan Automobile Manufacturers Association, Inc.(JAMA), with the objective of obtaining basic data for the introduction of lateral collision test methods in Japan. It includes the results of investigation for realities of lateral collision accidents and characteristics of motor vehicle. A comparison of these results with European and US results is also included.

TRAFFIC ACCIDENTS REALITIES

Outline of Traffic Accidents in Japan

As shown in Figure 1, the number of fatalities in traffic accidents in Japan reached a peak of 16,765 person in 1970 and thereafter declined by almost one half to 8,466. The trend then proceeded sideways thereafter and a steady increase was once again observed after 1998 and reaching almost 11,000 persons from 1989 on. Observation of the trend in the number of fatalities occurring under different accident conditions, as seen in Figure 2, showed an increasing trend for occupants of passenger vehicles only, while trend proceeded sideways for pedestrians and occupants of two-wheeled vehicles. This is presumed to have resulted from the separation of sidewalks and roadways and the installation of signal lights, etc. which occurred after 1970. In this manner, the percentage of the passengers in a car to fatalities increases and Japanese traffic accidents become close to the accidents analysis of European and US type gradually. Figure 3 shows the number of occurrence of different types of traffic accidents with all accidents and fatal accidents. The percentage of vehicle mutual accidents is the largest in any case and it exceeds 80% of all accidents less than 50% of fatal accidents. The percentage of single vehicle accidents and the accidents of vehicle-pedestrian was about 10% of all accidents. But it increased to about 25% to fatal accidents. It means that the damage of single vehicle accidents and the accidents of vehicle-pedestrian are serious compared with those of vehicle mutual accidents and it is easily surmised that sufferer of vehicle-pedestrian accidents are the non-guard persons.

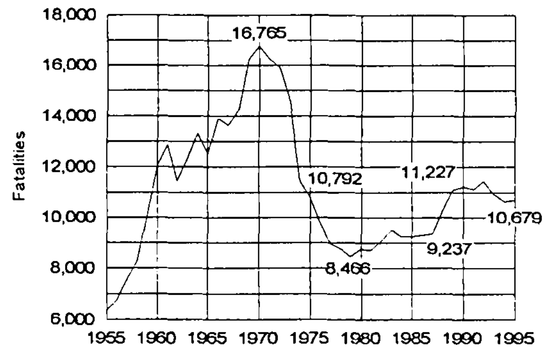


Figure 1. Annual trend of fatal traffic accidents.

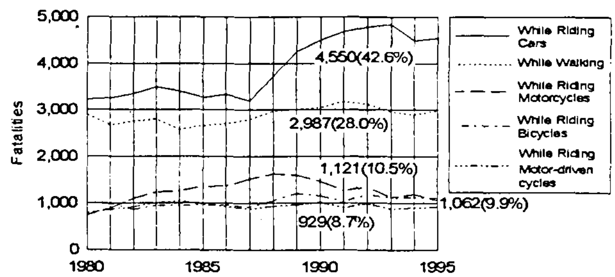


Figure 2. Annual trend in number of fatalities occurring under different accident conditions.

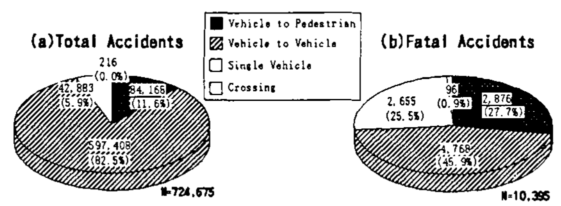


Figure 3. Number of occurrences of different types of traffic accidents.

Figure 4 shows the result of classifying the accidents with types restricting to the accidents of the highest percentage, vehicle mutual accidents. From this figure, the percentage of the accidents bumping into each other as they pass is highest in the both case of all accidents and fatal accidents, it occupies about 30% respectively.

In the few front end collisions which make up less than 10% of the total, fatal accidents have increased to 30%, causing high concern about fatalities. Conversely, in rear end collisions which make up 30% of the total, fatal accidents have been reduced to 10%.

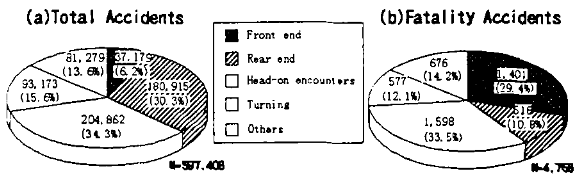


Figure 4. Number of occurrences of different types of vehicle mutual accidents.

In order to discuss the safety of automobile occupants with respect to the automobile structure, the analysis was restricted to occupants of passenger vehicles and the different parts of the automobile which received damage were analyzed because this is difficult to understand from an investigation of the different types of accidents. The results are shown in Figure 5. The locations receiving damage are divided into three - the front surface, the side surface, and the rear surface. The percentage of the number of persons receiving injuries in an accident in which the side surface of the vehicles received damage (supposing as a lateral collision) is the smallest at 14% (69,362 persons), and the percent of fatalities increased to about 25% (1,133 persons). This is surmised to be because mortal injuries are easily incurred because a person riding in a car in a frontal collisions can easily hit his head against the front glass, etc. If the percentage of fatalities to casualties is called the fatality ratio, this ratio for frontal collision is 1.7%, for lateral collisions 1.6%, and for rear end collisions 0.1%. Therefore the fatality ratio for occupants of vehicles involved in side collisions in high. These results also show that the protection of occupants for a lateral collision is very important.

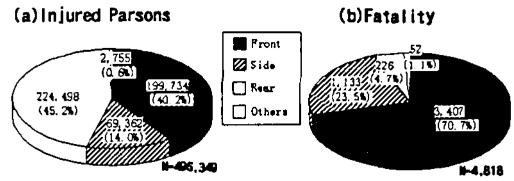


Figure 5. Number of casualties with different injury location of passenger in automobiles.

Realities Investigations of Lateral Collision Accidents

Data on accident statistics used in the investigations are from the National Police Agency traffic accident statistics for 1993 and the accident files of the Ministry of Transport from 1973 to 1990. Two types of statistical data were used because a microanalysis was not possible from the National Police Agency data alone and because that part complemented the Ministry of Transport data. From among these, examples of accidents in which the side of a vehicle of a first interested party or that of a second interested party was damaged were made the object of investigation. Injury to the occupants was examined only for occupants of vehicles with side damage. Injury to the occupants of the other vehicles in the accident was not considered. Further, the degrees of injury were classified as "no injury", "light injury" (requiring less than 30 days of treatment), "heavy injury" (requiring in excess of 30 days of treatment), and "fatal injury" (death within 24 hours).

<u>Different Types of Lateral Collision Accidents</u> - Based on the National Police Agency data, the accidents were divided into two types - those involving two automobiles and those involving a singe automobile. Figure 6 shows the rations of different degrees of injury to the

occupants of the side-damaged vehicle. The results show that vehicle mutual accidents accounted for almost 95% of the light injuries, while more than half to 60% of fatalities occurred in mutual vehicle accidents. This is presumed to be because accidents occurring simply because of a mistake on the part of the driver are decreasing because of paved roads, while vehicle mutual accidents are increasing because of the increase in the number of automobiles on the road. In both the European and US test methods, they simulate the vehicle mutual accidents, and this is also believed to be the case in Japan.

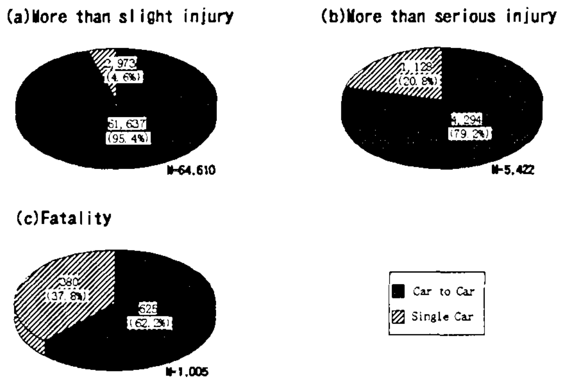


Figure 6. Ratios of different degrees of injury to occupants in lateral collision accidents.

<u>**Different Types of Vehicles in Lateral Collision Accidents**</u> - An analysis restricted to mutual vehicle accidents will be made from the above results from now.

From the National Police Agency data, the different types of vehicles making up the colliding vehicle and the collided vehicle in mutual vehicle accidents were investigated for vehicles involved in lateral collision accidents. The composition ratios are shown in Figure 7 and Figure 8. The vehicle receiving damage to its front surface is taken as the colliding vehicle and the vehicle receiving damage to its side surface as the collided vehicle. The vehicles in the figures are classified into 13 types in accordance with the classification system of the National Police Agency. A, B, and C classifications signify vehicles with body types referred to as one-box models, bonnet models, and cab-over models. In the distribution of the different vehicles types in the case of a mutual vehicle accident, the passenger vehicle B, specifically the bonnet model passenger vehicle, is the most plentiful. This is because the percentage of passenger vehicles among vehicles in Japan is naturally large. As reference, the number of automobiles owned in Japan at the and of 1993 is shown in Figure 9. However, because this data is based on the Statistics of Ministry of Transport, the method of classifying the different types of vehicles differs from that of the National Police Agency data.

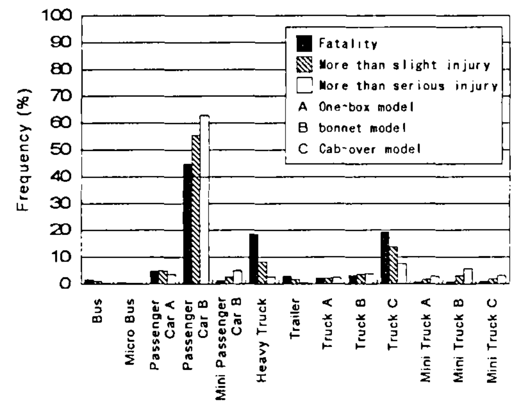


Figure 7. Degree of injury to occupants of side collided vehicles by different types of colliding vehicle(frontal collisions).

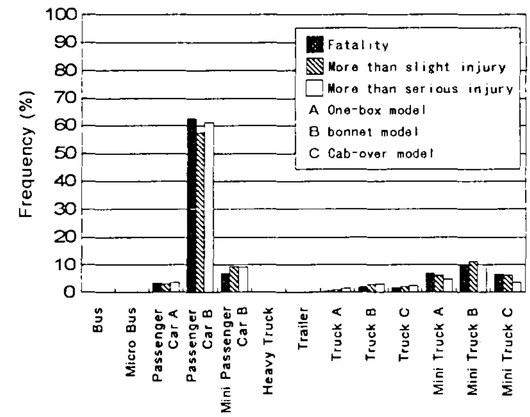


Figure 8. Degree of injury to occupants of side collided vehicles by different types of collided vehicle(lateral collisions).

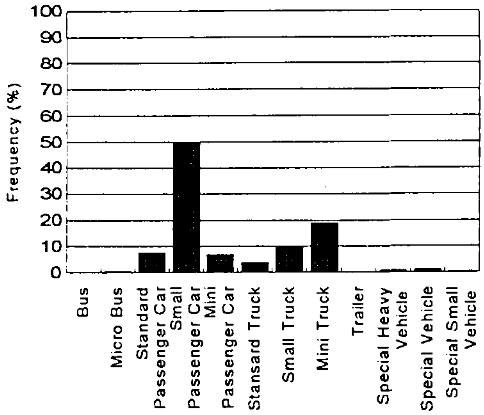
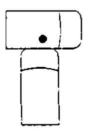
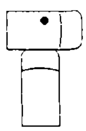
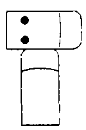


Figure 9. Ratio of occupation of different vehicle types of retention vehicles.

<u>Position of Occupant in Lateral Collision Vehicle when Accident Occurs</u> - From the National Police Agency data, Table 1 shows the results of investigating the number of fatalities when classifying the occupants in the lateral collision vehicle as to their different locations.

Table 1.
Ratio of number of casualties to location of occupants in lateral collisions

		Front seat of crashed side 	Front seat of not crashed side 	Rear seat 
Number of people	More than slight injury	21,796	16,671	4,952
	More than serious injury	1,583	890	400
	Fatality	232	138	62
Ratio	More than slight injury	50.20	38.40	11.41
	More than serious injury	55.10	30.98	13.92
	Fatality	53.70	31.94	14.35

From the table, about 90% of the fatalities in a lateral collision accident are front seat passengers. In addition, the front seat passengers on the crashed side are known to make up more than half the total. This is believed to be because the ratio of occupants in the rear seat is naturally low. It can be perceived that the collision side of the front seat is under extreme conditions, receiving a more direct impact. Based on these results, the analysis will hereafter be restricted to the front seat passenger on the collision side in a bonnet model passenger car.

<u>Velocity of Related Vehicles when Accident Occurs</u> - Figure 10 shows the results from the National Police Agency accident data for the velocity directly before the accident in a lateral collision accident. In their accident statistics the National Police Agency has adopted the running velocity at which the driver operated the vehicle immediately before the accident, in order to avoid the accident, rather than the collision velocity. This is a value higher than the actual collision velocity. From this result it can be surmised that the damage to the occupant increases because the higher the velocity of the colliding vehicle, the higher the impact on the collided vehicle. At a collision velocity of 50 km/hr, the cumulative 90th percentile above the light injury classification corresponds to the cumulative 70th percentile above the heavy injury classification. This covers the larger portion of injuries resulting from a lateral collision accident.

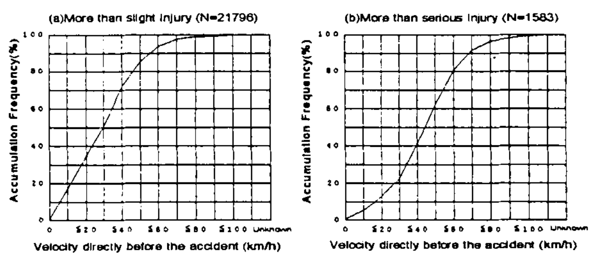


Figure 10. Distribution of running velocities directly before accidents.

<u>Direction of Collision</u> - The results of a study of the Ministry of Transport accident data covering the angles between the colliding and collided vehicles at the moment of collision in a lateral collision accident are shown in Figure 11. This graph shows that the angle formed between the two vehicles is 90°, right angle, in about 70% of total accidents. The angle described here is based

on the direction in which the collided vehicle was proceeding, and does not discriminate the right and left.

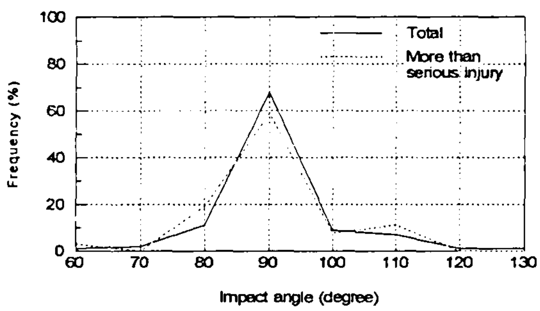


Figure 11. Distribution of angles between vehicles at moment of collision.

<u>Realities of Injury to Occupants</u> - Figure 12 shows the locations of injuries received by the front seat occupants on the collision side of the collided vehicle arranged by different degrees of injury, taken from the National Police Agency accident data. This graph shows that there is a tendency for injuries in the head, neck, thoracic, and pelvic regions to be comparatively frequent for the location of the injured occupants in a lateral collision, and the ratio of head and thoracic injuries increase as the degree of injury increases. In particular, head injuries make up more than 50% of injuries sustained in fatal accidents. This trend is close to the results from investigation of the basic data in the European test methods. In the US, the thinking differs with respect to the location of injuries received by the occupant. Normally, internal organs, etc., are treated as part of the abdomen and are included in the thoracic region. Therefore the US results show that the degree of injury is high in the thoracic and pelvic regions.

Because the acquisition of data for standards of injuries to the living body is difficult in Japan, there is no investigative data to report. However, accidents realities in Japan are believed to almost conform to the injury standards in the European test methods when considering the location of the above-mentioned injuries caused by an accident.

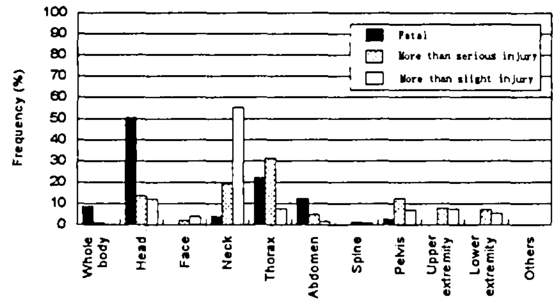


Figure 12. Distribution of injury location in vehicle mutual accidents.

Examination of the dummies used in the European and US side collision test methods reveals that there are major differences in the structures of the SID used in the US tests and the EUROSID-1 used in the European test as well as differences in the items measured, and the like. The dummies are determined spontaneously from the details of the injury standards introduced into the test methods. The results of an ISO study about the degree of faithfulness to a living human body provided by the dummy including actual Japanese results, show that the EUROSID-1 provides an adequate degree of faithfulness to the living body and reproducibility when used in lateral collision tests, but the SID cannot be said to provide such an adequate degree of faithfulness.

CHARACTERISTICS OF JAPANESE VEHICLES (MDB SPECIFICATIONS)

The market realities for domestically produced bonnet model passenger vehicles launched in 1993 was investigated to decide on the main items for the MDB used in lateral collision tests in Japan. In the actual investigation, empty vehicle weight, dimensions of each part of the front surface, and frontal stiffness were examined for all vehicle types sold domestically. The data obtained was weighted according to the number of the respective vehicles sold.

Weight of Vehicle

The empty vehicle weight of the cumulative 50^{th} percentile of Japanese passenger vehicles is 1080 kg, as shown in Figure 13. A comparison with the European and US test methods shows that this is about 290 kg lighter than the US MDB and about 130 kg heavier than the European MDB. The US MDB weight is based on the empty weights of the cumulative 50^{th} percentile of passenger vehicles and light trucks contributing to lateral collision accidents resulting in injuries classed as heavy or greater in 1986. Provision has also been made to include a forecast of lighter vehicle weights in the future. The weight of the European MDB is based on the cumulative 50^{th} percentile of empty weights of passenger vehicles sold in 12 European countries in 1976. In addition, the weight of one occupant is added to the empty weight of the vehicle to determine the weight of the European MDB. The investigation of vehicles in Europe and the US was implemented more than 10 years before such investigations began in Japan. It is believed that if the empty weights of Japanese vehicles had been investigated at that time, the value of the cumulative 50^{th} percentile of 865 kg would be close to the results of the European investigation.

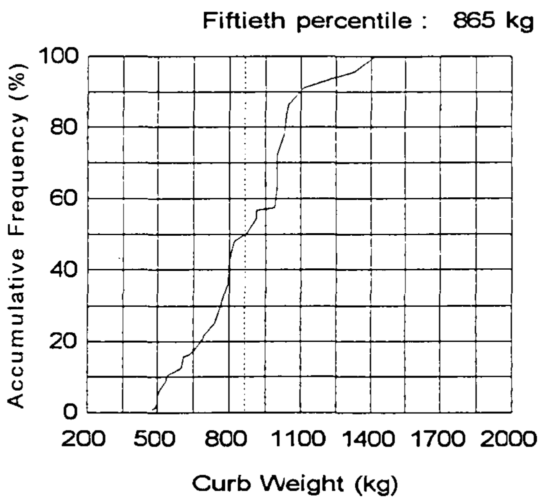


Figure 13. Cumulative ratios of vehicle weights.

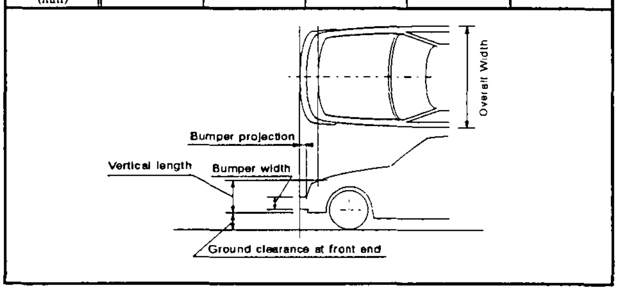
Front Dimensions.

The cumulative 50^{th} percentile of the amount of bumper projection, bumper width, and minimum height above ground of Japanese automobiles are 61mm, 290 mm, and 240 mm respectively, as given in Table 2. The structure of front surface contains parts which do not contribute to the stiffness in a collision. Also, it is thought that dimension changes result from deformation in a collision. When these factors are taken into account, an examination of the vertical length at a position 300 mm toward the rear from the front end and of the front dimensions with the distance between the corner sections at both ends of the bumper as the width shows that the cumulative 50^{th} percentile of the dimensions are 500 mm, and 1570 mm respectively.

The results of an analysis made in the US, with 1978 autos as the base, showed that for the MDB dimensions the vertical length was 559 mm, the width 1676 mm, the bumper projection 102 mm, the bumper width 203 mm, and height above ground 280 mm.

Table 2.
Cumulative average values and location of parts of vehicle front surfaces

Part	Overall width	Vertical length	Bumper projection	Bumper width	Ground clearance at front end
Dimension (mm)	1685	426	61	290	240



An investigation was made in Europe using 45 types of 1976 model vehicles. Using the barrier dimensions developed by the European Experimental Vehicle Committee (EEVC), the Transport Research Laboratory (TRL), and the Committee of Common Market Constructors

(CCMC) respectively as reference, the values obtained for the MDB dimensions were vertical length, 500 mm, width, 1500 mm, bumper projection, 60 mm, bumper width, 250 mm, and height above ground, 300 mm.

From the above values, the front dimensions of Japanese automobiles can be said to be close to the European MDB dimensions.

Frontal Stiffness

The characteristics of the MDB used in the European lateral collision testing methods were determined obtained from load-displacement characteristics of a representative 15 types of 1976 model passenger cars, resulting in a six part structure of two parts vertical and three parts right and left.

When the load-displacement characteristics for the fronts of almost all types of Japanese automobiles is arranged by the cumulative averages for each amount of displacement, as shown in Figure 14, most fall within the range of characteristics for the European-proposed MDB.

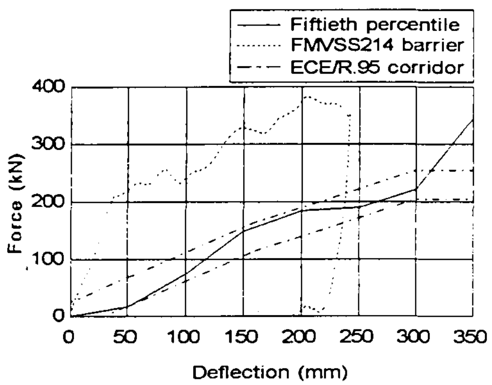


Figure 14. Comparison of frontal stiffness of Japanese vehicles and characteristics of European and US MDB.

The frontal characteristics of the MDB used in the US lateral collision testing method were investigated using 1978 vehicles as the object. Based on the frontal characteristics of the Chevrolet Citation as the representative of that type of vehicle, these characteristics were considered to be equivalent to those of a small truck. As shown in Figure 14, the Japanese cars showed widely different characteristics for frontal stiffness.

The above results show that the frontal stiffness characteristics of Japanese vehicle are also close to those of the European MDB.

CONCLUSION

Japanese accident analysis and vehicle characteristics in Japanese market were investigated and compared with the test conditions for the European and US testing methods for lateral collisions. A summary of the results is given in Table 3. A summary of this report including Table 3 is as follows.

(1) No large differences were observed in the distribution of the injury locations for Japanese lateral collision accidents realities and injury realities. It would rather close to European conditions.

(2) Japanese values for vehicle weights were almost midway between the European and US investigation results. However, the Japanese investigations lagged the European and US investigation by about 15 to 20 years. If vehicles from the same period had been studied, it can be assumed that the Japanese investigation results would be close to the European and US results.

(3) As with the weights, the periods for the Japanese investigations of vehicle frontal dimensions differed from those of the European and US investigations, but the results were close to the European results. This is thought to be because there were no great differences in the vehicle dimensions over a period of 20 years.

(4) If all characteristics of frontal stiffness are examined, the results are in the range of the European-proposed MDB characteristics and approach the European MDB characteristics.

Based on these results, Japan will introduce regulations equivalent to the European test method

with a target date of October 1998. Lateral collision standards will be introduced by the point adjusting the European standards to make them somewhat stricter and harmonizing with European standards. The height above ground of the MDB is scheduled to become 300 mm.

Table 3.
Comparison of European and US testing methods and Japanese investigation results

		ECE/R. 95	FMVSS214	Japan
Weight (kg)		950	1369	1080
Width (mm)		1500	1676	1567
Length (mm)		500	559	500
Depth (mm)		500	482	—
Ground clearance (mm)		260	280	240
Stiffness (kN)	Dfl. 100mm	60～110	245	75
	Dfl. 200mm	140～190	380	175
	Dfl. 300mm	210～260	—	210
Material		Non regulation	Aluminum honeycomb	

REFERENCE

D.R.Gebbels, "The CCMC Mobile Deformable Barrier for Lateral Collision Testing". 10th ESV. July 1985.

S.Davis, C.Ragland, "Development of a Deformable Side Impact Moving Barrier". 8th ESV. October 1980.

M.Ueno, T.Harigae, H.Ohmae, "A Current Situation of Side Collision Accidents in Japan". Journal of JARI No.95028. October 1995.

NHTSA, "Final Regulatory Impact Analysis "New Requirements for Passenger Cars to Meet a Dynamic Side Impact FMVSS 214"".

ECE/R.95, "Uniform Provisions Concerning the Approval of Vehicle with Regard to the Protection of the Occupants in the Event of a Lateral Collision".

Traffic Safety Policy Office Management and Coordination Agency, "White Paper on Traffic Safety '92 in Japan Abridged Edition".

National Police Agency, "Statistics '94 Road Accidents Japan".

EEVC Working Group, "Structures Improved Side Impact Protection in Europe". 9th ESV. November 1982.

M.Danner, K.Langwieder, "Car/Vehicle Side Impacts-A Study of Accident Characteristics and Occupant Injuries". 6th ESV. October 1976.

A.Burgett, J.R.Hackney, "Status of the National Highway Traffic Safety Administration's Research and Rulemaking Activities for Upgrading Side Impact Protection". 7th ESV. June 1979.

K.Ono, T.Sato, "Review of MOT Vehicle Accident Investigation in Past Seven Years". 9th ESV. November 1982.

THE ROLE OF THE UPPER INTERIOR IN CAR OCCUPANT BRAIN INJURY

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ABSTRACT

Crashes involving passenger cars have been investigated as part of the ongoing study of brain injury mechanisms being conducted by the NHMRC Road Accident Research Unit (RARU) and also in the course of an at the scene in-depth study of rural road accidents.

The information available in 74 fatal cases includes the results of a detailed investigation of the vehicle and the crash circumstances, and the neuropathologist's report on the nature and extent of the injury to the brain, together with details of other injuries sustained by the occupant in the crash. The exact location of the impact or impacts to the head has also been recorded. In 43 non-fatal cases, the information on the injury to the brain is based on neurosurgical diagnosis, often supported by the results of CT scans.

On a case by case basis, selected characteristics of the injury to the brain are related to characteristics of the impact to the head and the object struck to identify those cases in which the provision of some means of energy absorption might reasonably be expected to prevent, or significantly reduce the severity of, the injury to the brain in a similar crash.

INTRODUCTION

The aims of this investigation were to examine the role of the upper interior of the passenger compartment in the occurrence of brain injury to crash-involved car occupants and to assess the likely benefit of padding.

METHOD OF INVESTIGATION

Case Selection

The investigation was based on three samples of crash-involved car occupants studied by the NHMRC Road Accident Research Unit (RARU).

Two of the samples were investigated in the course of an on-going study of brain injury mechanisms in road crashes. The first of these comprises car occupants who were fatally injured and who sustained a brain injury, although it was not necessarily the cause of death. The few cases in this sample who did not sustain any discernible brain injury are not included in the following analyses.

The second sample from the study of brain injury mechanisms consists of injured car occupants who were admitted to neurosurgical care at the Royal Adelaide Hospital or the Adelaide Children's Hospital.

The third sample of cases was drawn from car occupants who were injured in rural road crashes to which an ambulance was called. Each of the crashes was investigated at the scene by a member of the NHMRC Road Accident Research Unit before the vehicles had been moved. The cases selected from this sample all had evidence of some degree of brain injury, although it was often of minor severity.

It should be noted that this investigation is based solely on cases in which a car occupant sustained a discernible brain injury. Therefore it is not possible to estimate the risk of a crash-involved car occupant sustaining a brain injury from the data presented.

Rating Brain Injury Severity

The severity of the brain injury in each case was assigned to one of three categories: minor, moderate or severe, according to the following criteria:

For non-fatal cases:

Minor: Evidence of concussion or a period of unconsciousness,

Moderate: Prolonged unconsciousness, usually resulting in some degree of permanent neurological impairment, and

Severe: Brain injury of a severity likely to be unsurvivable. (There were no such cases in the non-fatal sample.)

In the fatal cases:

Brain injury severity was assessed according to the nature and extent of the brain lesions identified by neuropathological examination and the cause or causes of death as determined at autopsy by the forensic pathologist.

Impact Location on the Head

All of the cases selected had an identifiable point of impact on the head. In cases in which there was more than one impact to the head the location was taken to be the point of the more significant impact.

The location of the impact on the head in the fatal cases was determined by a RARU investigator at the autopsy.

Object Struck by the Head

A detailed inspection was made of the vehicle or vehicles involved and the crash scene in an attempt to determine the object associated with the sole, or main, impact to the head. This inspection was performed with knowledge of the nature of the scalp lesion resulting from the impact. In the absence of evidence of a head impact with an identifiable object, the object struck is listed as unknown.

RESULTS

In total, 117 cases met the above selection criteria. Seventy four (63%) of the 117 cases were fatal.

Characteristics of the Cases by Outcome

The characteristics of the cases are summarised in Table 1 in terms of age, sex, seated position, belt use and ejection, together with whether the outcome was fatal or non-fatal.

There were no meaningful differences between the fatal and non-fatal cases by either age or sex. There was a higher percentage of fatal cases who were more than 75 years of age, as would be expected because case fatality rates are higher for the elderly, but the numbers of cases were very small in this age group.

More than 80 per cent of the injured occupants listed in Table 1 were seated in the front seat and most of them were drivers. There were more occupants who were wearing a seat belt at the time of their crash than those who were not, in both the fatal and non-fatal groups. However, the belt wearing rate was very much lower than was seen in surveys of belt use in the general population of car occupants. For example, a survey based on the capital city and selected rural areas of South Australia in 1988 yielded an estimated belt wearing rate of 85 per cent. (Rungie and Trembath, 1988)

There was a higher percentage of fatal than non-fatal cases for which belt wearing could not be reliably established. This was partly due to the severity of the damage to the vehicles in some of the fatal cases but it is likely that in most of the cases for which belt wearing is listed as "unknown" the belt was not worn.

The frequency of jection from the car was greater among the fatally injured cases, which is consistent with the well established increased risk of sustaining a severe or fatal injury if ejected.

The higher proportion of fatal than non-fatal cases involved in crashes in 60 km/h speed limit zones was primarily a consequence of most of the latter group being drawn from the study of rural crashes on roads having a speed limit of 80 km/h or greater.

Table 1.
Characteristics of the Cases by Outcome

	Outcome		(Column %)
Variable	**Fatal**	**Non-Fatal**	**Total**
Age (years)			
0-15	9.5%	9.3%	9.4%
16-30	54.1	48.8	52.1
31-45	14.9	20.9	17.1
46-60	8.1	14.0	10.3
61-75	5.4	4.7	5.1
76+	8.1	2.3	6.0
Sex			
Male	68.9	72.1	70.1
Female	31.1	27.9	29.9
Seated position			
Driver	54.1	60.5	56.4
Front centre	1.4	-	0.9
Front left	33.8	20.9	29.1
Rear right	2.7	9.3	5.1
Rear centre	-	4.7	1.7
Rear left	8.1	4.7	6.8
Seatbelt worn			
Yes	40.5	48.8	43.6
Probably yes	5.4	2.3	4.3
Probably no	8.1	7.0	7.7
No	23.0	39.5	29.9
No belt available	1.4	-	-
Unknown	21.6	2.3	14.5
Ejection			
No	87.8	95.3	90.6
Partial	2.7	-	1.7
Complete	4.2	9.5	12.0
Speed limit (km/h)			
60	32.4	20.9	28.2
80	16.2	11.6	14.5
100	9.5	7.0	8.5
110	41.9	60.5	48.7
Total: Row %	63.2	36.8	100.0
No. of cases	74	43	117

The year of manufacture of the case vehicles ranged from 1966 to 1990 with both the mean and the median year being 1977. The age of cars in use in Australia has not changed greatly over the past decade. It has clear implications for the rate at which improvements in the crashworthiness of new cars can be expected to benefit the whole population of car occupants.

Head Impact and Injury by Outcome

The locations of the impact points on the head are grouped into five categories shown in Table 1, with the boundaries between the zones being at 45 degrees to the fore and aft axis of the head as viewed from above, and the fifth category being for impacts on the vertex.

More than 85 per cent of the impacts were to the front or sides of the head in both the fatal and non-fatal cases. (Table 2) There was a higher percentage of impacts to the sides of the head among the fatal cases. This difference is statistically significant (Chi square $_{1\ d.f.} = 4.11$, $p < 0.05$) but no allowance has been made for possible differences in the severity of the impacts to the head in the two outcome groups.

Table 2.
Head Impact and Injury by Outcome

Variable	Outcome	(Column %)	
	Fatal	**Non-Fatal**	**Total**
Impact on head			
Front	41.9%	65.1%	50.4%
Left	17.6	14.0	16.2
Right	25.7	9.3	19.7
Rear	12.2	4.7	9.4
Top	2.7	7.0	4.3
Skull fracture			
Yes	59.5	34.9	50.4
No	40.5	65.1	49.6
Brain injury			
Minor	21.6	74.4	41.0
Moderate	12.2	25.6	17.1
Severe	66.2	-	41.9
Total: Row %	63.2	36.8	100.0
No. of cases	74	43	117

Skull fracture was proportionally almost twice as common in the fatal group, mainly because 70 per cent of the non-fatal cases were taken from the rural crash study files. The case selection criteria for that study included only a requirement that an ambulance be called to the scene of the crash. Although those criteria are modified here by the selection of cases who had evidence of injury to the brain, many of those cases of brain injury were of minor severity.

The definition of brain injury severity naturally resulted in a high percentage (66.2%) of the fatal cases being rated as severe. Brain injury was in fact the sole cause of death in most (61.2%) of these severe cases. In the cases in which death was not thought to have been due to injury to the brain, most (68%) had a fatal injury to only one body region, with the remainder having multiple fatal injuries to body regions other than the head.

The ratio of minor to moderate brain injury severity among the non-fatal cases was higher than for the fatal cases. Once again, this was largely a consequence of the case selection criteria for the rural road crash study, as noted above.

Brain Injury Severity

The severity of the brain injury sustained by each occupant was assigned one of three levels, as noted above. The distribution of the variables listed in Table 1 is shown in Table 3 by brain injury severity. As noted above, the number of cases in the various categories is often small, and no attempt has been made to control for the severity of the impact to the head.

There was little evidence of a relationship between brain injury severity and seated position. Although seat belt wearing does not appear to be associated with brain injury severity in Table 3, in most cases in which seat belt wearing is listed as "unknown" it is likely that the belt was not worn, as noted earlier. If that possibility is allowed for, there is an inverse association between belt wearing and brain injury severity.

Table 3.
Characteristics of the Cases by Brain Injury Severity

Variable	Brain Injury Severity (column percentages)		
	Minor	**Moderate**	**Severe**
Sex			
Male	64.6%	66.7%	76.0%
Female	35.4	33.3	24.0
Age (years)			
0-15	6.3	9.5	12.0
16-30	45.8	57.1	54.0
31-45	22.9	14.3	16.0
46-60	12.5	9.5	8.0
61-75	8.3	-	4.0
76+	4.2	9.5	6.0
Seated position			
Driver	62.5	47.6	54.0
Front left	22.9	33.3	34.0
Front centre	-	-	2.0
Rear right	4.2	9.5	4.0
Rear left	8.3	4.8	6.0
Rear centre	2.1	4.8	-
Seatbelt worn			
Yes	45.8	33.3	46.0
Probably yes	4.2	9.5	4.0
Probably no	6.3	14.3	6.0
No	37.5	28.6	20.0
No belt available	2.9	-	-
Unknown	4.2	14.3	24.0
Ejection			
No	91.7	90.5	88.0
Partial	4.2	-	-
Complete	4.2	9.5	12.0
Speed limit (km/h)			
60	12.5	55.0	32.7
80	12.5	20.0	14.3
100	8.3	10.0	8.2
110	66.7	15.0	44.9
Total: Row %	40.3	17.6	42.0
No. of cases	48	20	49

The apparently negative association between the speed limit at the crash site and brain injury severity is primarily

a consequence of the fact that the sample of "out of town" rural crashes contained many cases of comparatively minor injuries, as noted previously.

The presence of an impact on the front of the head, compared to elsewhere on the head, was negatively associated with the severity of brain injury. (Table 4) This probably reflects differences in the three samples of cases on which this study is based as much as any possibly greater tolerance of the brain to an impact to the front rather than to the side of the head. The number of cases of occipital, or rear, impact was too small to discern any meaningful relationship with brain injury severity.

Table 4.
Head Impact and Skull Fracture by Brain Injury Severity

Variable	Brain Injury Severity (Column percentages) Minor	Moderate	Severe
Skull fracture			
Yes	27.1	38.1	78.0
No	72.9	61.9	22.0
Impact on head			
Front	66.7	47.6	34.0
Left	8.3	28.6	18.0
Right	12.5	14.3	32.0
Rear	6.3	4.8	14.0
Top	6.3	4.8	2.0
Total: Row %	40.3	17.6	42.0
No. of cases	48	20	49

Location of Impacts on the Head

Figures 1 and 2 show the location of impacts on the head for the non-fatal and fatal cases, respectively. Note that the fatal injury was not necessarily to the head.

There was a higher proportion of the impacts to the face compared to the cranium in the non-fatal cases. The impacts also tended to be distributed on the front and sides of the head.

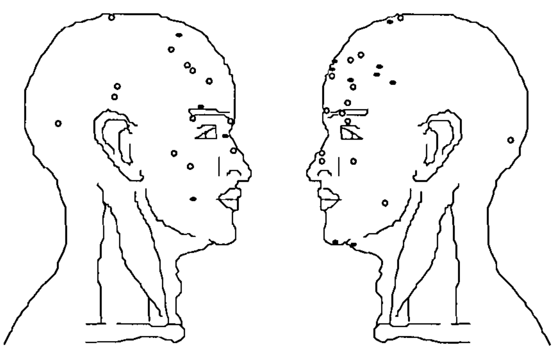

Figure 1. Location of car occupant head impacts in cases of non-fatal injury.

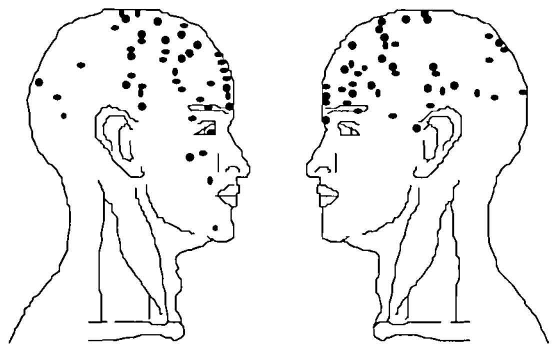

Figure 2. Location of car occupant head impacts in cases of fatal injury.

Figures 3 to 5 show the location of the sole or major impact to the head by the severity of the resulting brain injury. It can be seen once again that the impacts are concentrated on the front of the head, and particularly on the forehead, as was indicated by the data in Tables 2 and 4. The proportion of impacts on the face compared to the cranium decreases markedly with increasing brain injury severity.

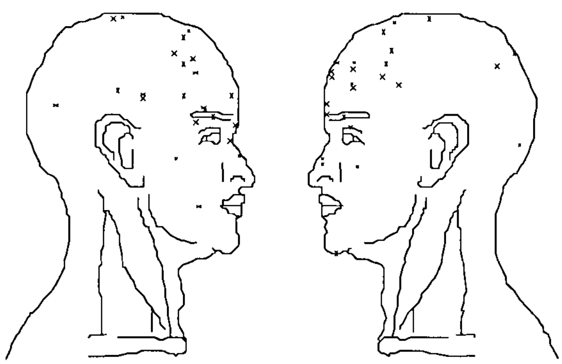

Figure 3. Location of car occupant head impacts in cases of minor brain injury.

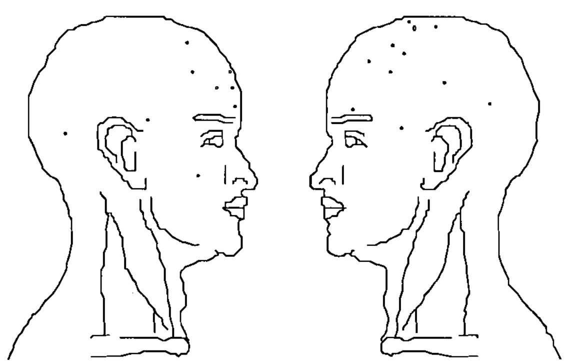

Figure 4. Location of car occupant head impacts in cases of moderate brain injury.

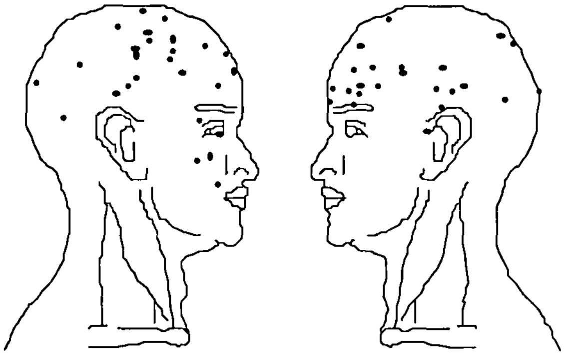

Figure 5. Location of car occupant head impacts in cases of severe brain injury.

Objects Struck by the Head

The identifiable objects struck by the head included parts of the interior of the car, other objects outside the car, the ground and another occupant. In just over 30 per cent of the cases, although there was evidence of an impact to the head, we were not able confidently to identify the object struck. The objects struck are related to the severity of the resulting brain injury in Table 5.

Table 5.
Objects Struck by the Head by Brain Injury Severity

	Brain Injury Severity (Number of Cases)		
Object Struck	**Minor**	**Moderate**	**Severe**
Windscreen	6	2	1
Steering assembly	7	1	2
Instrument panel	3	1	3
A-pillar*	1	1	3
B-pillar*	1	3	4
C-pillar*	-	2	-
Roof side rail*	-	2	2
Roof*	7	1	6
Side window	2	1	-
Door frame	-	3	4
Striking object	1	-	10
Other occupant	-	-	1
Other/unknown	20	3	13
Number of cases	48	20	49

*Note: Objects which are included in the definition of the "upper interior" of the passenger compartment are marked with an asterisk.

The relatively high frequency of head impacts with the roof of the car is due partly to marked deformation of the passenger compartment in side impact collisions, with and without rollover. In some cases the part of the roof struck by the head had been forced in and downwards by a lateral impact with a pole or tree, and so the roof panel was interposed between the occupant's head and the intruding object.

This draws attention to the possible benefit to be gained from padding the interior surface of the roof panel, even though the panel itself may deform readily when struck by the head of an occupant. There will, of course, always be some cases in which a practicable thickness of padding will not be able to absorb enough of the energy of what is effectively a head impact with a pole to modify the outcome to any meaningful extent.

The objects marked with an asterisk in Table 5 are those which are included in the definition of the "upper interior" of the passenger compartment in the amendments to the relevant United States Federal Motor Vehicle Safety Standard (FMVSS 201) which requires a specified level of energy absorption in the event of a head impact. These objects accounted for 40 per cent of the identified head impact locations in this study. When the "unknown object struck" cases are taken into account, this percentage could be reduced to about 30 per cent.

As noted previously, all of the cases selected for this study had some degree of injury to the brain, so the data presented here should not be taken as an indication of the risk of the head striking the upper interior.

Reducing Head Impact Severity: Effect on Recovery from Injury

In each case an assessment was made of whether reducing the severity of the head impact would have changed the outcome of the crash in terms of eventual recovery or otherwise from the injuries sustained.

This assessment was made in the context of each crash. In most instances it was not realistic to assume that the head impact could have been prevented and so an attempt was made to estimate the likely effect of the largest practicable reduction in head impact severity.

The results by fatal and non-fatal are shown in Table 6 and the results for the three severities of brain injury are shown in Table 7.

Table 6.
Effect of Reducing the Head Impact Severity on Recovery from Injury (by Fatal / Non-Fatal)

	Observed Outcome (Column percentages)		
Beneficial Effect	**Fatal**	**Non-Fatal**	**Total**
Yes	4.1%	25.6%	12.0%
Probably	13.5	27.9	18.8
Possibly	14.9	16.3	15.4
Unlikely	16.2	23.3	18.8
No	51.4	7.0	35.0
Number of cases	74	43	117

Collapsing the "beneficial effect" categories into "probably" and "unlikely" by splitting at the mid point of "possibly" indicates that reducing the severity of the head impact may have been likely to have had a beneficial effect on recovery from injury in about 25 per cent of the

cases in which the observed outcome was a fatality. This means that the predicted effect is a 25 per cent reduction in fatalities. Of course, the residual disabilities among the additional survivors may still have been severe.

This may appear to be an unexpectedly small reduction but it should be remembered that there were fatal injuries to other body regions in some cases. It was also often difficult to allocate a realistic probability of survival to a case involving a clearly fatal brain injury and a very severe injury to another body region. If the severity of the brain injury were to have been substantially reduced by reducing the head impact severity, it was by no means clear that the injury to the other body region would not have been a threat to life.

It is therefore not surprising that the probable effect of reducing the severity of the head impact appeared likely to be greater for the non-fatal cases. Given the maximum realistically possible reduction in head impact severity, 62 per cent of the cases may have experienced a beneficial effect on outcome in terms of recovery from injury

Table 7.
Effect of Reducing the Head Impact Severity on Outcome (by Brain Injury Severity)

	Observed Brain Injury Severity (Column percentages)		
Beneficial Effect	**Minor**	**Moderate**	**Severe**
Yes	12.5%	25.0%	6.1%
Probably	16.7	20.0	20.4
Possibly	14.6	10.0	18.4
Unlikely	25.0	5.0	18.4
No	31.3	40.0	36.7
Number of cases	48	20	49

Assessing the likely effect of reducing the head impact severity for each of the three categories of observed brain injury severity indicated that the outcome might have been improved in 37 per cent of the cases of minor brain injuries, 50 per cent of moderate brain injuries and 36 per cent of serious brain injuries. Once again, it is important to remember that most of these occupants had injuries to other body regions as well as to the head. In some cases the other injuries were the main determinant of the eventual outcome.

Padding the Upper Interior

There was a head impact with an identifiable object in 81 cases (69.2%) out of the 117 in the study. Of these, 69 were with the structure of the occupant's car and 33 of the 69 involved a part of the car that is relevant to the proposed amendment to FMVSS 201, viz: the roof, the roof side rails, and the pillars of the car.

An assessment was made of whether the addition of padding to the part of the vehicle struck (in cases in which that part could be padded) would have been likely to have changed the outcome of the crash. The results by fatal and non-fatal head injury are shown in Table 8 and the results for the three severities of brain injury are shown in Table 9.

The low number of cases with known head impact locations on parts of the car that can be padded makes interpretation of the Tables difficult. However, they indicate that padding would be likely to have a much greater effect on non-fatal cases than fatal cases. The effect is also likely to be greatest for moderate brain injury followed by minor brain injury and appears likely to have very little benefit for severe brain injury.

Table 8.
Effect of Padding the Upper Interior of the Car on Outcome (by Fatal / Non-Fatal)

	Observed Outcome (Column percentages)		
Beneficial Effect	**Fatal**	**Non-fatal**	**Total**
Yes	-	9.1	3.0
Probably	-	54.5	18.2
Possibly	9.1	36.4	18.2
Unlikely	40.9	-	27.3
No	50.0	-	33.3
Number of cases	22	11	33

Table 9
Effect of Padding the Upper Interior of the Car on Outcome (by Brain Injury Severity)

	Observed Brain Injury Severity (Column percentages)		
Beneficial Effect	**Minor**	**Moderate**	**Severe**
Yes	11.1	-	-
Probably	11.1	55.6	-
Possibly	33.3	11.1	13.3
Unlikely	11.1	11.1	46.7
No	33.3	22.2	40.0
Number of cases	9	9	15

Following the procedure outlined above, it is predicted that padding would be likely to change the outcome in 39 per cent of cases of minor brain injuries, 61 per cent of moderate brain injuries and 7 per cent of severe brain injuries. These estimates apply to case vehicles in which upper interior padding could have been placed at the primary head impact site.

To obtain an overall effectiveness measure, regardless of the object struck by the head, the above percentages are multiplied by the proportion of cases that involve an impact with an area that would be padded under compliance with FMVSS 201. Based on the 81 cases for which the object struck by the head was identified, these percentages are reduced by a factor of 33/81. The result is that the outcome of a crash would be expected to be improved meaningfully by padding of the upper interior in

16 per cent of minor brain injury cases, 25 per cent of moderate brain injury cases and 3 per cent of severe brain injury cases.

The corresponding calculation for fatal versus non-fatal outcome yields a predicted overall effectiveness of upper interior padding in effecting a meaningful improvement in outcome of 33 per cent for non-fatal cases and 42per cent for fatal cases.

This apparently greater benefit for non-fatal cases is not consistent with predictions of the probable effect of the amendment to FMVSS 201. The Preliminary Regulatory Impact Analysis for Upper Interior Head Protection contains estimates which indicate a substantially greater effect on fatalities than on AIS 2-5 injuries. (NHTSA, 1992)

The estimates in this paper of the likely effectiveness of padding the upper interior of the vehicle involve two notable assumptions. The first assumption is that in about 40 per cent of the cases in which the object struck by the head was not identified it was actually part of the upper interior of the car.

The second, and more important, assumption is that the sample of cases considered here is representative of the whole population of cases of brain injured car occupants in Australia. It is likely that such bias that exists is towards the more severe cases of brain injury. Because padding of the upper interior of the car is estimated to be more likely to be beneficial in cases in which the brain injury is less severe, it is probable that the above estimates of the likely overall effectiveness of padding the upper interior of the car in reducing the severity of brain injury and improving the outcome are conservative.

CONCLUSIONS

The results of this investigation indicate that there is considerable potential for reducing the severity and the consequences of brain injuries by padding the upper interior of the passenger compartment. This benefit appears likely to be greatest for cases of brain injury of moderate severity.

ACKNOWLEDGEMENTS

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REFERENCES

Rungie CM, Trembath R. "Rural In-Town Restraint Use Survey 1988". Adelaide: Department of Transport, Road Safety Division. Report Series 11/88.

NHTSA. "Preliminary Regulatory Impact Analysis. Upper Interior Head Protection. FMVSS NO. 201." Washington DC. National Highway Traffic Safety Administration. 1992.

HEAD IMPACT TOLERANCE IN SIDE IMPACTS

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ABSTRACT

In order to assess side impact protection it is necessary to establish criteria for head impact tolerance in side impacts. The paper describes research undertaken to investigate the tolerance of the head to lateral impact using experimental and numerical methods. A series of direct lateral head impacts were conducted with unembalmed cadavers. Damped and undamped impacts were performed. The linear and angular head centre of gravity accelerations were calculated from the measured head accelerations. Impactor force and velocity were measured. A detailed autopsy was performed post-test.

To investigate relationships between the independent variables (head acceleration, HIC, impactor force etc.) and the dependent variable maximum AIS injury severity, the logistic regression model was used. Selected tests were simulated using MADYMO and the effect of impact location on head acceleration was examined. The paper describes the results of these tests and applies these to the discussion of head protection in side impact including occupant protection criteria.

INTRODUCTION

Lateral head impacts can occur to vehicle occupants in a range of vehicle collision orientations. In side impacts the occurrence of head injury is of particular concern (Morris et al 1995 and Fildes & Vulcan 1990).

During a lateral collision the occupant's head can contact either the vehicle interior or the leading surface of the striking vehicle. The contact surfaces may be rigid or flexible, i.e. glass. With the current focus of occupant protection on side impacts and side impact test dummies, it is appropriate that head injury and injury tolerance criteria for lateral head impacts are examined.

Head injury mechanisms are divided into two main groups, contact events and acceleration events. In the case of motor vehicle accidents, the occupant's head normally experiences both contact forces and acceleration. Therefore the magnitude of these variables should be related to head injury severity, and injury should be a function of one or more of them. The direction of impact will influence injury as the mechanical properties and structure of the skull and brain are not uniform. The morphology of rigid and semi-rigid tissues, e.g. the cranium and the falx cerebri, impart a different set of initial conditions during lateral impacts in comparison to frontal impacts.

At present the Head Injury Criterion (HIC) is applied as an indicator of head injury likelihood irrespective of the head impact site, however its origins do not affirm this application. HIC and its equivalent, HPC, are applied in FMVSS 214 and ECE R95 respectively.

This report describes a series of 16 lateral head impacts and will examine the statistical relationships between head impact responses, impact conditions and injury. This process is intended to develop more appropriate head injury criteria and tolerance thresholds for lateral head impacts. This report also describes an alternate method for assessing head injury potential.

While current assessment of occupant protection involves the physical testing of the vehicle with an instrumented occupant dummy and the derivation of pass/fail criteria from the dummy's measured mechanical responses, the mechanical responses could be used as an input into a sophisticated numerical model of a body segment. Such a model could provide more than a single pass/fail criterion, information about injury location and pathology could be determined. This process may not yet be appropriate for a regulatory procedure, but would be highly suitable as a tool in the development phase of a occupant protection system. The paper presents a preliminary evaluation of two dummy models in MADYMO with experimental data presented in this report.

METHODS

A) Head Impact Experiments

16 lateral head impact tests were undertaken using unembalmed cadavers. The sample contains the group of lateral head impact cases from McIntosh et al (1993) plus subsequent tests conducted at the University of Heidelberg. The same test set up was used in all cases, only the impact conditions (velocity and damping) were altered. A comprehensive description of methodology can be found in McIntosh et al (1993).

<u>Test Subjects:</u> 16 tests were conducted with 14 cadavers. The mean age was 45 years with range from 22 to 77 years.

<u>Test Matrix:</u> The test matrix is shown in table 1.

<u>Impactor:</u> The tests were performed using a linear piston pneumatic impactor. The impact surface was a flat rigid aluminium plate of diameter 15cm. In some experiments a 2.54 cm. thick polyurethane foam material (Ensolite) was used to attenuate the head impact energy and distribute the impact forces. These experiments are suffixed with 'D' for damped impacts.

The axis of the impactor was aligned to the junction between the temporal and parietal bones superior to the external acoustic meatus.

Table 1.
Test Matrix for Head Impact Experiments

TEST NUMBER	IMPACT VELOCITY m/s
1	2.8
2D	2.9
3D	3.7
4D	2.9
5D	3.6
6	6.0
7	6.1
8	5.9
9	6.1
10D	5.9
11D	5.9
12D	5.9
13	5.7
14	5.9
15	5.8
16	6.1

<u>Instrumentation:</u> Impactor head acceleration was measured with a single linear accelerometer (Endevco 7264-2000) and impact velocity was measured with a timing gate. A nine-accelerometer array of the 3-2-2-2 configuration was used to calculate the 3 axis 6 degrees of freedom motion of the head. The array was mounted rigidly in the mid-sagittal plane on the top of the head.

<u>Signal Processing:</u> All data were filtered with a channel class 1000 filter and digitised at 10,000 Hz. Signals from the nine head accelerometers were filtered with a fourth order digital low pass filter. The cut off frequency was 175 Hz. with a 185 Hz 3dB point.

<u>Data Analysis:</u> The nine head accelerometer data sets were used to calculate the head's angular and linear centre of gravity acceleration time histories. The MERTZ 3D program was used to perform these calculations. The program incorporates the algorithms developed by Padgaonkar et al. (1975). The 3D version was developed by Dr. Paul Begeman at Wayne State University. The Head Injury Criterion (HIC) was calculated from the head centre of gravity resultant acceleration time-history.

Injury Determination: Following the experiments, all cases were immediately autopsied and skull x-rays were repeated. The autopsies followed standard procedure and the injuries were coded according to the revised AIS 1990.

Statistical Analysis: To assess statistical relationships between predictor variables and injury outcome, the logistic regression model was chosen. Analyses were executed with SAS software. As the logistic regression model is best suited to analysis of dichotomous variables, some modifications were made to the data set. Head injury severity classification was simplified by using the Maximum AIS (MAIS) score. MAIS is the greatest single AIS score from a patient with polytrauma. Thus, the highest head AIS score was selected to represent injury severity, the dependent or outcome variable. As the sample size was small and predominated with MAIS 0, 3 or 4 head injuries, the dependent variable was further simplified. Injury outcome was modelled as a dichotomous variable, MAIS=3 or MAIS<3. This demarcation also has significance in terms of injury severity. MAIS head injuries equal to three represent injuries that would require hospitalisation.

B) Head Impact Simulations

The lateral head impact experiments were simulated with MADYMO using the Hybrid III and Eurosid-1 database. The experimental and numerical simulation results were compared. Through the modelling of head impacts with MADYMO, the influence of head impact location on head acceleration magnitude and HIC were investigated. Figure 1 shows the model of the head impact test set-up with the Eurosid I dummy. The impactor conditions of mass, velocity and impact location were simulated and time-histories for linear and angular centre of gravity (CG) head acceleration were derived. HIC was calculated from the CG head acceleration.

Damped and undamped lateral head impacts at 2.9 m/s, 3.6 m/s and 5.9 m/s were simulated

RESULTS

A) Head Impact Experiments

Injury: There were two distinct types of injury, skull fracture and brain injury. In the undamped impacts skull fracture was accompanied by coup and/or contre-coup injury. Head injuries of AIS severity 2 were not observed, as these injuries can only occur with a living subject. AIS severity 1 injuries were not coded.

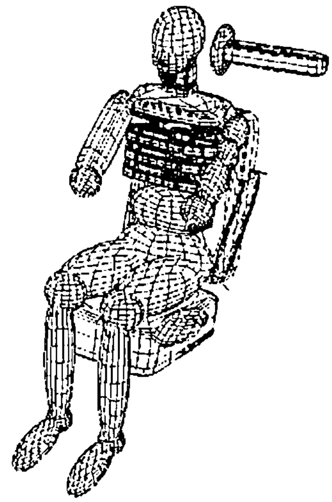


Figure 1: Head impact test arrangement with Eurosid I dummy simulation.

Head Kinematics: The resultant centre of gravity (CG) head acceleration and HIC were calculated for each case. Head acceleration maxima (MAcc) and HIC values are presented in table 2.

Injury Relationships: Relationships between kinematic variables and head injury severity were examined using the logistic regression model. In general, during the lower severity damped impacts no head injuries were observed. With increasing impact velocity, head injury severity increased. The presence of damping material reduced the likelihood of skull fracture, but not brain injury in the higher velocity impacts.

The results of the statistical analysis show that all three variables, maximum CG head acceleration, HIC and impact velocity, are correlated with head injury severity. As the magnitude of these variables increases, the likelihood of injury increases. Logistic regression curves for the maximum resultant head acceleration and HIC are presented in figures 2 & 3.

Table 2.
Head Impact Kinematics and Injury Severity Score

TEST NUMBER	MAX CG HEAD ACC (g)	HIC	IMPACT VEL. (m/s)	HEAD MAIS
1	232	1679	2.8	0
2D	80	113	2.9	0
3D	97	408	3.7	0
4D	61	113	2.9	0
5D	106	441	3.6	0
6	254	2181	6.0	3
7	239	1944	6.1	3
8	201	1297	5.9	3
9	201	1257	6.1	3
10D	137	621	5.9	3
11D	111	463	5.9	0
12D	116	500	5.9	3
13	181	938	5.7	3
14	172	841	5.9	3
15	226	1602	5.8	3
16	250	2129	6.1	3

The estimated logit function $\hat{g}(x)$ for the three models are presented below. The estimated logit function for univariate models has the general form $\hat{g}(x) = \beta_0 + \beta_1 x$. Table 3 presents an analysis of the fit of each model.

$$\hat{g}(x) = -3.845 + 0.0282 \text{ MAcc}$$
$$\hat{g}(x) = -1.6809 + 0.00248 \text{ HIC}$$
$$\hat{g}(x) = -19.2493 + 3.6431 \text{ Vel}$$

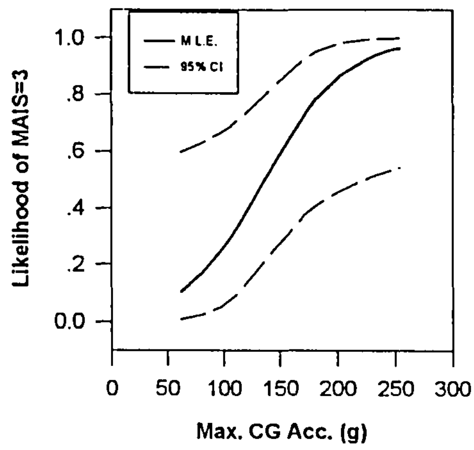


Figure 2: Logistic regression for head acceleration maxima vs. the likelihood of MAIS=3 head injury

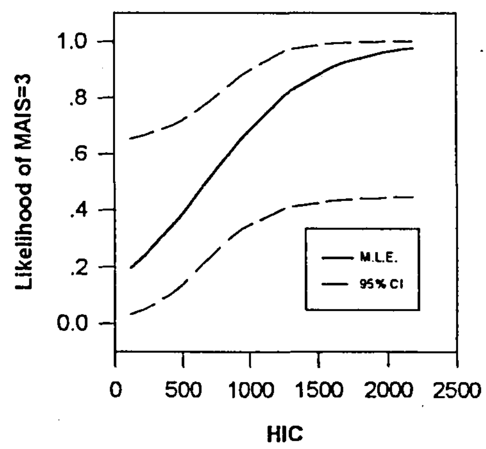


Figure 3: Logistic regression for HIC vs. the likelihood of MAIS=3 head injury

Table 3.

Significance Tests for Logistic Regression Models

	-2 Log Likelihood			Score	
Variable	d.f.	χ^2 for covariate	p-value	Test Statistic	p-value
Macc	1	7.429	0.0064	6.496	0.0108
HIC	1	5.933	0.0149	4.966	0.0259
Vel	1	14.540	0.0001	11.811	0.0006

Table 5.

Results from the MADYMO simulations (HIC).

Test Condition	EUROSID-1	HYBRID III
	HIC	
unpadded at 2.9 m/s	178	132
padded at 2.9 m/s	113	102
unpadded at 3.6 m/s	396	252
padded at 3.6 m/s	203	181
unpadded at 5.9 m/s	1370	990
padded at 5.9 m/s	635	523

B) Head Impact Simulation

There was a good correlation between the experimental and numerical simulation tests. Figures 4 and 5 show comparisons between the resultant CG head accelerations for undamped and damped 6 m/s impacts respectively. In figure 4 the time duration of the acceleration pulses were the same and the peaks similar, although the simulations predicted higher maxima. In figure 5 the acceleration maxima are more similar.

Table 4.

Results from the MADYMO simulations (MAcc).

Test Condition	EUROSID-1	HYBRID III
	Resultant CG Linear Head Acceleration	
unpadded at 2.9 m/s	122 g	95 g
padded at 2.9 m/s	55 g	50 g
unpadded at 3.6 m/s	166 g	117 g
padded at 3.6 m/s	69 g	63 g
unpadded at 5.9 m/s	242 g	215 g
padded at 5.9 m/s	119 g	97 g

Table 4 presents a summary of the maxima for the dummy head accelerations resulting from the lateral padded and unpadded head impact experiments. Table 5 presents a summary of the HIC values predicted by the two models under different impact conditions.

For both HIC and head acceleration maxima (MAcc) the Hybrid III model predicted lower magnitudes than the Eurosid I model.

A parametric study was undertaken using the MADYMO database to study the effects of the impact location on maximum resultant linear head accelerations and HIC. The results are presented in figures 6 and 7. The impact location was varied in the Z-X plane. Z and X displacements were varied between -80 and +80 mm about the head centre of gravity.

It can be seen from figures 6 and 7 that as the impact location is moved in an anterior and inferior direction the magnitude of acceleration and HIC increase significantly.

DISCUSSION

Head impact experiments were undertaken to investigate relationships between head kinematics and injury. The experimental data were then correlated with numerical simulations of the experiments. Finally a parametric study of the influence of head impact location on head acceleration maxima and HIC was undertaken.

A statistical analysis of the relationship between head acceleration maxima and the likelihood of MAIS 3 severity head injury demonstrated that above 200 g, there is a very high risk (≈80%) of moderate head injury.

Figure 4: Head Side Impact

Impactor: undamped, v = 6 m/s, m = 26 kg
Testobject: Cadaver, Simulation of HIII-Dummy & EUROSID-1
Parameter: Res. CG linear acceleration time-history

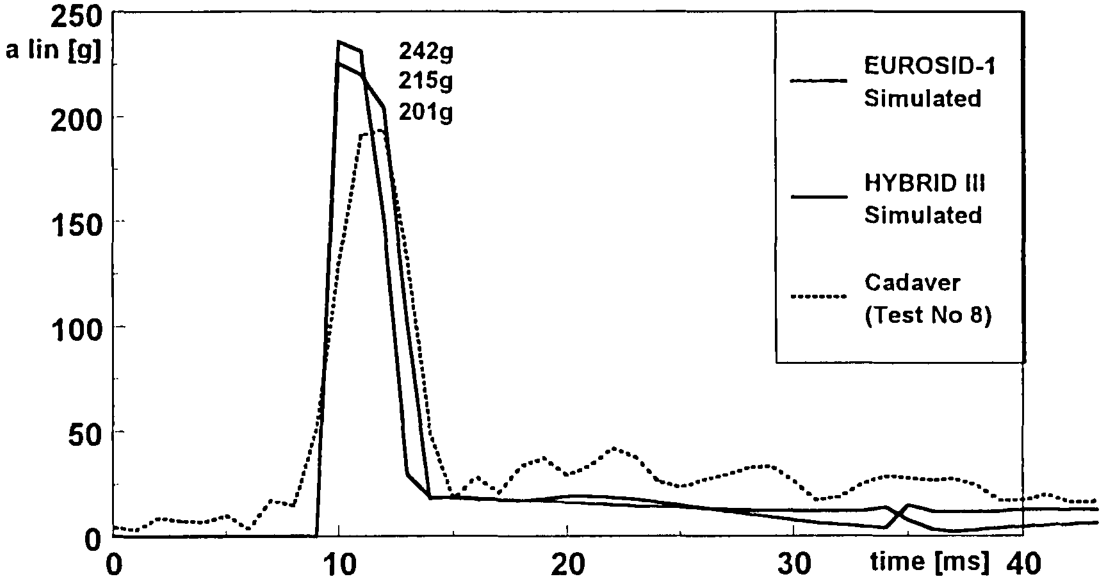


Figure 5: Head Side Impact

Impactor: damped (1'' Ensolite Foam), v = 6 m/s, m = 26
Testobject: Cadaver, Simulation of HIII-Dummy & EUROSID-1
Parameter: Res. CG linear acceleration time-history

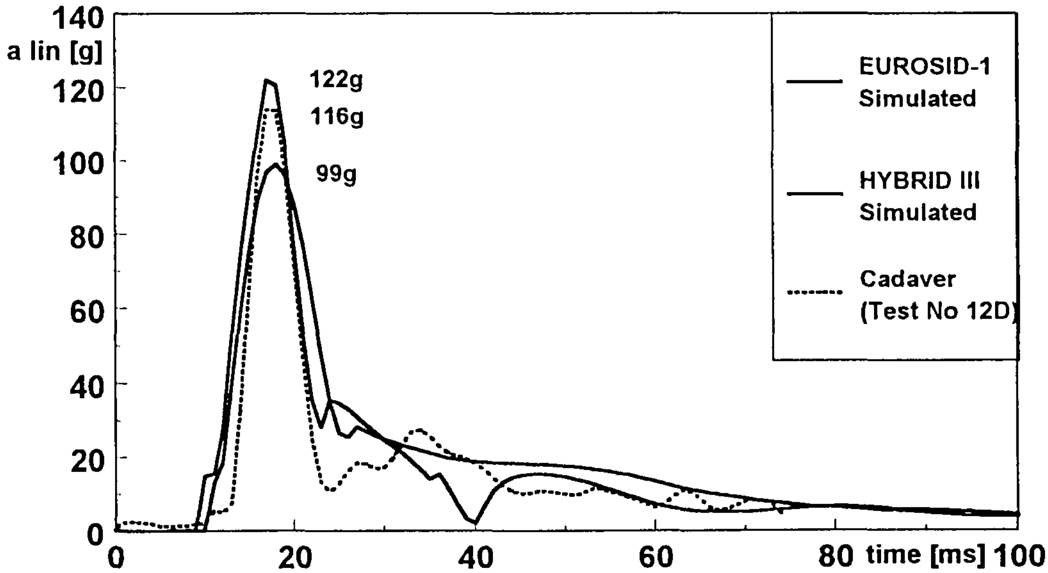


Figure 6: Parametric Study of Impact Location (MAcc)

Impactor: damped (1" Ensolite Foam), v = 6 m/s, m = 26
Testobject: EUROSID-1 Dummy (MADYMO) with Variation of Impact
Parameter: Max. resultant CG linear head acceleration

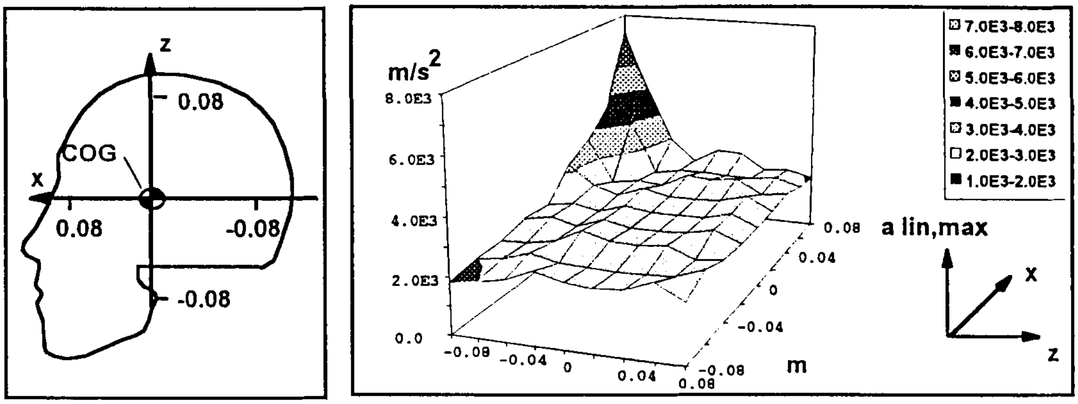
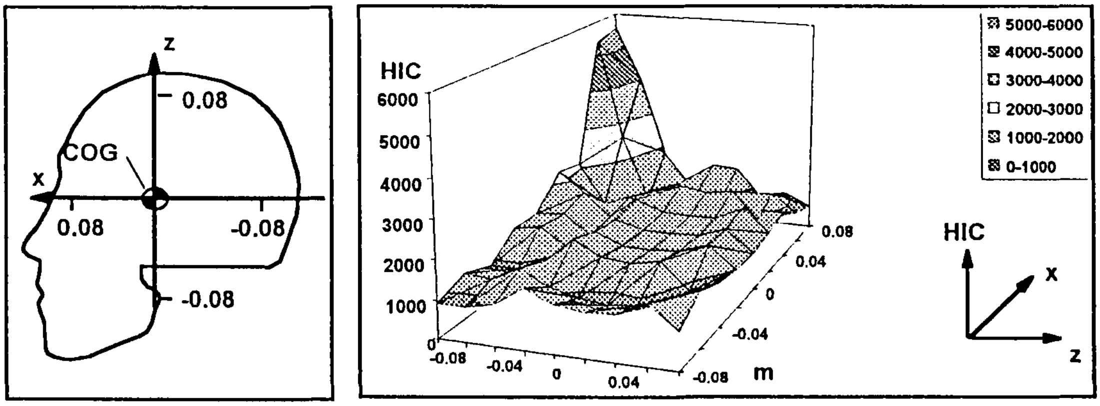


Figure 7: Parametric Study of Impact Location (HIC)

Impactor: damped (1" Ensolite Foam), v = 6 m/s, m = 26
Testobject: EUROSID-1 Dummy (MADYMO) with Variation of Impact
Parameter: Head Injury Criterion



At HIC of 1000 there is a risk of around 70% of moderate head injury. The test statistics showed that maximum head acceleration explained the data better than HIC.

The implications of this analysis are that maximum headform acceleration can be used confidently as a predictor of head injury likelihood, and the pass/fail criteria should be more demanding, e.g. MAcc < 150 g. and HIC < 700.

Numerical models of the Hybrid III and Eurosid I dummies can be used to investigate lateral impact scenarios. There were good correlations between experimental and numerical head kinematics. Further evaluation of these models is recommended and improvements would be expected.

According to the numerical simulations the location of head impact in lateral impacts is critical in determining the magnitude of head acceleration and subsequently HIC. Head impacts to the anterior-inferior aspect of the face result in higher head acceleration. As injury severity is correlated with head acceleration magnitude, then occupant protection systems should protect the head from these impacts. It is possible that impacts in these locations would result in fracture of the facial bones or mandible, which would attenuate the impact energy and lessen the head acceleration.

A model of a frangible head, e.g. an anatomical model, would permit more realistic evaluation of these impact scenarios, particularly when material failure is probably, e.g. fracture. TU Berlin is involved in the development of a model of the head using finite element methods.

CONCLUSIONS

Head injury criteria can be based on characteristics of the head's kinematics. In lateral head impacts permissible headform acceleration should be less than 200 g. and preferably below 150 g.

For the range of impact severities and injuries in this study, head acceleration is statistically better correlated with head injury than HIC.

Numerical simulations of head impacts can be applied to examine impact scenarios. The models require correlation with existing data and should be used within the boundaries determined by the correlation.

ACKNOWLEDGEMENTS

Our thanks is expressed for technical support from staff at the involved universities.

REFERENCES

Association for the Advancement of Automotive Medicine. *The Abbreviated Injury Scale - 1990 Revision*. 1990.

Fildes.B.N. & Vulcan.A.P., 'Crash Performance and Occupant Safety in Passenger Cars involved in Side Impacts', *Proceedings of IRCOBI Conference*, 1990, p.121-140.

Padgaonkar.A., Krieger.K. & King.A., 'Measurement of Angular Acceleration of a Rigid Body using Linear Accelerometers', *Journal of Applied Mechanics*, Vol. 42, 1975, p.552-556.

McIntosh.A.S., Kallieris, D., Mattern.R. & Miltner.E., 'Head and Neck Injury Resulting from Low Velocity Direct Impact', *Proceedings of the 37th. Stapp Car Crash Conference*, 1993, p.43-58.

Morris.A., Hassan.A., Mackay.M. & Hill.J., 'Head Injuries in Lateral Impact Collisions', *Accid. Anal. and Prev.*, 27(6), 1995, p.749-756.

UPPER INTERIOR HEAD IMPACT PROTECTION OF OCCUPANTS IN REAL WORLD CRASHES

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Paper Number 96-S8-O-05

ABSTRACT

The safety problem associated with head injuries due to impacts against upper interior components continues to be of concern to automobile manufacturers and others. Even with increased safety belt usage, and when the entire fleet would consist of air bag equipped vehicles only, the magnitude of fatalities and serious injuries that are likely to continue to occur would be significant. Based on 1988-1993 National Accident Sampling System (NASS) data, it is estimated that about 2200 fatalities and over 3600 serious injuries would likely occur due to head impacts against upper interior components in light vehicles, annually.

NHTSA conducted research to develop countermeasures to reduce the head injury potential in upper interior head impacts in vehicles. A test device and procedure were developed. Using these along with the standard head injury criterion (HIC), the safety performance of baseline and modified vehicles were determined by conducting several tests.

Based on these test results, it is estimated that over 1000 fatalities will be prevented, and up to about 800 serious head injuries will be reduced by the test procedures developed and implemented into an amendment to Federal Motor Vehicle Safety Standard (FMVSS) No. 201.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) Authorization Act of 1991 stipulated that the agency initiate rulemaking action and issue a final rule to provide improved head impact protection from interior components of passenger cars; i.e., roof rails, pillars, headers etc. Accordingly NHTSA issued a Notice of Proposed Rulemaking (NPRM) in February 1993, and a Final Rule in August, 1995.

FMVSS No. 201 is the standard that specifies requirements to afford occupant protection in interior impacts of vehicles. This standard applies to passenger cars, and to multipurpose passenger vehicles, trucks and buses with a GVWR of 4540 kg or less.

FMVSS No. 201 sets forth minimum requirements for instrument panels, seat backs, interior compartment doors, sunvisors and armrests. For the instrument panels and seat backs, a target within the "head impact area" is impacted by a 6.8 kg, 16.5cm diameter headform at a velocity of 24 kph (except for vehicles that meet the occupant protection requirements of FMVSS No. 208 by means of inflatable restraint systems for which the designated test speed is 19.3 kph). Interior compartment doors are subjected to the inertia load requirements of SAE J839b, "Passenger Car Side Door Latch Systems", May 1965 or approved equivalent. The sunvisors are to be constructed of or covered with energy absorbing materials and are not allowed to have any rigid material edge radius of less than 3.2mm. The armrests are to be constructed with or covered with energy absorbing materials so as to prevent occupant contact with any underlying rigid materials in crashes.

In response to the statutory requirements in the NHTSA Authorization Act, the agency has amended FMVSS No. 201 to require passenger cars, multipurpose passenger vehicles, light trucks and buses with a GVWR of 4540 kg or less to provide protection when an occupant's head strikes upper interior components, including pillars side rails, headers, and the roof, during a crash.

THE SAFETY PROBLEM

The NASS data provide the necessary information on the incidence of head and face injury due to contacts against upper interior components of vehicles. Partyka [1]* analyzed the head injury problem in light passenger vehicles due to contacts against pillars, rails and headers. Based on 1988 - 1989 NASS data and the Fatal Accident Reporting System (FARS) data for 1989, she estimated that, in 1989, there were about 7900 maximum abbreviated injury scale (MAIS) 3 or greater injured survivors and 4000 fatalities where contacts with upper interior components caused the highest level of injury. An unusually large proportion of the injuries were coded as those caused by contact with side windows and frames. However, these were identified through hard copy analyses to be due to contacts against other interior components. Therefore, the injury distribution for the various upper interior components was revised. This revision showed that the injuries to non-ejected, belted occupants caused by head contacts were predominantly due to A-pillars, followed by side rails, B-pillars, and headers. It is estimated that over 75 percent of the head/face injuries occur due to impacts against components that could be covered by energy absorbing materials that would cushion such impacts and reduce the injury potential and/or reduce the injury severity.

The generally held belief is that occupant restraints (safety belts and air bags) are the best means to protect occupants from sustaining head injuries from contacts against upper interior components in vehicle crashes. While safety belts are an effective means to reduce the frequency and severity of head injuries in frontal crashes, it must be recognized that even when belted, it is difficult to eliminate the total forward and lateral movement of the head in accidents so as to prevent all contacts against interior components, especially the ones in close proximity of an occupant. Similarly, air bag restraints can not eliminate large head movements in side impact and rollover crashes. NHTSA has closely examined this issue and concluded that the effectiveness of safety belts in reducing head injuries is relatively the same as its overall effectiveness in reducing other injuries. Further, it is also noted that, even though restraint use has increased over time, head injuries due to contacts against upper interior components has steadily increased between 1982 and 1989 [2].

Figure 1 shows the total annual occupant fatalities and serious injuries in passenger cars and light trucks and vans (LTV's). Based on the 1982-1989 accident statistics, the estimated annual fatalities that result from pillar, side rail and header contacts are over 3300. Serious head injuries that result from contacts against the same components are estimated to be about 6800. Over 72 percent of the fatalities and over 66 percent of the serious injuries occur to unrestrained occupants. Figure 2 shows the percent distribution of serious injuries by components for restrained and unrestrained occupants. While the total number of serious injuries in restrained occupants are lower than for unrestrained occupants, the percent distribution by components has dramatically changed. For example, while there is a reduction in the percentage of A-pillar caused injuries in restrained occupants in comparison to unrestrained occupants, on a percentage basis, the trend is reversed for injuries that result from B-pillar and side rail contacts. It must, therefore, be concluded that while safety belts are effective in reducing the

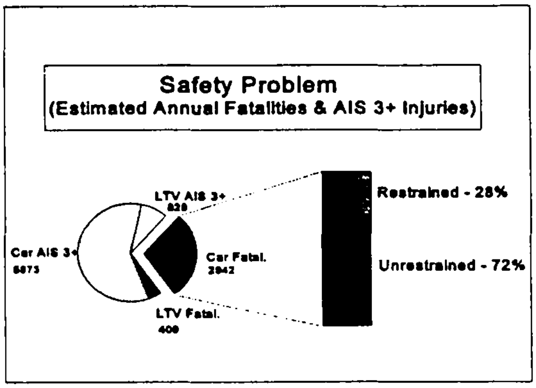

Figure 1. Estimated fatalities and serious injuries.

*Numbers in brackets indicate references at the end of the paper.

injuries that result from contacts against certain forward interior components, they are not necessarily as effective in components that are located to the side as in forward components. Because of the safety concerns indicated by the accident data analyses, NHTSA, in its amendment

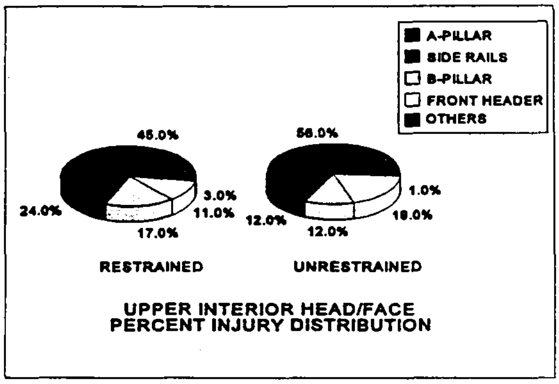

Figure 2. Percent distribution of serious head injury by components for restrained and unrestrained occupants.

to FMVSS No. 201 extended the requirements to all upper interior structural components such as the pillars, the headers, side roof rails and the roof to protect occupants from head injuries.

Figure 3 shows the distribution of injuries by crash type and crash mode. As seen in this figure, about seventy percent of serious head injuries caused by upper interior contacts result from multi-vehicle accidents and only thirty percent of the serious injuries are in single vehicle crashes. The most predominant crash mode resulting in serious head injuries is side impact, followed by frontal impact and rollover accidents. About forty five percent of the serious head injuries occur in side crashes. Only thirty percent of the injuries occur in frontal impacts and the remaining occur in rollover crashes. Approximately seventy percent of these injuries occur to unrestrained occupants.

In response to the NPRM, several automobile manufacturers and their associations submitted comments on the agency's proposal to include the aforementioned upper interior components under the purview of FMVSS No. 201 (amended). American Automobile Manufacturers' Association (AAMA) suggested that NHTSA should delete from any final rulemaking the A-pillars and windshield headers. The basis for this request was because of their belief that the effectiveness of air bags in an all air bag vehicle fleet would markedly reduce head contacts with the aforementioned forward components. They argued that the occupant interaction with air bags would substantially reduce the frequency and severity of head contacts with the A-pillars and front headers in frontal crashes. Further, AAMA

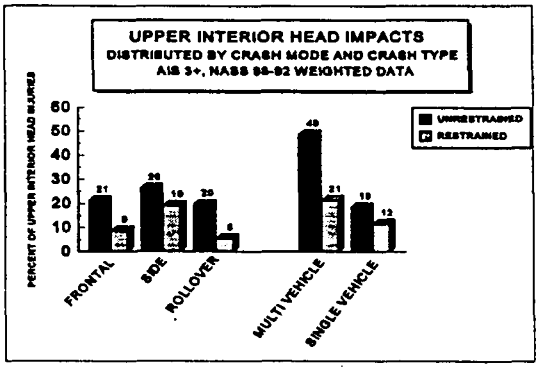

Figure 3. Distribution of injuries by crash type and crash mode.

contended that AIS 3 or greater injuries due to A-pillar contacts are generally due to violent crashes of extreme severity resulting in massive A-pillar intrusion. In these cases, countermeasures such as padding would be of no value. Therefore, they recommended that NHTSA re-examine its accident data with respect to air bag equipped vehicles and determine if A-pillar performance requirements are necessary to improve the needed head impact protection.

The agency s previous analyses of accident data for the 1982-1989 period assumed belt usage rate prevalent in those years. In the previous target population estimates for the NPRM, accident data for air bag equipped vehicles were scarce, and therefore, no adjustments were made to the target population estimates to account for the increased presence of air bag equipped vehicles in the fleet. However, surveys on belt usage indicate that belt usage has risen steadily for the past few years. Further, full frontal air bags will be required on all passenger cars by model year 1998 and on all LTV's by model year 1999. These factors are also likely to mitigate the incidence and severity of head/face injuries in the future. Therefore it is important that the target population estimates be revised to take into account the increase in seat belt usage and the availability of air bags in all

light vehicles.

For the Final Rule, NHTSA revisited the accident data to assess the effect of increased belt use and the changes in the fleet due to the presence of air bag equipped vehicles. Figure 4 shows the revised annual fatalities and serious injuries that could result in passenger cars and LTV's even when all vehicles in the fleet would be equipped with air bags. It is estimated that the fatalities would be reduced by approximately thirty five percent and serious head injuries by about forty six percent from the previous estimates. This reduction is significant. However, A-pillar, B-pillar, side header and front header continue to be predominantly involved in causing these serious head injuries and fatalities. Therefore, it is important that these components be protected to reduce their potential to cause serious harm to the

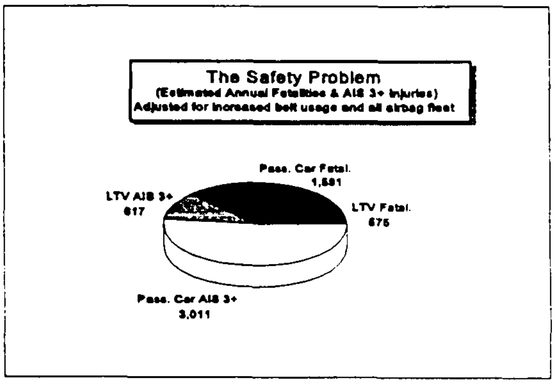

Figure 4. Estimated annual fatalities and serious injuries with 100 percent air bag fleet.

occupant due to head impacts in vehicle crashes and, consequently, the Final Rule did not exclude them from the performance requirements.

TEST PROCEDURE AND EQUIPMENT

NHTSA has amended FMVSS No. 201 to require passenger cars, and trucks, buses, and multipurpose passenger vehicles to provide protection when an occupant's head strikes upper interior components; i.e. pillars, side rails, headers, and the roof, during a crash. A test procedure was developed to test these components according to the proposed performance requirements.

A Free Motion Headform (FMH) is used to measure accelerations when impacted against the upper interior components. The FMH is a modified Hybrid III dummy head, weighing about 4.54 kg and measuring 15cm in width, used to simulate the responses of a human head. The modifications included replacing the skull cap with a steel skullcap plate and removing the nose on the head. The plate allows the FMH to be mounted by means of a magnet to a device that propels the headform against the upper interior target. The FMH is noseless to reduce the potential for interference from the nose contacting the struck surface during the test. The FMH is instrumented with a tri-axial accelerometer array at the headform's center of gravity to measure the accelerations. The magnitude of the potential for injury resulting from the impact is calculated using the Head injury Criterion (HIC).

In the research conducted by NHTSA, the FMH was propelled into the component by a pneumatic impactor developed by General Motors and refined by NHTSA. It uses high pressure compressed nitrogen to propel the headform. The headform is held to the propulsion unit by a magnet and when the compressed gas is released, it propels a piston forward about 7.5cm and the headform is pushed off the magnet into a free flight until it strikes the impacted target. The FMH has a forehead impact zone. When impacting a selected target, the first contact must occur within the forehead impact zone.

It is believed that the "free flight" test has two advantages over a guided test. First, since the FMH does not use a guiding mechanism, it can simulate the glancing and non-perpendicular impacts experienced in real-world crashes. The second advantage is that rotational accelerations can be measured in FMH impact tests. It is valuable to measure this since head rotation has the potential to be used for assessing head injuries in the future.

The FMH impact velocity is set at 24.1 kph. This speed was chosen primarily for two reasons. First, it is the current test speed being used in FMVSS No. 201 for instrument panels and other interior components currently included in the standard. Secondly, it is also the average speed at which the onset of serious injuries (between AIS 2 and AIS 3) are likely to occur [3]. Therefore, this

test speed is used as the threshold of the impact speed that could discriminate the potential for serious head injuries due to upper interior head impacts in real-world vehicle crashes.

HIC measurements are calculated from the measured accelerations of the FMH and transformed to a full dummy HIC (HIC_d) using the following equation:

$$HIC_d = 0.75446(\text{FMH HIC}) + 166.4$$

This equation was derived by relating the full dummy head impacts with upper interior components and FMH head impacts into the same components (r^2=0.97).

In its NPRM of 1993, NHTSA proposed two alternate HIC levels in the proposed requirements for amending FMVSS No. 201. In one, it was proposed to use a HIC of 1000 as the pass/fail criteria for all upper interior components. In the second, a two tiered HIC level was proposed; 1000 HIC for all forward components and 800 HIC for the side components and the roof. Based on comments to the NPRM and the concern that such a requirement may not be feasible for side components, NHTSA has chosen to adopt a HIC level of 1000 for all upper interior components in its Final Rule.

IMPACT LOCATION AND ANGLES

To aim the FMH at a target point inside the vehicle, its orientation is specified by vertical and horizontal approach angles. An orthogonal coordinate system consisting of X, Y, and Z axes is used to define the horizontal and vertical impact angles. The origin of the coordinate system is the center of gravity of the headform at the time of launch for each test. The X-axis of the coordinate system is parallel to the longitudinal axis of the vehicle. Figure 5 shows the coordinate system relative to a full scale vehicle, where +X is to the rear of the vehicle and +Y is to the right of the vehicle. The horizontal approach angle is the angle between the +X axis and the headform impact velocity vector projected onto the horizontal X-Y Plane and measured in the counter-clockwise direction. The vertical approach angle is the angle between the horizontal plane and the velocity vector, measured in the midsagittal plane of the headform. The angle is measured from the X-Y plane and is positive in the upward direction (+Z) and negative in the downward direction (-Z).

The impact location is defined as the location of first contact between the FMH forehead impact zone and the target upper interior component. All component impact zones include the upper interior surfaces only. The Final Rule specifies targets and procedures for locating targets, as well as relocating targets that are not contactable by the FMH.

In its research, the agency tested several production vehicles to determine the baseline performance of various models. The results of this research was published by the agency earlier [4]. Recently, the agency conducted additional tests of two 1995 model vehicles to evaluate the performance differences between the more recent models and the vehicles tested earlier. The vertical impact angles selected in these tests are an attempt to achieve "nearly worst case" angles to make the velocity vector nearly perpendicular to the impacted surface. The "worst case" horizontal angles could be approximated by the angle indicated in the X-Y plane by the outward normal vector at the selected target location. The results of these tests are discussed below.

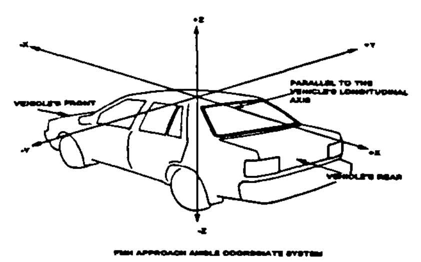

Figure 5. Schematic of the coordinate system.

RESULTS

A full set of tests carried out on a 1995 2-door Nissan 240SX, and a 1995 Ford Windstar are tabulated in Tables 1 and 2. Figures 6 and 7 illustrate the location of typical target points that could be tested in selected passenger cars and vans.

The Tables show that the HIC_d for the A and B-pillars generally produce higher HICs at least for those points closer to the joints. Several test locations also do not appear to have sufficient margin of safety that manufacturers would have to set their HIC design goals for these components lower for the entire length of the components proposed to be tested. Other vulnerable tested targets include locations near header joints and belt anchorages.

The agency's prior research data and the data provided by several manufacturers indicated that most of the current production vehicles would not be able to comply with the requirements for all the covered components. The test results of the 1995 model vehicles confirm this conclusion.

Table 1. 1995 2-Door Nissan 240SX

Structure Conditions		Approach Angle		Full Dummy
Structure	Target	Horiz.	Vertical	HIC_d
A-Pillar	AP1	225	49	943
A-Pillar	AP2	135	50	1045
A-Pillar	AP3	156	43	1003
Fr. Hdr.	FH1	180	50	612
Fr. Hdr.	FH2	180	50	426
Sde. Rail	SR1	270	15	523
Sde. Rail	SR2	90	38	851
Sde. Rail	SR3	90	50	735
B-Pillar	BP1	270	27	913
B-Pillar	BP2	90	20	943
B-Pillar	BP3	313	5	939
Rr. Pillar	RP1	270	33	638
Rr. Hdr.	RH	0	50	314

Table 2. 1995 Ford Windstar

Structure Conditions		Approach Angle		Full Dummy
Structure	Target	Horiz.	Vertical	HIC_d
A-Pillar	AP1	202	44	875
A-Pillar	AP2	225	30	742
A-Pillar	AP3	158	42	805
Fr. Hdr.	FH1	180	50	540
Fr. Hdr.	FH2	180	50	515
Sde. Rail	SR1	90	30	521
Sde. Rail	SR2	270	35	812
Sde. Rail	SR3	270	40	898
B-Pillar	BP1	270	18	865
B-Pillar	BP2	90	0	601
B-Pillar	BP3	270	4	701
B-Pillar	BP4	270	-10	685
Ot. Pillar	OP1	90	15	593
Ot. Pillar	OP2	270	0	630
Rr. Pillar	RP1	225	40	766
Rr. Pillar	RP2	345	20	799
Rr. Hdr.	RH	0	45	1006
Sldg. Dr.	SD	90	25	612

POTENTIAL BENEFITS FROM REDUCED INJURIES

The development of the HIC-1000 injury criterion has a long history and a detailed discussion on the development of HIC was presented in FMVSS No. 208 rulemaking documents. The relationship between HIC and the probability of head injury was formalized by Mertz and Prasad[5]. At HIC 1000, the probability of serious injury (AIS 4+) is about 18 percent. Recently NHTSA expanded this risk curve to probability of different injury levels by

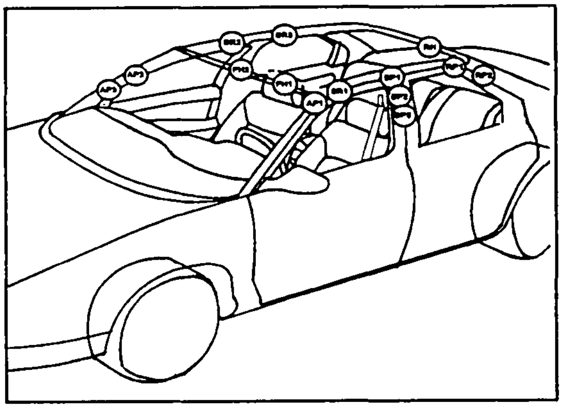

Figure 6. Location of typical car target points.

extrapolating from the probability of injury curves developed for the Thoracic Trauma Index (TTI) used in side impact protection[3]. By equating the MAIS 4 curve for TTI as equivalent to HIC-MAIS 4 curve representing head injury, a set of curves representing cumulative probabilities of injury for a given HIC for all AIS levels from 1 to 5 were developed. These curves are shown in Figure 8, in which a HIC of 1000 represents a 50 percent probability of sustaining AIS 3+ injuries.

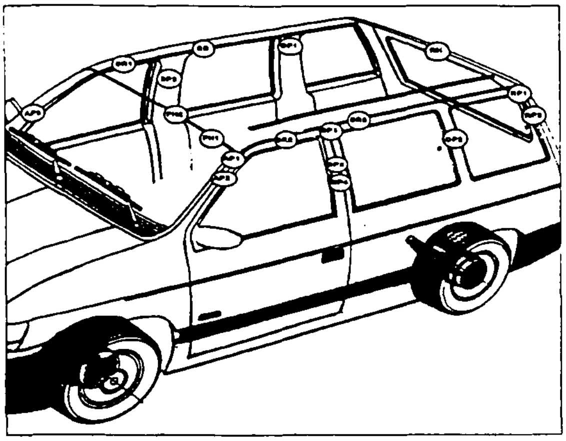

Figure 7. Location of typical van target points.

A method was developed using the probability curves and HIC distribution in real-world crashes to determine how injuries are shifted from high severity to low severity by reducing HIC. HIC reduction in the fleet would be accomplished by adding countermeasures such as padding to upper interior components, or by re-designing the upper interior structures. To calculate specific shifts from fatalities to injuries at different AIS levels and from moderate and serious injuries to injuries of lesser severity and no injuries as a result of this standard, several assumptions had to be made.

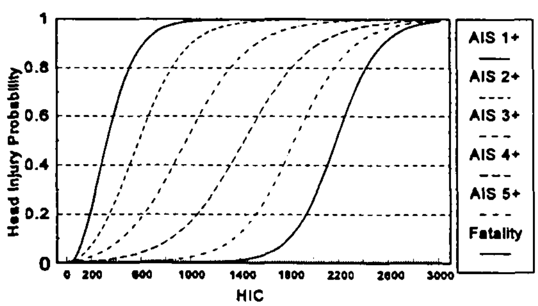

Figure 8. Probability of injury curves.

First, it is assumed that the HIC distribution which is found in real world accidents would remain the same for each injury level. After countermeasures are designed into vehicles, this distribution is assumed to be different from the distribution assumed before design changes. In both cases, the distribution differences between injury levels are neglected. This may not be totally valid since the mean HIC and the percent frequency might shift from injury to injury both in baseline and padded vehicle fleets involved in real-world accidents. However, since there is no available procedure to accurately determine these distributions, the above assumption that the HIC distribution remains constant is essential to develop a procedure to compute the percent shift in injuries as HIC's are reduced. The HIC distribution for baseline and modified fleets involved in crashes are presented in Figure 9. The baseline fleet's HIC distribution is based on real world head and face injury accident data. The distribution of injuries against vehicle delta v from accident data has been combined with vehicle test data to obtain this distribution.

The modified fleet distribution was developed from padding effectiveness estimates at each HIC level. The effectiveness was determined by a combination of HIC results of FMH impacts into the upper interior components with 1.3cm to 3.8cm of padding, and the distribution of real-world head injuries from the baseline(production) components. The effectiveness was applied to the HIC numbers in the baseline distribution to determine the new HIC values for padded vehicles. The frequency of occurrence at the new HIC value for padded vehicles is assumed to be the same as the frequency of occurrence for baseline vehicles. Thus, the distribution for padded vehicles is shifted to the left of the baseline as shown in Figure 9.

Second, since we are only interested in the percent shift in injured persons from one HIC level to another, the baseline injury and fatality counts used are immaterial.

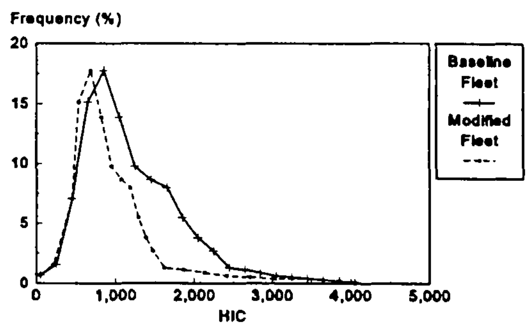

Figure 9. HIC distribution for baseline and modified fleet.

For purpose of the calculation, the total fatalities and injuries determined to be the target population at each AIS level can be used. These numbers are not necessarily the true fatalities and injuries at any specific HIC level.

The percent change at each injury level between AIS 1+ and AIS 5+, as well as fatalities and uninjured persons, as HIC is reduced from 1800 to 1000, 1800 to 800, and 1800 to 600, were computed. The number of injuries and fatalities at each HIC level are computed by using the cumulative percent probability for a single injury level (for example, see AIS 5+ curve) and the percent frequency of occurrence for the baseline vehicle fleet or the modified vehicle fleet, at a specific HIC value under consideration. The product of these two percentages represent the fraction of the casualty count at that HIC. This fraction, when multiplied by the target population, yields the actual count of the number of injuries likely to occur at that HIC. The distribution for the baseline fleet gives the injury count for baseline vehicles, and the use of the frequency distribution for padded vehicles gives the count for modified vehicles. Using this procedure, the casualty count for each HIC level for baseline and padded vehicles are calculated. With HIC 1800 as the base, the ch ınge in casualty count for reduced HIC's of 1000, 800 and 600 are computed and they are expressed as a percent of the base count. These values are presented graphically in Figures 10a and 10b. As HIC is reduced from 1800 to 1000, 98 percent of the fatalities are eliminated, with all fatalities disappearing as HIC approaches 600. The reduction in AIS 3+ injuries range from 16 percent to 50 percent for HIC reduction from 1800 to the range of 1000-600. It is interesting to note that while a large portion of the serious and severe head injuries are reduced, minor injuries (AIS 1+) increase by about 136 percent when HIC levels drop to 600. However, moderate injuries (AIS 2+) increase to 36 percent at HIC 1000, 78 percent at HIC 800 and 39 percent at HIC 600. The increase in AIS 2+ head injuries is higher for HIC reduction from 1800-800, than at HIC reduction from 1800-600. This is due to the differences in the probability of AIS 2+ and AIS 1+ curves. It is seen that the slope of the probability of injury curves for AIS 1+ and AIS 2+ at HIC levels of 600, 800, and 1000 are different. While the trends for AIS 1+ and AIS 2+ injuries as HIC drops from 1800 to 600 and 1000 are similar, for 800 HIC, AIS 2+ show a rising trend.

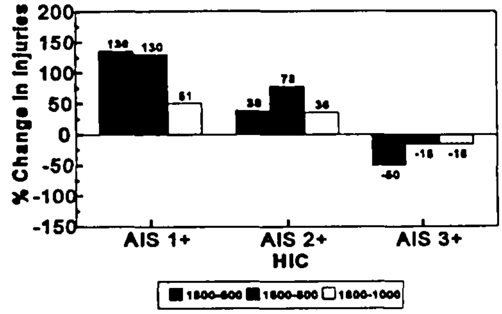

Figure 10a. Percent change in injuries due to HIC reduction.

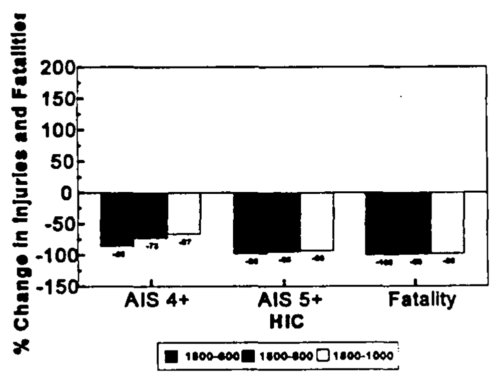

Figure 10b. Percent change in injuries due to HIC reduction.

This is due to the differences in the probability of injury curves for AIS 1+ and AIS 2+ at HIC 800.

It is also noted that the number of uninjured persons also increase as HIC level drop below 1000. Since there are no uninjured persons at a base HIC of 1800, the percent calculation using the base count would yield unrealistic numbers, and therefore, the percent increase in uninjured count is not presented. However, assuming a base of 100,000 occupant head contacts with upper interior components, the expected increase in uninjured occupants is 79 and 1884 when HIC is reduced from 1800 to 1000 and 600, respectively.

POTENTIAL BENEFITS IN REDUCING FATALITIES

In Figure 4, the estimated population with serious head/face injuries from upper interior components adjusted for 100 percent air bag fleet was presented. The fatalities and injuries represent the target population used to estimate benefits from the countermeasures introduced in baseline vehicles for upper interior protection. To determine the benefits from the countermeasures, the effectiveness of countermeasures, and the resulting reduction in injury severity were determined. The calculated benefits reflect the injuries prevented and the lives saved from reducing HIC levels to below 1000.

Effectiveness estimates were derived to reflect the percent reduction in HIC that would result from added padding. Baseline and padded tests were conducted with the FMH on passenger vehicle upper interior components. The agency examined the reduction in HIC between baseline and padded component tests and derived an estimated effectiveness for each upper interior component. Effectiveness values were used along with the injury probability curves in Figure 9, and the real-world injury distribution, to estimate the benefits. The analysis indicated that, if all passenger cars and light trucks currently on the road met the 1000 HIC requirements, there would be estimated benefits of approximately 1045 lives saved and 768 MAIS 2-5 injuries avoided each year.

COST

Estimated cost of implementing the countermeasures necessary to bring the fleet into compliance with the 1000 HIC requirement is based on the average number of square inches of the structural components that need padding in passenger cars and light trucks. Using weighted sales data and the total padding requirements, the estimated average weight of padding to reduce HIC below 1000 was calculated for the fleet. To this weight, the secondary weight increase was added to arrive at an estimate of the total weight increase of a vehicle due to countermeasures. The estimated average weight increase including secondary weight is 3.9 lbs and 6.4 lbs for passenger cars and LTV's, respectively.

Consumer cost per vehicle is derived from the cost of the padding material, plus the lifetime fuel penalty of carrying the extra weight of the padding and the secondary weight. Lifetime fuel penalty costs were based on the historic relationship between weight and fuel economy, as well as vehicle miles traveled. The consumer cost is estimated to be about $33 per passenger car, and $51 per LTV.

COST EFFECTIVENESS

Costs and benefits were combined to provide a comparison of the estimated injuries and lives saved per dollar spent. A cost per "equivalent" fatality is provided for comparison of the cost effectiveness of this rulemaking action as it applies to passenger cars and LTV's. The approach used to determine how many injuries are "equivalent" to a fatality is based on "willingness to pay". This approach measures individuals' willingness to pay to avoid the risk of death or injury based on societal behavioral measures, such as pay differentials for more risky jobs. "Equivalent" lives saved were calculated by comparing the values of a fatality to a specific injury level to estimate how many injuries are "equivalent" to one fatality. Based on this, injuries were converted to equivalent fatalities and the total benefits were determined in terms of equivalent lives saved. The cost/equivalent life saved is based on this estimate of the equivalent lives saved. Table 3 summarizes the cost, benefits, and cost effectiveness estimates for the current vehicle fleet.

Table 3. Costs, Benefits, and Cost per equivalent life saved.

	Incremental Consumer Cost per Vehicle	Benefits		Cost per equivalent Life Saved ($000)
		Fatalities	AIS 2-5 Injuries	
Passenger Cars	$32.53	711	465	542
Light Trucks and Vans	$51.03	334	303	1304

CONCLUSIONS

• NHTSA developed a test device and test procedure to evaluate head injury potential of production vehicles as occupant heads strike upper interior components in crashes.

• Two vehicles were tested using the above procedure. The test results were presented from impacts of typical targets impacted at 24.1 kph with the FMH. Two A-pillar impacts and one rear header impact exceeded the 1000 HIC limit. These components and others near the 1000 limit would require countermeasures to reduce the HIC to a desirable level considering the margin of safety generally used by manufacturers.

• Potential benefits from reducing HIC from 1800 to 800 and 600 showed a high potential for reduction of serious injuries (AIS3+); however, these injuries were shifted to lower level injuries where there was an increase in the number of injuries.

• It is estimated that if all upper interior components of vehicles on the road were brought down to perform at or below 1000 HIC, 1045 lives would be saved and 768 MAIS 2-5 injuries would be avoided.

• The cost per equivalent life saved in thousands of dollars is $542 for passenger cars and $1304 for LTV's to meet the 1000 HIC limit for upper interior components.

REFERENCES

1. Partyka, Susan. 1991. Serious Head Injury in Light Passenger Vehicles from Rail, Header, and Pillar Contact. Office of Vehicle Safety, National Highway Traffic Safety Administration, Washington, DC 20590.

2. Partyka, Susan. 1993. Head and Face Injury in Light Vehicle Towaway Crashes. Office of Vehicle Safety, National Highway Traffic Safety Administration, Washington, DC 20590.

3. Preliminary Regulatory Impact Analysis. Upper Interior Head Protection, FMVSS No. 201. Docket No. 92-28.

4. Willke, Donald. 1992. Upper Interior Head Protection Research Reports. Vol. I and Vol. II. DOT-HS-807-865 and DOT HS-807-866.

5. Prasad, Priya and Mertz, Harold J., "The Position of the United States Delegation to the ISO Working Group 6 on the Use of HIC in the Automotive Environment," SAE Technical Papers Series 851246, 1985.

6. Code of Federal Regulations: 49 CFR, Parts 400 to 999, 571.201, Occupant Protection in interior impact.

7. Final Economic Assessment. Upper Interior Head Protection. FMVSS No. 201 Docket No. 92-28

8. Federal Register. 49 CFR Parts 571, 572, and 589. Federal Motor Vehicle Safety Standards; Head Impact Protection. Vol. 60 No. 160. August 1995.

FREE MOTION HEADFORM TESTING: RESULTS AND POTENTIAL DESIGN COUNTERMEASURES

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ABSTRACT

This paper provides an overview of Free Motion Headform (FMH) impact testing on vehicle upper interior components from the perspective of typical testing results from conventional vehicles, a general methodology to interpret test results, and available design options for improving the crashworthiness characteristics in the event of head impact. Actual test data, as well as a statistical summary of testing results from tests conducted on many vehicles, is presented. Emphasis is placed on converting the test data from a time-based to a displacement-based format. A simple approach which can be used to estimate effective design countermeasure characteristics is described. A general discussion of available design countermeasure alternatives to increase the level of safety provided by interior components is provided. Readers of this paper will view testing results from a different perspective in that less focus will be directed to the specific injury index value, but more on the mechanics which caused the result. This perspective allows the engineer to focus on how to improve FMH test results through commonly accepted force management techniques.

INTRODUCTION

The requirements of the upgrade to Federal Motor Vehicle Safety Standard (FMVSS) 201 - Upper Interior Head Impact Protection present new challenges to automotive design/safety engineers. As is the case with new and unique vehicle requirements, the reaction of some engineers to meeting these requirements is that it is a nearly impossible situation. The main reason for this type of reaction is that there has not been an extensive amount of research conducted to date directed toward understanding test results, interpreting them and developing acceptable design countermeasures to improve these results.

This paper draws on a very wide range of laboratory FMH impact testing experience and attempts to provide the reader with enough background information so that the overall nature of the problem is understood better. Although this paper does not provide a "cookbook recipe" on how to improve the FMVSS 201U testing results for a given vehicle, it does take the first steps in defining such an approach. It is thought that some of the information presented here can be integrated into the overall development process for head impact protection, similar to techniques used in frontal and side impact protection.

Any approach which is used to address head impact protection issues must recognize that the problem is essentially experimental, i.e., cumulative successful results must be determined from a series of component level impact tests conducted according to the requirements specified by FMVSS 201U. The steps taken to achieving favorable results somewhat depend on what design alternatives are used, but the interpretation process used in analyzing testing results can be similar regardless of what type of design countermeasure is utilized. This point is emphasized because it allows the safety engineer to consider all testing results with a uniformed approach. This makes the sometimes difficult process of determining which design alternatives are most effective much easier to do.

Subsequent discussion covers basic parameters of a FMH impact test, examples of actual test data, how to process and interpret specific testing results, statistical analysis of testing results from numerous vehicles, a generic approach for estimating ideal design countermeasure characteristics, and design alternatives for improving results obtained from FMH impact testing. Accordingly, the information presented in this paper has been taken from many projects conducted concerning this problem.

Free Motion Headform Impact Test

It is assumed that the reader is familiar with the basic requirements of a FMH impact test (in this paper, "FMH" and "FMVSS 201U" impact tests are considered interchangeable); however, specific procedural information and testing criteria are available through publicly available literature. Here, only a very basic description of a FMH test is discussed and the purpose here is to set the stage for subsequent discussion.

The general parameters of the test are as follows:

- 10 pound modified Hybrid III dummy head in free flight
- 15 mph impact velocity
- impact configuration perpendicular to the surface
- test data includes center of gravity X, Y, Z acceleration
- impact areas include pillars, roof, headers, and side rails
- acceleration-based injury index criteria

In general, the steps involved in conducting a FMH test series include "targeting" the vehicle. This process consists of determining impact point locations and angles per government procedures. Next, the vehicle is prepared for the test series by providing supports so that its suspension is inactive (i.e., the vehicle is lifted off of the ground). Following this, the impact tests are conducted on each applicable point, while adhering to specific FMH calibration and "soak" time requirements. Acceptable injury criterion, as defined by the National Highway Traffic Safety Administration (NHTSA), is as follows:

$$\text{HIC (d)*} \leq 1000$$

Presented in Figures 1-3 are photographs illustrating typical FMH impact test setups. In general, the actuator (which is defined as any device used to accelerate the FMH up to the impact velocity) is positioned to propel the FMH so that it impacts the intended target with first contact in the forehead region (defined by FMVSS 201U) on a directional vector perpendicular to the surface. Positioning of the actuator is typically done using a template. The template simulates the shape of the FMH and accounts for an acceptable amount of free flight distance prior to impact.

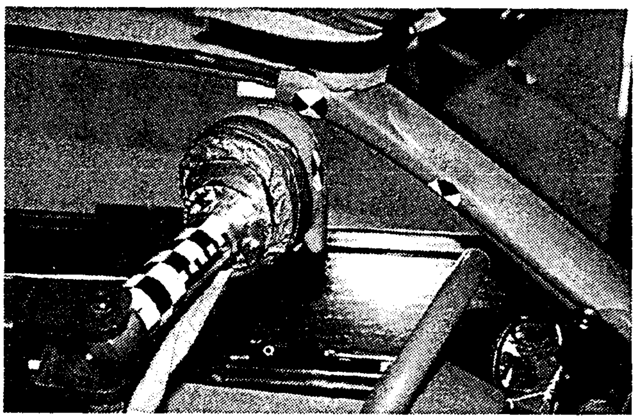


Figure 1. Upper A-pillar impact.

***HIC(d)** = 0.75446(**HIC**) + 166.4 where **HIC** =

$$\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2-t_1)$$ and a is the resultant acceleration.

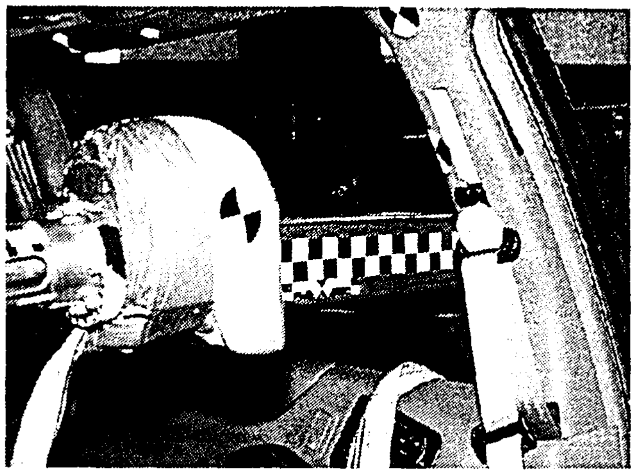


Figure 2. B-pillar D-ring impact.

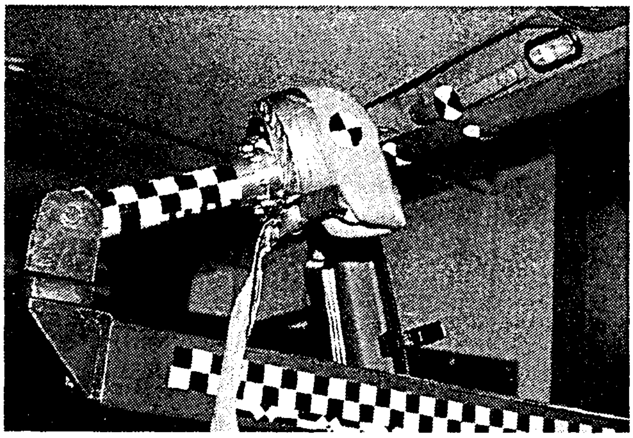


Figure 3. Driver side rail impact.

<u>**Statistical Analysis of FMH Impact Testing Data**</u> - In order to better understand the overall nature of head impact occupant protection and FMH testing, it is helpful to analyze the results from a large quantity of tests conducted on many types of conventional vehicles (passenger cars, light trucks, vans, etc.). Such a study will allow a safety engineer to quickly realize where the problem areas of a vehicle are and to consider the best approach towards effectively dissipating the kinetic energy of the headform in such a way that favorable testing results can be achieved with suitable design changes.

The data used in this section was obtained from

approximately 400 FMH impact tests carried out on the interior structures of different vehicles. Average HIC(d) and peak resultant acceleration G's obtained from the actual tests were approximately 1100 and 180, respectively. All of the tests considered were conducted per procedures specified in the Notice of Proposed Rulemaking (NPRM) issued by the NHTSA in February 1993.

Presented in Figure 4 is a graph showing the HIC(d) as a function of peak resultant G's. The solid line in Figure 4 represents the best fit curve for the data set. Although significant variation in HIC(d) exists for the same value of the peak resultant G's, HIC(d) increases polymonially with increasing G's. According to nonlinear regression carried out on the measured data, the equation representing the variation in HIC(d) as a function of the peak resultant G's (G) is as follows:

$$HIC(d) = 110 + 2.7G + 0.016G^2 \qquad (50 < G < 300) \qquad (1.)$$

From Eq. (1.), the maximum allowable G's to have the HIC(d) be less than 1000 is in the vicinity of 170 G's or less. This figure, 170 G's, is obviously a rough estimate of the maximum G's which will result in a HIC(d) of 1000. It is important to point out that 170 G's is strictly a nominal value taken as the average HIC(d) over many impact tests. Referring to Figure 4, the peak G's for a HIC(d) of 1000 can vary from 140-220 G's. The reason for this wide range is because HIC(d) not only depends on peak resultant G's, but also is dependent on the time and the shape of the acceleration event. This, in combination with peak resultant G's, can vary HIC(d) substantially. The point here, and in subsequent discussion, is to shift attention away from HIC(d) and more so on the maximum levels of force which can be encountered by the headform while still achieving favorable results.

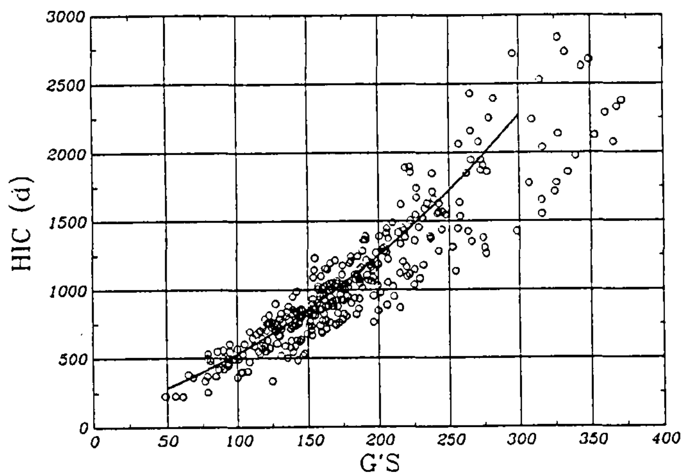


Figure 4. Variation in HIC(d) as a function of the peak resultant G's.

Presented in Table 1 is a summary table showing the observed range in HIC(d) for various impact regions.

Table 1.
Statistical Data Showing the Range in HIC(d) for Various Interior Structures

G's	HIC(d)	Impact Area
<125	<700	Grab handle, front & rear headers, sun visor, roof
125 ~ 165	700 ~ 1000	B-pillar lower, C-pillar mid, side rail, D-ring anchor
165 ~ 190	1000 ~ 1200	B-pillar & A-pillar mid, double-layered pillar junction
190 ~ 210	1200 ~ 1400	B-pillar upper, B-pillar flange
> 210	> 1400	A-pillar upper and flange, A-pillar at roofrail junction

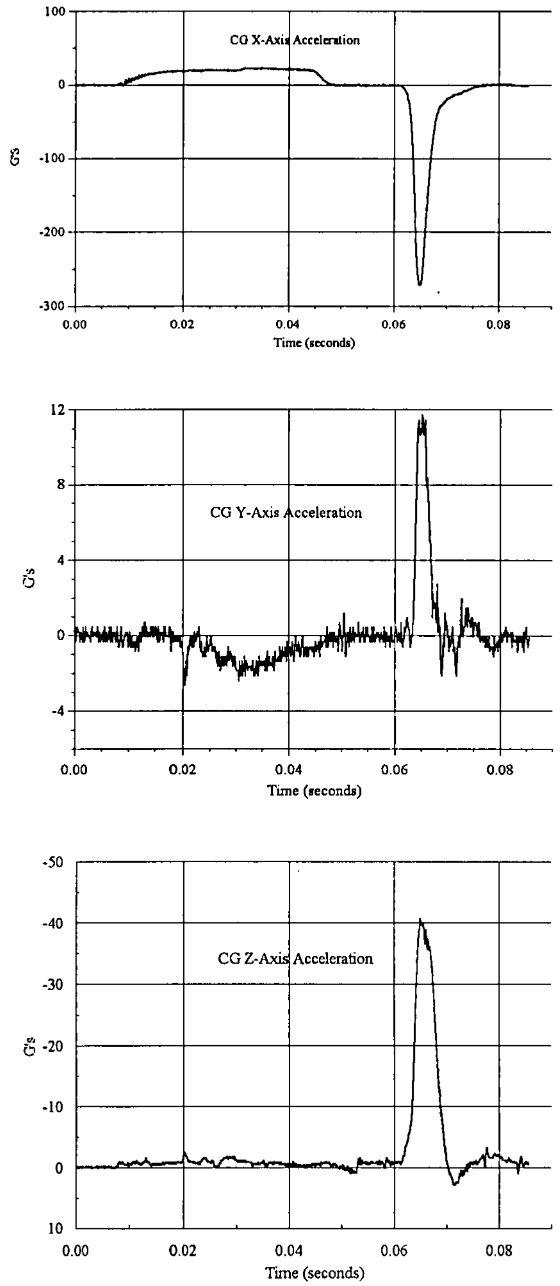
According to these and subsequent test results, pillar structures have shown the highest injury index levels. In particular, the upper A-pillar on most vehicles has demonstrated a significantly high HIC(d), generally above 1400. This is due to the fact that the stiffness of the A-pillar structure is probably the highest among all the interior structures of concern. The results in Table 1 have been presented to provide the reader with background information defining the scope of the problem. It should be noted that results from a specific vehicle may not fall under these numerical ranges, but based on testing experience, most vehicles will produce results similar to the data presented here.

Interpretation of FMH Testing Results - Whenever a FMH impact test is conducted, the data which is generated can be quite helpful in considering potential designs to improve results. This is only correct if the data is presented in a format which is easier to interpret from a design standpoint. As is the case with most mechanical loading tests, the problem is much easier to handle if it is addressed from a displacement-based reference, instead of a time-based reference. This concept is sometimes difficult for safety engineers to embrace because the data produced from a dynamic test is typically referenced relative to time as opposed to quasi-static based evaluations, in which the data is usually produced in a displacement-based format. Typically, the general consensus among safety engineers is that displacement-based data is easier to interpret and understand.

With this in mind, the time-based data from a FMH impact test must be converted to a displacement-based format. This should be one of the first steps in interpreting testing results.

This translation is very straightforward through simple data processing manipulation.

Presented in Figure 5 is the data from a typical FMH impact test. The data is the acceleration-time histories from the accelerometers mounted at the center of gravity X, Y, and Z directions in the headform. Also included in this figure is the resultant acceleration of the FMH. As shown by this data, the loading is primarily in the X direction. This is usually the case with FMH impact test data.



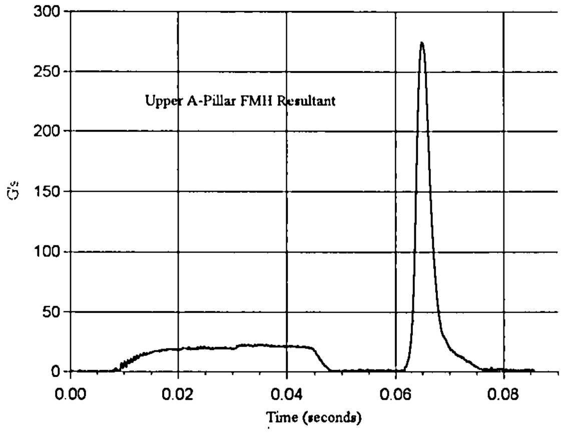


Figure 5. Typical data from a FMH impact test.

For interpretation purposes, only the X-axis acceleration is used. Considering only a single axis of data makes the problem much easier to address. First of all, the data must be integrated twice with respect to time. This will result in a headform displacement-time relationship. Using Newton's 2nd Law, the X-axis acceleration-time response can then be multiplied by the mass of the headform to calculate a force-time relationship. "Cross-plotting" these two relationships results in a force-displacement relationship. This derivation of displacement and force relationships is shown in the following equations:

$$v(t) = \int a(t)\, dt \qquad (2.)$$

$$d(t) = \int v(t)\, dt \qquad (3.)$$

$$f(t) = m \cdot a(t) \qquad (4.)$$

where a(t) is the X-acceleration of the FMH and m is the mass of the FMH.

The force-displacement relationship derived here is considered only a close approximation since the FMH is unconstrained and rotational effects have been ignored. The intent of this derivation is not to determine a specific stiffness characteristic, but only one which provides test data in a displacement-based format which can be used to evaluate potential design countermeasures. Figure 6 shows the force-displacement relationship which has been calculated from the data in Figure 5. This curve, when used from the standpoint of management of the FMH's kinetic energy, can be very useful to a FMH design engineer.

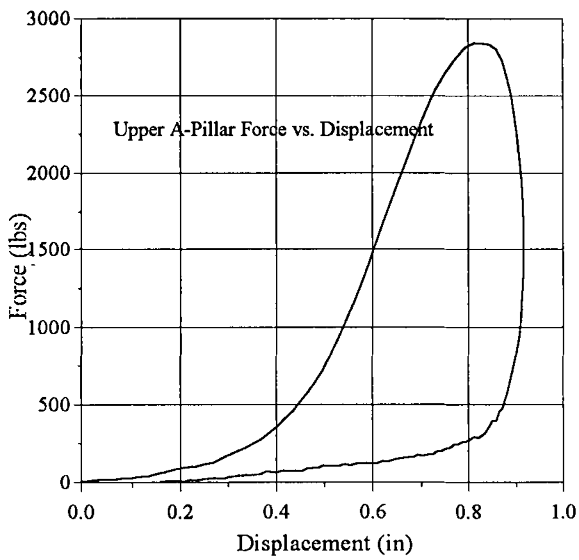


Figure 6. Force-displacement data calculated from X-axis acceleration.

Contribution of Various Components on FMH Testing Results - Throughout a FMH impact event, the headform will dissipate kinetic energy via various deformation process', such as deformation of the headskin, trim, padding, and sheet metal. The energy absorption properties of each of these components is quite important from the standpoint of controlling the maximum forces experienced by the headform. Understanding the role that each of these has in dissipating the energy of the FMH is critical when considering the characteristics that an ideal padding material exhibits. In this paper, the term "padding material" refers not only to plastic foam, but also to all other energy management devices which could be used as FMH design alternatives.

For simplicity, the force-displacement curve associated with a headform impact (as seen in Figure 6) can roughly be assumed as having a triangle shape with an area of approximately 900 in·lbs (900 in·lbs is the approximate kinetic energy of a 10 lb. mass traveling at 15 mph). Although a triangular shape is not typical for all FMH impact tests, it is used here only to demonstrate a generic approach to energy management of the headform. Based on the statistical analysis of FMH test data presented earlier, the maximum acceleration of the headform should not exceed 170 G's to achieve a HIC(d) of less than 1000. Therefore, the maximum force encountered by the headform has to be less than approximately 1700 lbs. It should be emphasized that 1700 lbs has been chosen here only to demonstrate a methodology to improve FMH testing results. The numerical value 1700 lbs is by no means a "magical" figure with regard to FMH forces. Any value which produces a favorable result could be used with the approach described in this paper.

One possible way to dissipate the kinetic energy of the headform, while maintaining maximum headform forces of less than 1700 lbs is to allow more penetration of the headform into the structure. This can be achieved either by using a thick and soft padding material or making the pillar structure less stiff. However, these alternatives could detract from other safety features, such as visibility or roll-over, front, and side impact protection. Therefore, the approach of increasing the total displacement in an effort to minimize the headform force is not considered to be ideal.

In order to dissipate 900 in·lbs of the FMH kinetic energy, and assuming a triangular force-displacement curve, a minimum of approximately 1 inch of displacement is needed. Presented in Figure 7 is a schematic representing the force-displacement curve showing the maximum allowable force level, as well as minimum displacement under a given kinetic energy. Since the allowable range of the headform displacement is limited to maintain a HIC(d) of less than 1000, it is desirable to consider the energy absorption capability of each element involved in the impact event. These elements include the FMH headskin, trim, padding, vehicle structure, etc. These elements can be represented as a spring mass model in which four springs are connected in series, as show in Figure 8.

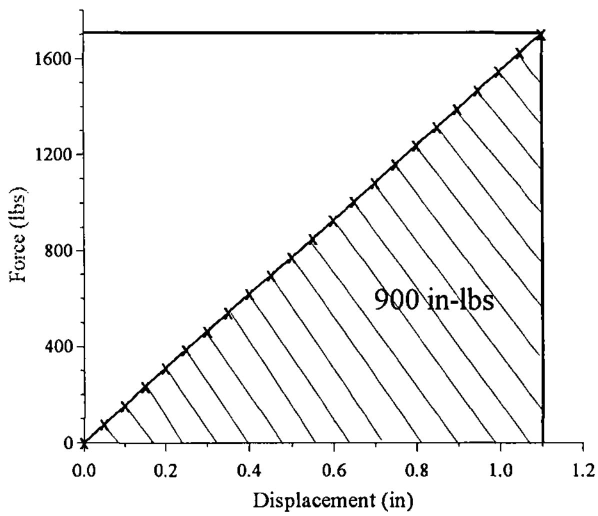
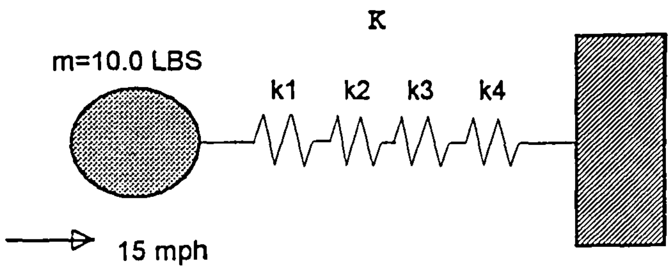


Figure 7. Force-displacement curve with maximum allowable force level under a given kinetic energy.



where k_1 = stiffness of the headform
where k_2 = stiffness of the trim
where k_3 = stiffness of the padding material
where k_4 = stiffness of the vehicle structure
where K = stiffness of the headform/pillar spring

Figure 8. Spring-mass model of the headform/pillar impact.

The headform skin is believed to absorb a minimal amount of the kinetic energy. This is due to the fact that, as shown in Figure 9, the stiffness of the headskin is significantly higher than those of the other elements, such as the trim, padding material or vehicle structure. Referring to Figure 9, dynamic impact tests were conducted on the FMH headskin and also on upper A-pillar structures with no trim to demonstrate the stiffness differences in these elements.

Furthermore, based on test results, the amount of energy absorbed by conventional trim materials was found to be insignificant. Most trim materials absorb approximately 5% to 7% of the total kinetic energy, depending on the stiffness of the trim material and the interspacing between the trim and pillar surface. An exemplary plot showing this feature is shown in the region enclosed by the ellipse in Figure 10. The data plot in Figure 10 is the force-displacement characteristic from a FMH test conducted on an A-pillar. As shown, by the time the trim has contacted the surface of the pillar structure (as indicated by the arrow in the graph), approximately 45% of the total displacement has already taken place. This simply indicates that the remaining kinetic energy of the headform has to be absorbed by the vehicle structure, usually causing an excessively high force, i.e., G's. Figure 11 presents a plot of the velocity of the headform prior to contact with the vehicle structure. The trim reduced the velocity of the headform only a very small amount. In order to reduce the headform forces, the velocity of the headform has to be substantially reduced by the time the headform impacts the vehicle structure. This can be achieved by absorbing as much energy as possible in the earlier stage of the impact event. One way to effectively dissipate the kinetic energy of the headform is through the use of padding materials, modified trim structures, or other energy management devices designed to do this during the early stages of the impact event.

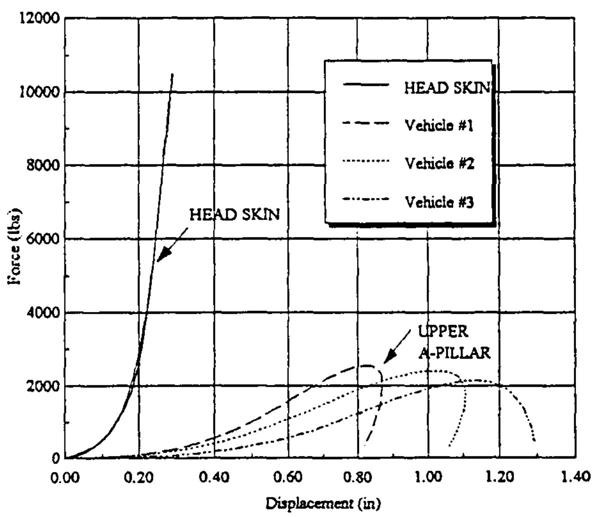


Figure 9. Dynamic force-displacement characteristics of the headskin and upper A-pillar.

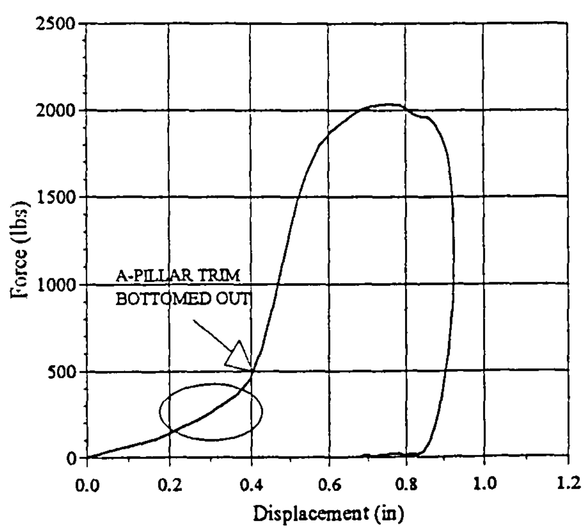


Figure 10. Contribution of conventional trim material in a FMH impact.

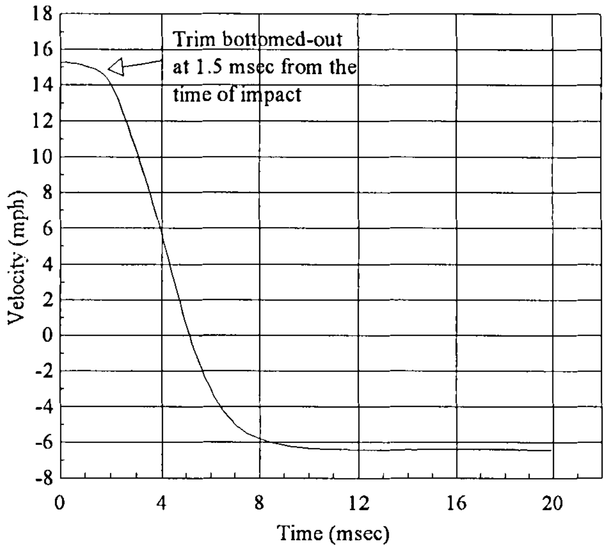


Figure 11. Velocity-time profile showing the velocity of the FMH at the time of vehicle structure contact.

Examples of "Soft" and "Hard" Padding Effects on FMH Testing Results - During a typical test, when the FMH impacts the upper A-pillar protected with a "soft" energy absorption material, only small amounts of the kinetic energy are absorbed by the material before "bottoming-out" occurs and the FMH loads into the surface of the pillar structure. The term "bottoming-out" refers to the case where a padding material (or other energy management device) has been compressed to the point that the stiffness characteristics are very large and the material has very little influence on the FMH. As a result, the FMH will penetrate into the vehicle structure at a sufficiently high speed, resulting in high headform forces.

However, if the stiffness of the energy absorption material is high enough to avoid "bottoming-out", most of the headform energy will be absorbed by the padding material. As a result, the headform will penetrate into the vehicle structure at a lower speed, resulting in lower headform forces. Figure 12 demonstrates the difference between "soft" and "hard" padding materials.

As a result, the padding material has to be selected so that it is stiff enough to dissipate a substantial amount of the kinetic energy of the impact, yet still moderately soft enough to keep the headform forces within an acceptable level. The question regarding an ideal stiffness range for padding materials to maintain a HIC(d) of less than 1000 depends on the impact area. For example, in the case of an A-pillar impact, the contact area of the headform is relatively small, while in the case of a B- or C-pillar, the impact area is most often larger. As a result, stiffer padding material would be appropriate to protect the A-pillar, while less stiff padding materials may work better for other areas of the vehicle.

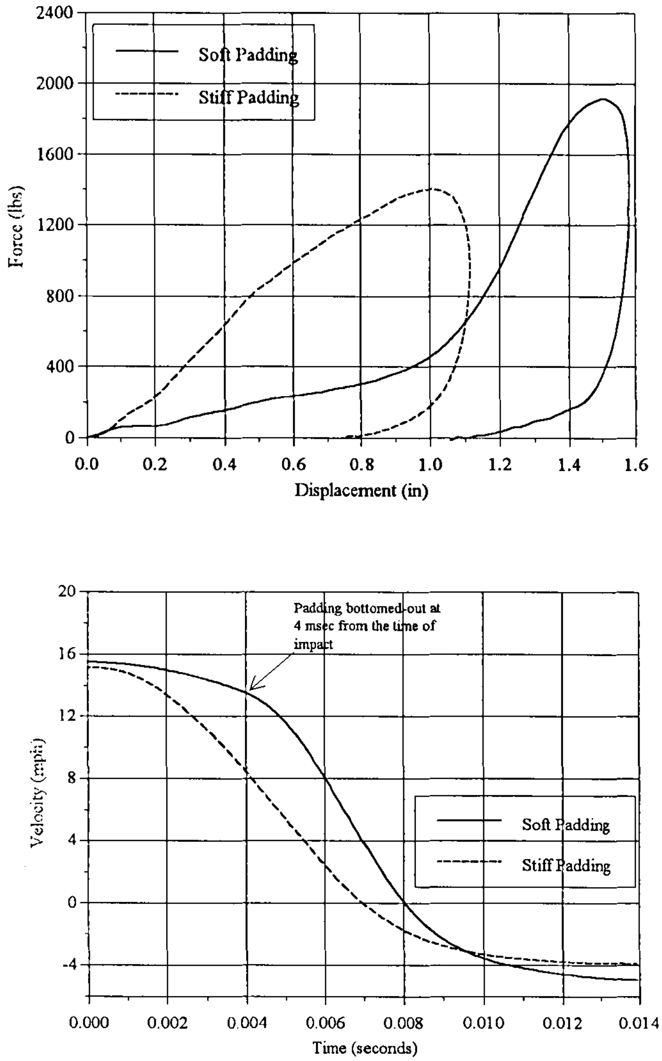


Figure 12(a). Effect of the padding material stiffness on peak force levels. (b) Variation in the headform velocity as a function of time.

Determination of an Ideal Padding Material Stiffness - In order to determine the ideal stiffness of a padding material, the Spring-Mass model simulating the headform/interior impact presented in Figure 8 can be used.

The effective stiffness (K) of the system can be expressed as a function of the stiffness of the individual spring elements

in the system and defined by the following equation:

$$\frac{1}{K} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{k_4} \qquad (5.)$$

Equation (5) is representative of the spring mass model in Figure 8 if all of the spring elements are considered. Since the energy absorbed by the trim material is very small, and since the plastic trim covering will have even lesser influence if it is backed by padding, Equation (5) can be simplified by removing the trim stiffness (k_2). This results in the following equation:

$$\frac{1}{K} = \frac{1}{k_1} + \frac{1}{k_3} + \frac{1}{k_4} \qquad (6.)$$

or

$$K = \frac{k_1 k_3 k_4}{k_3 k_4 + k_1 k_4 + k_1 k_3} \qquad (7.)$$

Solving this equation for the padding material stiffness (k_3) results in the following equation:

$$k_3 = \frac{K k_1 k_4}{k_1 k_4 - K k_4 - K k_1} \qquad (8.)$$

All of the stiffness characteristics on the right side of the equation ($k_1 k_4 K$) can be determined via dynamic impact tests. Presented in Figure 9 are characteristics of k_1 (stiffness of the headform) and k_4 (stiffness of the vehicle structure) for three different conventional vehicles. These characteristics were derived through impact testing. To implement this approach during FMH development, k_4 values would be determined through testing. As more of this type of work is done, the design engineer will develop a better understanding of what the stiffness levels are for various areas of the vehicle. As experience with this approach is gained, less tests on vehicle structures or trim will be needed as it will be shown that specific classes of vehicles (small, mid-size, light truck, etc.) all have similar characteristics.

A note of caution is needed regarding this methodology. The approach presented here is not intended to give a precise answer with regard to specific numerical design countermeasure stiffness. It is thought that this approach could definitely be used to provide "ballpark" estimates of what a suitable countermeasure property should be.

Example of How to Estimate Padding Material Characteristics - Presented in Figure 13 is the resultant acceleration and force-displacement from a FMH test conducted on an A-pillar of a mid-size vehicle.

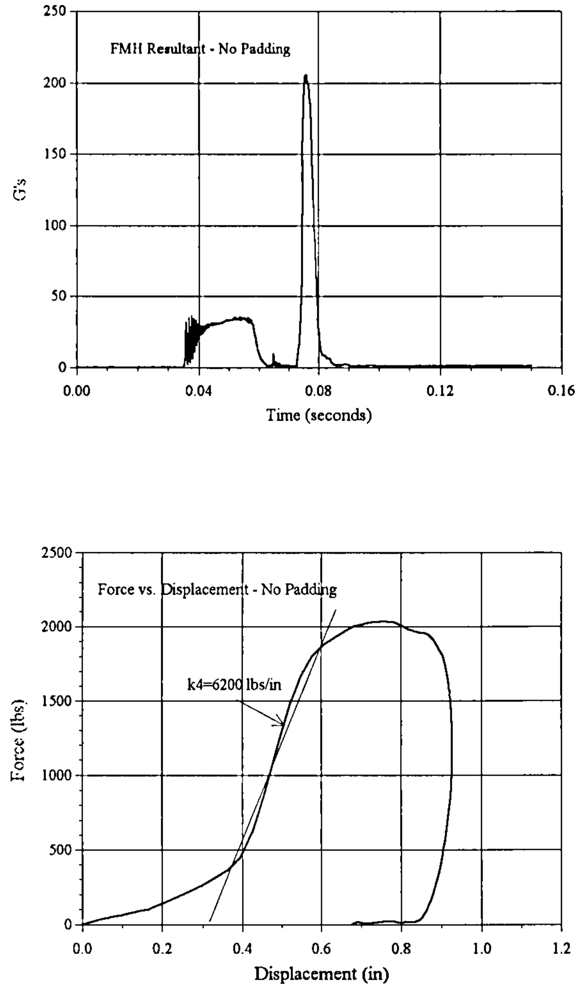


Figure 13. Resultant acceleration (top) and force-displacement (bottom) from a FMH impact test conducted on an A-pillar.

The HIC(d) for this test was 1420. Utilizing the approach outlined in the previous section, Equation (8.) can be used to estimate the ideal stiffness for a potential design modification. The effective stiffness (K) based on the data presented in Figure 13 is obviously much greater than 1700 lbs/inch. From the force-displacement in Figure 13, the stiffness characteristic for k_4 (vehicle structure) can be determined by measuring the slope between .4 and .6 inch (as shown). The headform stiffness (k_1) can be estimated from the data presented in Figure 9. These estimated values are $k_1 \approx 70{,}000$ lbs/inch and $k_4 \approx 6{,}200$ lbs/inch.

Since the purpose of this calculation is to determine the value for k_3 which produces the ideal effective stiffness for the headform/pillar model, Equation (8) should be utilized with K set at 1700 lbs/inch. Substituting these values (k_1, k_4, K) into the equation yields the following:

$$k_3 = \frac{(1700\ \#/in)\ (70000\ \#/in)\ (6200\ \#/in)}{(70000\ \#/in)(6200\ \#/in)-(1700\ \#/in)(6200\ \#/in)-(1700\ \#/in)(70000\ \#/in)}$$

$$k_3 \cong 2400\ \text{lbs/inch}$$

Based upon these calculations, adding a padding material to the pillar structure which has a stiffness property of approximately 2400 lbs/inch should result in a HIC(d) value equal to or below 1000. Figure 14 presents the force-displacement data from a static test conducted on a padding sample having a general stiffness of approximately 2500 lbs/inch. A one-inch thick sample of this padding was placed behind the trim panel and an A-pillar FMH test was conducted. Presented in Figure 15 are the results of the impact test. The peak acceleration (G's) was reduced from 206 to 146, while the HIC(d) was reduced from 1420 to 846. Perhaps of more importance is the change in the shape of the force-displacement curves as derived from the X-axis acceleration. As can be seen, the padding material which was added managed to absorb much of the kinetic energy of the headform before high force levels were achieved due to loading into the vehicle structure.

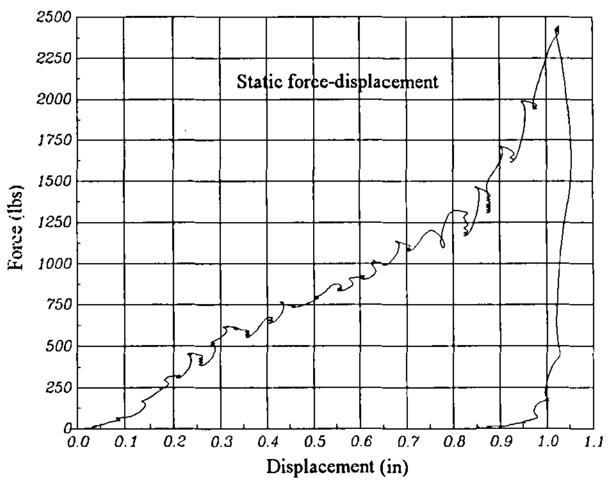


Figure 14. Force-displacement results from a static test conducted on a padding sample.

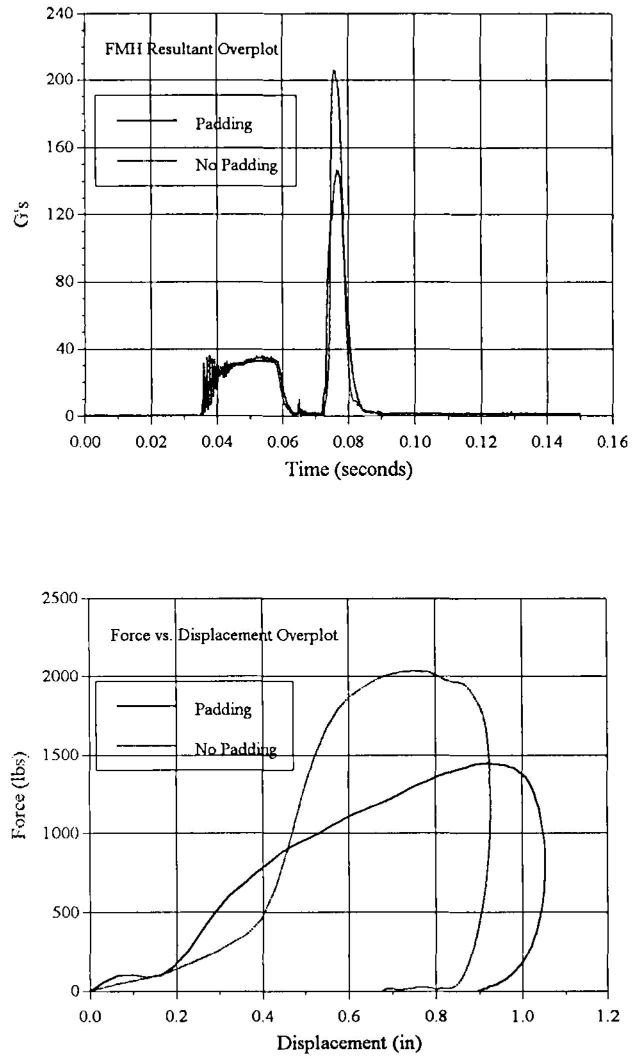


Figure 15. Resultant acceleration and force-displacement overplots demonstrating the effects of adding a padding material with proper k values.

The purpose of this example is mainly to demonstrate how some of the information in this paper could be used. The main point being that the approach demonstrated here (or a similar one) could be used with all FMH testing results and different countermeasures in a very quick and effective manner.

Alternatives for Improving FMH Testing Results - Currently, automobile manufacturers are in the process of determining which are the best alternatives for improving the levels of head impact protection provided by their vehicle. The purpose of the discussion in this section is not to differentiate and evaluate the various alternatives, only to

briefly overview what the industry is considering. There are other issues involved in this process that are not considered here. These include ease of production, cost, temperature effects, durability, etc.

Presented in Figure 16 are photographs illustrating design alternatives currently under consideration by various manufacturers. Examples of design alternatives primarily consist of various types of plastic foam or plastic trim covers designed with energy management characteristics. With regard to plastic foams, various types are being considered including recoverable, non-recoverable, composites, etc. This design application would be used in conjunction with a plastic trim cover.

Integrated trim components are designed with a "webbing" or "ribbed" backing underside which is designed to crush in a way to effectively manage the FMH impact energy. Other options, such as aluminum honeycomb structure or collapsible pockets of air embedded in a composite material are also being evaluated. Regardless of which design alternative is under consideration, the methodology described in this paper can be utilized for defining what stiffness characteristics the material must have to achieve favorable results.

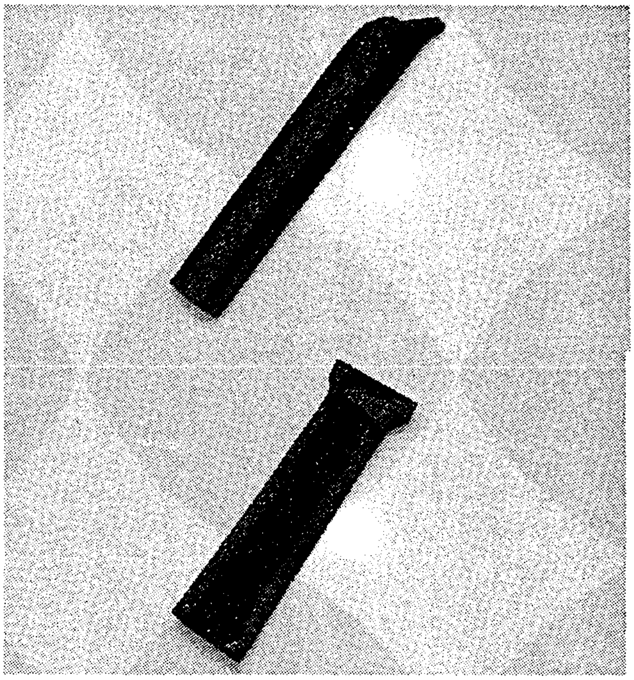


Figure 16a. Plastic foam A-pillar and B-pillar design alternatives.

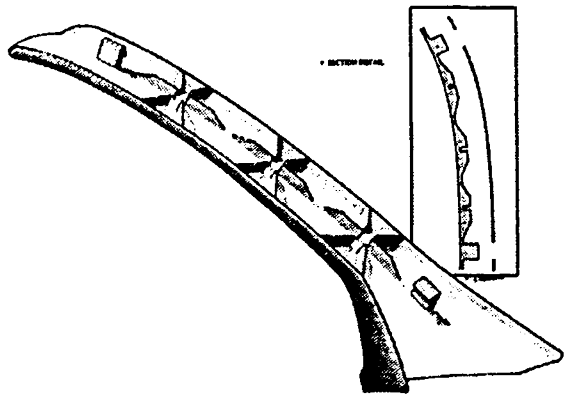


Figure 16b. Example of integrated trim component. Conceptual drawing courtesy of GE Plastics.

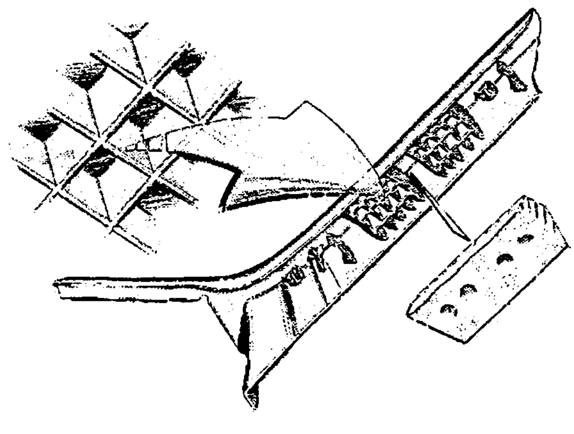


Figure 16c. Example of integrated trim component. Conceptual drawing courtesy of DOW Chemical Co.

CONCLUSIONS

The data, results, and analysis presented in this paper outline a generic approach which can be used to address head impact protection. As is the case with most new major safety rules, initially there is a great deal of apprehension because there is very little known as to how to handle the problem. The intent of this paper is not to present a detailed "recipe" for meeting the new requirements, but more so to present novel approaches which may be implemented into development already being done.

Crashworthiness is essentially experimental in nature. For the new FMVSS 201U regulation, acceptable performance is based upon results from a series of dynamic tests. All data are basically time dependent histories. In conjunction, vehicles are designed to convert kinetic energies into work done on the vehicle. With this in mind, energy dissipation is better understood in terms of force-displacement, which are referenced relative to displacement, and not time. Engineers tend to consider energy dissipation more from the standpoint of structural spatial relationships. Therefore, the transition from a time-based relationship to a displacement-based relationship is essential in developing design solutions geared toward effectively dissipating the kinetic energy of the headform.

This paper presents a direct method to make this transition. Although the problem is three-dimensional, most of the loading occurs in only one direction. Considering only one axis is acceptable since the nature of the discussion is directed towards estimating what characteristics a potential design solution exhibit. Once again, the intent here is not to present a specific approach on how to determine the best characteristics for a design alternative, but to cause the engineer to consider FMH results from a perspective of "force level" management, and not only a "what's the HIC" mentality.

It will not be known for a few years what actual effects the new legislation will have on vehicle designs or injury/fatality rates. In the meantime, engineers must use some degree of ingenuity to address this new standard. This is similar to what has happened for frontal and side impact protection. The approach presented in this paper, in addition to other approaches being developed, will ultimately result in safer vehicles for the driving public.

ACKNOWLEDGMENTS

The authors of this paper wish to express thanks to the associates at MGA who have worked very hard in this and other areas. Also, appreciation is expressed to engineers in this industry who we have worked with in developing test methodologies, procedures, equipment, and analytical approaches all directed towards head impact protection.

REFERENCES

Code of Federal Regulations, Title 49 (Transportation), Chapter V (NHTSA, DOT), Part 571, 572, and 589- Federal Motor Vehicle Safety Standards; 201U, Head Impact Protection. Docket 92-28, Notice 4, August 18, 1995.

NHTSA, Laboratory Test Procedure for Federal Motor Vehicle Safety Standard No. 201U, Upper Interior Head Impact Protection (TP-201U-00, 1995).

NHTSA, Notice of Proposed Rulemaking to Amend Federal Motor Vehicle Safety Standard No. 201 - Head Impact Protection. Docket No. 92-28; Notice 2, U.S. Department of Transportation, Washington, D.C.

Miller II, P. Michael, Rychlewski, Helen, & Phillips, Suzanne. Upper Interior Impact: Test Equipment and Testing Techniques, written presentation at the ESV Conference, Melbourne, Australia, May 13-17, 1996.

THE EVALUATION OF SUB-SYSTEMS METHODS FOR MEASURING THE LATERAL HEAD IMPACT PERFORMANCE OF CARS

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ABSTRACT

The EEVC Side Impact Test Procedure includes the measurement of head impact with the EUROSID dummy. It was recognised that this would evaluate only a limited range of the potential head contact locations within the vehicle. EEVC commenced a study of accident analysis and the evaluation of potential head impact sub-systems tests. Three alternative headforms have been appraised and the effect of free flight and linearly guided impacts have been examined. The objective was to develop a simple, repeatable and representative sub-system test procedure.

This paper presents progress of the EEVC study and the initial results of the test programme. Proposals are made for a possible test method and for a future validation test programme.

INTRODUCTION

The EEVC developed a new impact test procedure for the evaluation of the protection afforded to struck side car occupants in the event of a side impact to the passenger compartment. The final presentation of this test procedure was given in the EEVC paper to the Twelfth ESV Conference in 1989[1]. EEVC developed a new dummy for use with the test procedure (EUROSID) since there was no dummy available at that time suitable for use in side impact testing. The dummy was designed to be able to detect injury risk in the four areas of the body which were most frequently injured at AIS 3 or greater: the head, chest, abdomen and pelvis.

The test procedure is intended to evaluate the protection for a restrained occupant. Under these conditions, the area of the vehicle which impacts the occupant is in most cases confined to the area adjacent to that body area in the normal seating position and these are the areas that are evaluated in the test procedure. However this is not true for the head. Accident studies demonstrated that the area of the vehicle struck by the head is considerably wider than that adjacent to the head. In many cases of serious injury, the head impacts objects outside the vehicle. However there were a significant number of cases of serious injury to the head from contact with the interior of the vehicle. In typical side impact tests the head of the EUROSID dummy frequently does not make contact with the vehicle interior, passing through the side window which is usually broken before the dummy head reaches it. In those cases where the dummy head does strike the interior, it is at a position alongside the original position of the head. In the EEVC side impact test procedure, the dummy head will not evaluate the wide range of positions that are contacted by occupants' heads in accidents.

The EEVC recognised this situation in the final report of the side impact test procedure[2] and concluded that there was a need to investigate the requirements for a supplementary headform test.

EEVC Working Group 13 are developing a head impact test procedure for evaluating the head protection provided in the range of locations for head impact that have been observed in side impacts based on analyses of detailed accident studies. A three phase research programme has been developed to provide the basis for this test procedure which could be used as a supplement to the current full scale side impact test.

In the first phase, three potential headforms have been evaluated in free-flight impacts to targets representing simplified forms of the internal structures of cars that could be impacted by the head. The second phase will study the relative merits of free flight and linearly controlled impacts, using the preferred headform and the third phase will study the application of the proposed test method to whole vehicles and sub-systems and consider the practical level of improvement possible. One sample of the FMH and AAMA headform was available to the group. Each test laboratory used their own EEVC headform, thus the results for the EEVC tests include an additional level of variability not experienced with the other two headforms.

This paper reports on two accident analyses supporting the need for the work and gives the results of the first phase of the study.

ACCIDENT ANALYSIS

Accident investigations have identified head impact as a very important and common source of serious injury in side impacts. Otte[3] showed that over 47% of injuries occurred to the head of a struck side occupant in a side impact compared with only 30% to a driver in a frontal impact. Thomas et. al.[4] reviewed some UK accident data examining injury distribution and severity of injury in side impact. Thomas was able to determine that 41% of all head contacts were to the side glass, 11% were to the B post and seat belt anchorage, 6% to the header rail and 1% to the A post. NHTSA has recognised the importance of head impact and has developed its own subsystems test, although this is intended to cover front impacts and rollover in addition to side impacts. They estimate that 19% of head injuries would be affected if the contacted surfaces were padded.[5]

Table 1 Severity of head injury in TRL and Hannover accident samples (side impacts).

DATA BASE	TRL		Hannover	
AIS	1-2	3-6	1-2	3-6
Sub totals	227	81	285	51
Total	*308*		*336*	

In order to identify better the problems of head impact in side impacts, the data bases to which the working group have access have been interrogated. This analysis has concentrated on examining the severity of head injury against the areas of the vehicle interior that have been identified by the accident investigators as being contacted by the head. The two data bases examined are from TRL, the Co-operative Crash Injury Study (CCIS)[6], and the Hannover data base from Germany[7]. The analysis was restricted to side impacts with a direction of impact coded as 2, 3 or 4 o'clock and 8, 9 or 10 o'clock. The data were examined for both struck-side and non struck-side occupants with and without an occupant seated along side. Table 1 shows the size of the accident sample from which the working group analysis has been made. Tables 2 and 3 give the distribution of injuries against contacts as coded in the data for both struck-side and non struck-side occupants. These results indicate that between 40 and 60 per cent of head contacts were to the interior of the vehicle.

The two data bases show slightly different patterns of contact injury but this can easily be attributed to differences in

Table 2 Single Head Impact Contacts - Non struck-side occupant with impact on opposite side.

Contact	TRL		Hannover	
	AIS 1-2	AIS 3-6	AIS 1-2	AIS 3-6
A Pillar			5	
B Pillar		2	6	2
Windscreen	1			
Window frame and roof rail	1	1	7	4
Glass	6		9	2
Door	3	3	20	8
External object		1		
Other Contact	1			
Not Known	6			
Total number of cases	*18*	*7*	*47*	*16*

accident collection strategies. Even so there is a clear indication that the B pillar and structure around the side window is an important area for injury producing contacts. The data also clearly show that potential contacts can occur over a large area of the side of the vehicle. The full scale impact test only evaluates injury severity for the head at one contact location, if

Table 3 Single Head Impact Contacts - Restrained struck-side occupants

CONTACT	TRL		Hannover	
	AIS 1-2	AIS 3-6	AIS 1-2	AIS 3-6
A Pillar	6	2		
B Pillar	21	9	50	21
Windscreen	7	1		
Window frame and roof rail	6	3	33	6
Glass	76	2	120	4
Facia	3	1		
Door	7	6	83	4
Roof	3	2		
Light	1		1	
Steering Wheel	2	1		
Sun visor	1			
Rear Window	1			
Ejection		1		
Other Occupants	4		1	
External object	12	35		
Other Contact	1	3		
Not Known	57	7		
No Contact	1	1		
Total number of cases	*209*	*74*	*238*	*35*

head contact occurs at all in the particular test. The large area of possible head injury contacts shown in these studies strongly indicates that there is a need for additional impact evaluations, in order to reduce head injury risk in accidents.

HEADFORM EVALUATION

The aim of the research programme is to develop a reliable and sensitive subsystems head impact test procedure that can be used to reduce the severity of head injury in side impacts. Three headforms are currently available that could be used for evaluating the interior surfaces of vehicles. One is specified for use in the proposed ECE pedestrian test procedure[8] (called EEVC headform in this paper) another is based on the Hybrid III dummy head and is specified for use in FMVSS 201 test procedure[9] and is referred to as the FMH. The third headform, which, like the EEVC impactor, is also spherical, is called the AAMA headform in this report[10]. In order to determine which of the three headforms would be preferred for use in this test procedure, a comparative test programme has been developed within the Working Group.

The objectives of the first phase of the programme are to assess the three head forms in free flight impact by investigating :-

C sensitivity to changes in the structure impacted
C repeatability
C reproducibility

In addition to these parameters, other aspects of the headforms, such as details regarding handling, could be assessed.

The Annex to this paper describes in detail the configurations of impact used in the phase 1 programme.

For an impactor to be useful for determining variations in injury risk it must be able to discriminate between different paddings and be able to detect changes in any underlying yielding or non yielding structure and the presence of any hidden hardspots. Two types of test have been used to study these attributes. The first was based on a rigid surface onto which paddings with different characteristics were attached. In order to determine if the head forms could identify any hidden hard objects, this simple test was enhanced by adding a rigid object, in the form of a 10 mm square section steel bar, below the surface.

It was recognised that, in practice, the impactor would be likely to be used to evaluate padding fixed to yielding structures. Therefore some impact tests were included to check the ability of the head forms to discriminate paddings on a surrogate deformable B-post manufactured specifically for this test programme. For added realism, tests to modified B-posts, weakened by incorporating large holes, were performed to determine the relative effects on these head forms.

Impact tests to the B-pillar simulations were performed at 6.7 m/s while those to the padded rigid surfaces were performed at 2.5 m/s to keep the responses to within reasonable limits.

The simplest test to perform would be a perpendicular impact. However it was recognised that not all surfaces would be impacted normal to their surface in accidents. Therefore additional tests at 45E were performed to determine whether it would be necessary to include an angled impact test into the test procedure in order to be able to distinguish between different structural designs or whether the simple perpendicular impact would be sufficient to characterise the performance at that position. In addition offset tests, where the axis of the impact was not in line with the hidden structure changes, were performed to determine the head forms sensitivity to impact position.

The padding materials were chosen and manufactured specially for this evaluation in order to represent different yet typical automotive paddings. The padding thickness covering the B posts and plain rigid surfaces was 10 mm thick while that for the padded surfaces with a rigid hard spot was 25 mm thick. The stiffness of the B posts sections was calculated to be representative of real B posts and to allow deformation without complete collapse of the pillar. In order to standardise the impact surfaces characteristics all test surfaces were covered with a flexible vinyl covering.

In order to make some assessment of impact repeatability, all of the tests were performed twice except for the three simple certification drop tests from 376 mm onto a rigid surface which were replicated three times with each head form.

PHASE 1 TEST RESULTS

Phase 1 tests can be split into three types. Firstly 'certification' type tests based on tests that are used to verify that the response of dummy heads are within prescribed limits. The second type of tests were very simple flat surface tests which have been designed to evaluate the sensitivity of the head forms to different padding systems and the presence of hidden hard spots buried within the padding. The third test series was closer to the 'in vehicle' situation. These last tests are similar to the second type but in these, the padding was attached to a yielding surrogate 'B post'.

All of the following tables present the data in a similar manner. Since each test was performed more than once the mean value of the repeated tests is present along with the range expressed as a percentage of the mean.

Apart from Table 4, which gives the results of the certification type tests, the mean measurements are then compared for two test conditions. The difference between the mean for the second test condition from the first test condition is expressed as a percentage of the first mentioned mean test result. Since the head forms were instrumented with accelerometers the values of peak acceleration (g) and Head Injury Criteria (HIC) are presented. All data were filtered at Channel Filter Class 1000.

Each test configuration is categorised by a two digit code. The first character refers to the configuration type and the following letter refers to impact alignment. Full details of the configurations and coding are presented in the Annex.

Table 4 shows the results of the certification tests and Tables 5 - 18 the results of the free flight tests into different surfaces.

Certification tests

Table 4 Certification (and repeatability) tests of the head forms

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
TRL mean	240.9	251	233	803	863.4	682.3
TRL Std. deviation	24.9	15.9	3.7	130.6	103	22.3
TRL Coef of var (%)	**10.3**	**6.3**	**1.6**	**16.3**	**11.9**	**3.3**
TNO mean	251.3	245.7	227.9	784.8	791.2	608.8
TNO Std. deviation	6.3	4.0	7.5	29.2	22.7	18.9
TNO Coef of var (%)	**2.5**	**1.3**	**3.3**	**3.7**	**2.7**	**3.1**
BASt mean	240.1	218.7	236.4	737	661.9	675.2
BASt Std. deviation	3.5	3.8	2.5	13.4	16.1	11.8
BASt Coef of var (%)	**1.5**	**1.7**	**1.1**	**1.8**	**2.4**	**1.7**

Note - Three repeat tests.
- Single sample of AAMA and FMH head forms

Each head was dropped three times onto the rigid surface, configuration 1a. The results of these tests are presented in Table 4. Apart from indicating conformance to certification requirements the data can give some measure of repeatability under this simple controlled condition. The coefficients of variation for the test results are given in Table 4, although, as these are based on only three results, they cannot be regarded as reliable.

Effect of Padding

Tables 5 - 11 compare the sensitivity of the headforms to different types of padding. Table 5 compares the responses of the headforms in tests with two padding types supported on a flat rigid plate in perpendicular impacts (configuration 2a)

Table 5 Configuration 2a Discrimination of padding material in perpendicular impact

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Polyurethane mean	165.2	95.8	144.3	518.3	201.2	430.9
Polyurethane range	*1.9%*	*4.4%*	*2.1%*	*2.9%*	*10.4%*	*2.1%*
Polypropylene mean	242.7	151.2	200.6	959.5	395.4	684.3
Polypropylene range	*0.3%*	*1.2%*	*1.3%*	*1.3%*	*2.3%*	*3.0%*
Percentage variation from Polyurethane	**47%**	**58%**	**39%**	**85%**	**97%**	**59%**

Tables 6, 7, 8 and 9 show the responses in the presence of a hardspot hidden within the padding in perpendicular and angled impacts (configurations 3a, 3B, 3c and 3d)

Table 6 Configuration 3a Discrimination of padding material in perpendicular impact with hardspot

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Polyurethane mean	82.4	70.3	90.6	231.4	160.9	283.1
Polyurethane range	*2.9%*	*0.3%*	*1.8%*	*0.7%*	*0.1%*	*1.7%*
Polypropylene mean	132.2	74.9	121.1	356	145.1	318
Polypropylene range	*12.3%*	*17.1%*	*10.3%*	*18.0%*	*21.7%*	*13.0%*
Percentage variation from Polyurethane	**60%**	**7%**	**34%**	**54%**	**-10%**	**12%**

Table 7 Configuration 3c Discrimination of padding material in perpendicular impact with offset hardspot

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Polyurethane mean	86.9	70.8	90	247.9	163.8	273.6
Polyurethane range	*0.9%*	*1.4%*	*1.1%*	*0.8%*	*2.1%*	*2.7%*
Polypropylene mean	142.5	71.9	109.5	405.2	140.6	281.3
Polypropylene range	*3.6%*	*11.4%*	*15.7%*	*7.1%*	*16.6%*	*17.4%*
Percentage variation from Polyurethane	**64%**	**2%**	**22%**	**63%**	**-14%**	**3%**

Table 8 Configuration 3d. Discrimination of padding material in oblique impact with hardspot.

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Polyurethane mean	40.1	18.7	43.2	52.9	6.7	45.0
Polyurethane range	*4.4%*	*1.0%*	*4.3%*	*12%*	*0.8%*	*11.1%*
Polypropylene mean	170.8	58.3	108.9	585.9	90.0	246.2
Polypropylene range	*0.2%*	*7.7%*	*4.9%*	*1.3%*	*12.4%*	*8.1%*
Percentage variation from Polyurethane	**326%**	**212%**	**152%**	**1008%**	**1243%**	**447%**

Table 9 Configuration 3B Discrimination of padding material in oblique impact with offset hardspot

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Polyurethane mean	37.6	30.3	38.2	47.9	21.1	39.2
Polyurethane range	*37.2%*	*26.1%*	*32.2 %*	*84.8%*	*78.2%*	*78.1%*
Polypropylene mean	24.7	10.6	20.9	25	2.6	13.8
Polypropylene range	*37.7%*	*10.4%*	*17.2 %*	*80.8%*	*26.9%*	*44.9%*
Percentage variation from Polyurethane	**-34%**	**-65%**	**-45%**	**-48%**	**-88%**	**-65%**

Tables 10 and 11 compare the responses between padded and unpadded B-pillar simulations.

Table 10 Configuration 4a and 5a Discrimination of padding on B-post in perpendicular impact

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Unpadded mean	143.9	112.6	144	926.1	495	924.9
Unpadded range	*5.21%*	*8.0%*	*3.5%*	*12.0%*	*21.6%*	*3.0%*
Padded mean	148.8	161.5	123.4	1054.3	1183.3	669.1
Padded range	*4.2%*	*10.3%*	*2.8%*	*7.8%*	*15.4%*	*7.8%*

Table 11 Configuration 4B and 5B Discrimination of padding in oblique impact on B post

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Unpadded mean	108.9	78.5	104	567.4	219	414.9
Unpadded range	*8.2%*	*17.7%*	*5.6%*	*17.6%*	*41.4%*	*14.4%*
Padded mean	108.9	135.0	108.1	548.0	815.6	430.3
Padded range	*6.0%*	*5.3%*	*4.1%*	*7.3%*	*9.0%*	*5.1%*
Percentage variation from Unpadded	**0%**	**-72%**	**-4%**	**3%**	**-272%**	**-4%**

Table 12 Configuration 3a and 3c Discrimination of position of hardspot in perpendicular impact

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
Polyurethane padding	Peak Accel. (g)			HIC		
Direct hardspot mean	82.4	70.3	90.6	231.4	160.9	283.1
Direct hardspot range	*2.9%*	*0.3%*	*1.8%*	*0.7%*	*0.1%*	*1.7%*
Offset hardspot mean	86.9	70.8	90	247.9	163.8	273.6
Offset hardspot range	*0.9%*	*1.4%*	*1.1%*	*0.8%*	*2.1%*	*2.7%*
Percentage variation from direct hard spot	**5%**	**1%**	**-1%**	**7%**	**2%**	**-3%**
Polypropylene padding						
Direct hardspot mean	132.2	74.9	121.1	356	145.1	318
Direct hardspot range	*12.3%*	*17.1%*	*10.3%*	*18.0%*	*21.7%*	*13.0%*
Offset hardspot mean	142.5	71.9	109.5	405.2	140.6	281.3
Offset hardspot range	*3.6%*	*11.4%*	*15.7%*	*7.1%*	*16.6%*	*17.4%*
Percentage variation from direct hard spot	**8%**	**-4%**	**-10%**	**14%**	**-3%**	**-12%**

Table 13 Configuration 3d and 3B Discrimination of hard spot in oblique impact.

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
Polyurethane padding	Peak Accel. (g)			HIC		
Direct mean	40.1	18.7	43.2	52.9	6.7	45.0
Direct range	*4.4%*	*1.0%*	*4.3%*	*12%*	*0.8%*	*11.1%*
Offset mean	37.6	30.3	38.2	47.9	21.1	39.2
Offset range	*37.2%*	*26.1%*	*32.2%*	*84.8%*	*78.2%*	*78.1%*
Percentage variation from direct oblique hard spot	**-6%**	**62%**	**-12%**	**-10%**	**215%**	**-13%**
Polypropylene padding						
Direct mean	170.8	58.3	108.9	585.9	90.0	246.2
Direct range	*0.2%*	*7.7%*	*4.9%*	*1.3%*	*12.4%*	*8.1%*
Offset mean	24.7	10.6	20.9	25	2.6	13.8
Offset range	*37.7%*	*10.4%*	*17.2%*	*80.8%*	*26.9%*	*44.9%*
Percentage variation from direct oblique hard spot	**-86%**	**-82%**	**-81%**	**-96%**	**-97%**	**-94%**

Effect of Hardspots within Padding.

Tables 12 and 13 compare the results for impacts directly over with results for tests just adjacent to hardspots hidden within the padding, supported on rigid plates for perpendicular and angled impacts. Two types of padding were used in each condition.

Effect of Angled Impact

Tables 14 and 15 compare the perpendicular and angled impact responses in the presence of a hidden hardspot within the two types of padding and Tables 16 and 17 compare the responses in perpendicular and angled impacts to the unpadded and padded B-pillar simulations.

Table 14 Configuration 3a and 3d Effect of angle of impact to padded surface with hardspot in direct impact

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
Polyurethane padding	Peak Accel. (g)			HIC		
Perpendicular mean	82.4	70.3	90.6	231.4	160.9	283.1
Perpendicular range	*2.9%*	*0.3%*	*1.8%*	*0.7%*	*0.1%*	*1.7%*
Oblique mean	40.1	18.7	43.2	52.9	6.7	45
Oblique range	*4.4*	*1*	*4.3*	*12*	*0.8*	*11.1*
Percentage difference from perpendicular	**-51%**	**-73%**	**-52%**	**-77%**	**-96%**	**-84%**
Polypropylene padding						
Perpendicular mean	132.2	74.9	121.1	356	145.1	318
Perpendicular range	*12.3%*	*17.1%*	*10.3%*	*18.0%*	*21.7%*	*13.0%*
Oblique mean	170.8	58.3	108.9	585.9	90.0	246.2
Oblique range	*0.2%*	*7.7%*	*4.9%*	*1.3%*	*12.4%*	*8.1%*
Percentage difference from perpendicular	**-85%**	**-84%**	**-81%**	**-96%**	**-98%**	**-95%**

Table 15 Configuration 3c and 3B Effect of angle of impact to padded surface with hardspot in offset impact

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
Polyurethane padding	Peak Accel. (g)			HIC		
Perpendicular mean	86.9	70.8	90	247.9	163.8	273.6
Perpendicular range	*0.9%*	*1.4%*	*1.1%*	*0.8%*	*2.1%*	*2.7%*
Oblique mean	37.6	30.3	38.2	47.9	21.1	39.2
Oblique range	*37.2%*	*26.1%*	*32.2%*	*84.8%*	*78.2%*	*78.1%*
Percentage difference from perpendicular	**-57%**	**-57%**	**-58%**	**-81%**	**-87%**	**-86%**
Polypropylene padding						
Perpendicular mean	142.5	71.9	109.5	405.2	140.6	281.3
Perpendicular range	*3.6%*	*11.4%*	*15.7%*	*7.1%*	*16.6%*	*17.4%*
Oblique mean	24.7	10.6	20.9	25	2.6	13.8
Oblique range	*37.6%*	*10.4%*	*17.2%*	*80.8%*	*26.9%*	*44.9%*
Percentage difference from perpendicular	**-83%**	**-85%**	**-81%**	**-94%**	**-98%**	**-95%**

Table 16 Configuration 4a and 4B Effect of angle of impact to unpadded B-post

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Perpendicular mean	143.9	112.6	144	926.1	495	924.9
Perpendicular range	5.2%	8.0%	3.5%	12.0%	21.6%	3.0%
Oblique mean	108.9	78.5	104	567.4	219	414.9
Oblique range	*8.2%*	*17.7%*	*5.6%*	*17.6%*	*41.4%*	*14.4%*
Percentage variation from perpendicular	**-24%**	**-30%**	**-28%**	**-39%**	**-56%**	**-55%**

Table 17 Configuration 5a and 5B Effect of angle of impact to padded B- post.

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Perpendicular mean	148.8	161.5	123.4	1054.3	1183.3	669.1
Perpendicular range	4.2%	10.3%	2.8%	7.9%	15.4%	7.8%
Oblique mean	108.9	135	108.1	548	815.6	430.3
Oblique range	*6.0%*	*5.2%*	*4.2%*	*7.1%*	*8.7%*	*5.1%*
Percentage variation from perpendicular	**-27%**	**-16%**	**-12%**	**-48%**	**-31%**	**-36%**

Effect of Weakening to B-Pillar.

Table 18 compares the responses of the three headforms between perpendicular impacts to the padded B-pillar simulations with and without a hole cut into the sheet metal below the impact point

Table 18 Configuration 5a and 5aN Sensitivity to presence of a hole in the padded B-pillar

Headform	AAMA	EEVC	FMH	AAMA	EEVC	FMH
	Peak Accel. (g)			HIC		
Without hole mean	148.8	161.5	123.4	1054.3	1183.3	669.1
Without hole range	*4.2%*	*10.3%*	*2.8%*	*7.9%*	*15.4%*	*7.8%*
With hole mean	146.1	150.9	125.7	1011	1049	651.2
With hole range	*0.3%*	*3.1%*	*3.5%*	*1.4%*	*5.7%*	*2.6%*
Percentage variation from without hole	**-2%**	**-7%**	**2%**	**-4%**	**-11%**	**-3%**

PHASE 1 DISCUSSION

Phase 1 of the test programme allows many comparisons to be made some of which can be viewed as being of more importance than others.

The AAMA and EEVC head forms are both half spherical balls whereas the FMH head form is of an irregular shape with a clearly defined impact area. Some difficulties were experienced in using the FMH head form in respect of orientation within the test laboratories propulsion systems. It was felt that some difficulties might be encountered when testing complex vehicle interiors due to this lack of symmetry and the test houses ability to be able to fire the head form from existing propulsion systems without major changes. In the hard spot tests the FMH could be aligned in a number of different orientations each possibly giving a different response. In order to simplify the tests and to reduce variability a particular orientation of head form to hard spot was adopted.

Several evaluation criteria must be addressed when determining which of the three head forms is the better one.

Sensitivity

Sensitivity can be assessed by examining combinations of test conditions and the ability of the three headforms to discriminate between the different conditions

a) Sensitivity to padding in simple padding tests

The tests have shown (Table 5) that each of the head forms can discriminate between the selected materials. The indicated changes were of the order of 47% to 97% depending upon the chosen assessment parameter and head form. The EEVC head form indicated the greater difference and the FMH the least for both parameters.

b) Sensitivity to padding in the presence of a hard spot..

In the perpendicular impacts, the AAMA headform showed the greatest sensitivity to padding material and the EEVC headform the least. The HIC measured with the EEVC headform showed the opposite trend from the peak acceleration and the opposite trend to the other two headforms with both parameters

In the oblique impact tests directly to the hardspot (Table 9) all three heads showed a very large increase in response when changing from polyurethane to polypropylene padding but when testing with the hardspot offset from the impact point (Table 8), this change resulted in a decrease in response for all headforms. In this instance the EEVC headform showed the greatest sensitivity.

c) Sensitivity to presence of padding on B-post

In the perpendicular tests, only the FMH showed a reduction in response when the B-post was padded compared with the unpadded condition. (Table 10) The HIC, measured with the EEVC headform showed a considerable increase.

In the oblique tests, only the EEVC headform indicated a reduction in response (Table 11). The other two headforms indicated little difference.

d) Sensitivity to presence of hidden hardspot

In the perpendicular tests the AAMA headform showed the greatest sensitivity to the presence of a hardspot, but it indicted a reduction in response when impacting directly over the hardspot although the change was not very large. The FMH was the only headform consistently to indicate an increase in response when directly impacting the hardspot area.

In the angled impact with polypropylene padding, all three headforms demonstrated a large and similar reduction in response when impacting away from the hardspot. However, with the polyurethane padding, the EEVC headform indicated an increase. The other two headforms again showed a decrease, as would be expected, the FMH being slightly the more sensitive.

e) Sensitivity to angle of impact

In the tests with hardspot within padding, all three headforms showed the same sensitivity to angle with polypropylene. Overall, the FMH showed least sensitivity to angle with polyurethane padding. For the test procedure, it is probably desirable to be fairly insensitive to changes in angle.

In the unpadded B-post tests the AAMA headform showed least sensitivity, the EEVC and FMH being fairly similar. In the padded B-post tests the FMH showed least sensitivity for peak acceleration and the EEVC with HIC, although the differences are probably not significant.

f) Sensitivity to weakened B-post

The EEVC headform showed the greatest sensitivity to the presence of a hole in the B-post although the difference between the two B-post results were not very large.

Repeatability

Repeatability is a very important assessment parameter for any test device. All of the head forms have been tested more than once in each of the configurations. This allows some assessment to be made of head form repeatability. All the test results include an indication of repeatability as shown by the range of the responses for a single test condition expressed as a percentage of the mean response. This range value comparison as such is not very robust since it is based for most tests on only two values. However, a consistent difference between headforms over all tests would allow some judgement to be made on this aspect of performance. An initial assessment of repeatability has been made by ranking the headforms by percentage range for each test condition for both peak head acceleration and HIC. For the purposes of this assessment, the headforms were given equal ranking if the differences in the percentage range for two headforms were less than one quarter of the average range for those two headforms. i.e. the rankings were similar if :

$$\frac{[Head\ A\ range\ (\%)\ \&\ Head\ B\ range\ (\%)]}{[Head\ A\ range\ (\%)\ \%\ Head\ B\ range\ (\%)]\ (\ 0.5} < 0.25$$

The assessment methodology has been applied to the data partitioned between perpendicular and oblique impact directions. No headform appeared to perform consistently better regarding repeatability than the others using this assessment technique. In perpendicular impacts the AAMA appeared to be better than the FMH headform which in turn was better than the EEVC headform, for both peak g and HIC measurements. For oblique impacts the FMH head form was better than both the AAMA and EEVC head forms for peak g and HIC. In these oblique tests, the EEVC head form was

better than the AAMA as assessed by peak g but the trend is reversed when assessed by HIC. Overall the data do not show that one head form was notably better than the other two.

Further more detailed analysis of these results will be made before the headform for use in Phase II is selected. This preliminary analysis suggests that there is little to choose between them. If further analysis confirms this conclusion, other reasons, such as potential harmonisation, may dictate the choice of headform for future work.

CONCLUSIONS

The test programme was designed to evaluate the three head forms in a series of well controlled experiments, aimed at testing attributes thought to be important in a sub systems procedure. The initial analysis of the results have shown that there is little to choose overall between the three headforms-

1. The EEVC headform was more sensitive at distinguishing between paddings in the simple padding test and for detecting the presence of a weakened hole in the B-post
2. The AAMA headform was overall more sensitive to padding material in the tests involving the presence of a hidden hardspot.
3 Only the FMH gave a consistent and expected response to the addition of padding to the B-post
4 Only the FMH was consistently able to detect the presence of a hidden hardspot within the padding material.
5 None of the headforms was markedly superior to the others for repeatability in the interim analysis. Those differences that were observed suggest that the FMH and AAMA headforms are a little better than the EEVC, particularly for HIC, which is important if this is the parameter selected for evaluation.

FUTURE WORK

After further detailed analysis of these results, the preferred headform will be selected for the next Phase of the study. As mentioned above, the test programme consists of three phases. Phase II aims to examine the affect of linearly guided compared with free flight projection and Phase III will examine the performance of the preferred headform and projection system in vehicles. In due course the results of these other two phases will be published.

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Current members -

Mr Richard Lowne - Transport Research Laboratory (Chairman)
Mr Adrian Roberts - Transport Research Laboratory (Sec.)
Mr Flavio Fossat - Fiat Auto S.p.A.
Mr Dominique Cesari - INRETS
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Mr A Benedetto - Fiat Auto S.p.A.

Observer
Mr John Green - Rover Group

REFERENCES

1. R Lowne; EEVC Working Group 9 Report on the EEVC Side Impact Test Procedure. Proc 12th ESV Conference, Göteborg, May 1989, pp950-53.

2. EEVC; EEVC Report on the Side Impact Test Procedure. EEVC. April 1990.

3. Otte D. et al; Residual Injuries to Restrained Car Occupants in Front and Rear Seat Positions. 11th ESV Conference, Washington. 1987.

4. Thomas P. et. al; Side Impact Regulations - How do they relate to real world accidents? 12th ESV Conference, Göteborg, Sweden 1989,

5. NHTSA, Preliminary regulatory impact analysis: New requirements for passenger cars to meet a dynamic side impact test: FMVSS 214, Page IIIA-3, DOT HS 807 220, January 1988.

6. Transport Research Laboratory - 'Co-operative Crash Injury Study' (CCIS) - 1983 onwards. A large accident and injury study with several sponsors. TRL, Crowthorne, UK.

7. Otte D: Deformation Characteristics and Occupant Load Capacity in Lateral Impacts for Nearside Belted Front Car Passengers. SAE Paper 933126, 37th STAPP Car Crash Conference1993.

8. J Harris: EEVC WG10; Proposals for test method to evaluate pedestrian protection for cars. Proc 13th ESV Conference. Nov 1991 paper S3-O-06. pp293-302.

9. National Highway Safety Administration Federal Motor Vehicle Safety Standards ; Head Impact Protection. FMVSS 201.

10. Ramanujam N. N. et al: Preliminary Free-Motion Headform Testing of Vehicle Upper Interior Surfaces. SAE Paper 911216. Government/Industry meeting, Washington 1991.

ANNEX

PHASE 1 TEST PROGRAMME

a) Base line tests.
Three impact tests with each of three head-forms on three impact surfaces (rigid surface drop test - to duplicate cadaver and headform test certification conditions {Configuration 1a}, a simulated steel B-pillar {Configuration 4a} and a padded simulated steel B-pillar {Configuration 5a}). All impacts normal to the impact surface from a drop height of 376 mm.

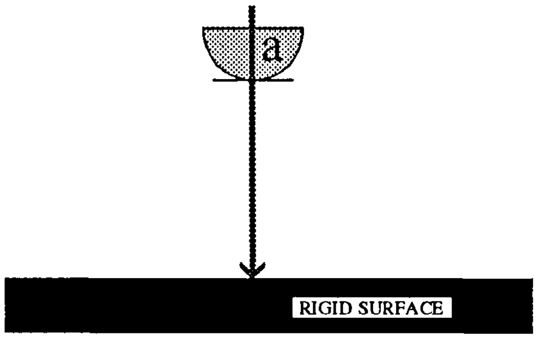
b) Affect of angles of impact.
Three impacts to each of the two B-pillar simulations with each of the three head-forms, all at 45° to the normal to the surface (Configurations 4B, 5B). plus three flat surface padded tests {Configuration 2b}. Impact velocity 2.5 m/s.

c) Sensitivity to hard spots, holes and padding.
Two impacts with each of the head forms onto padded surfaces with a hidden hardspot with two stiffnesses of padding and two impact positions on each padded surface (one over the hardspot {Configuration 3a} and one adjacent to it {Configuration 3c}), also test {Configuration 3B and 3d}. Two tests onto paddings with different characteristics {Configuration 2a}. The depth of the hard spot is 10mm with a padding cover of 10-12mm thick. Impact velocity 2.5 m/s.

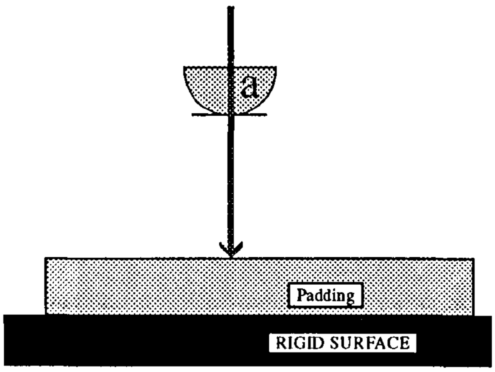
A modified 'padded B post' will be impacted with each of the three head forms, test configuration 5a. The modification to the 'B post' will consist of a 45mm diameter hole in the profiled section of the fabrication, with the hole centred below the point of impact. Each padded 'B post hole test' will be repeated once. Impact velocity 6.7 m/s.

Test Configurations

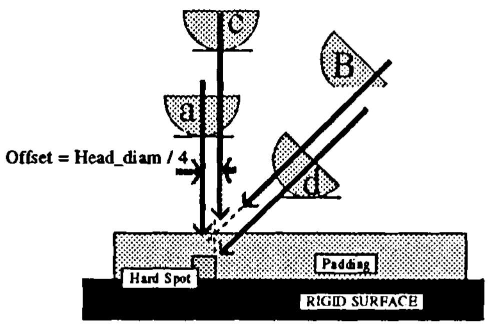
Angles of impact are 90° and 45° to the rigid surface, the arrows indicating the direction of impact. In the tests shown with lower case letters, the arrow represent the axis of the impactor. - Upper case letters indicate the point of contact of the headform with the surface, and the arrow direction shows the direction of impact only and does not indicate the central axis of the impactor. (None of the configurations is shown to scale).



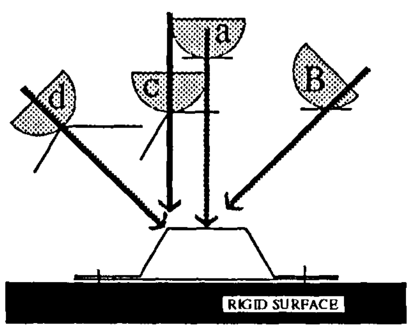
Test Configuration 1 - Rigid Surface



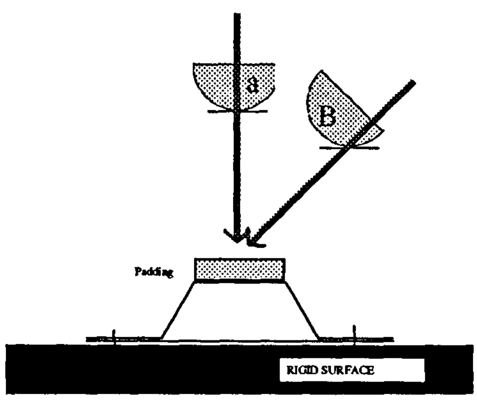
Test Configuration 2 - Padded Surface



Test Configuration 3 - Padded Hard Spot



Test Configuration 4 - Unpadded B Post



Test Configuration 5 - Padded B Post

DEVELOPMENT AND VALIDATION OF A DEFORMABLE FEATURELESS HEADFORM MODEL USING LS-DYNA3D

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ABSTRACT

A deformable featureless headform model was developed using LS-DYNA3D. The model used a visco-elastic material type based on data obtained from 2.68, 4.02, 5.36 and 6.71 m/s (6, 9 12 and 15 mph) head drop tests. The model predictions were validated against results from various experiments, such as drop tests, sheet metal and/or foam tests and vehicle upper interior impact tests. Comparisons between predicted and experimental results showed excellent correlations for all the cases studied. In addition, headform impact responses subjected to different impact conditions using the deformable headform model and the rigid headform model at reduced velocities were also compared. The application of the deformable featureless headform model to afore-mentioned test conditions indicates that the model is reliable when it is used to predict the dynamic responses of the headform.

I. INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) issued a Notice of Proposed Rulemaking [1] and published the final rule on interior Head impact requirements as an amendment to FMVSS 201 in August, 1995. The laboratory test procedure specified by NHTSA involves propelling a featureless headform as a projectile at 6.71 m/s (15 mph) against the vehicle upper interior. NHTSA has defined the impact targets, directions and locations on a typical vehicle for compliance verification which the automobile manufacturers may have to test during certification to verify full compliance of the entire vehicle upper interior. CAE modeling and simulations are essential for providing design directions and reducing the number of tests in vehicle development. To achieve accuracy in FEA simulation requires development and validation of a featureless headform model.

A featureless headform model can be either rigid or deformable. A rigid headform is easier to model but requires that a reduced impact velocity be used to take an energy loss in the rubber into account in the simulation. The lack of rigid-to-rigid contact simulation capability in most non-linear FE codes precludes simulations of a rigid headform impacting a thin foam which results in a "bottoming-out" condition. To circumvent these situations, a deformable headform model is needed for simulating direct head impact with vehicle upper interiors. The deformable material model may also be applicable to full FE dummy model for better simulating knee impact with the instrument panel in a frontal impact and chest impact with side door structure during a side impact.

The featureless headform (described in Section III) consists of an aluminum skull covered with a layer of vinyl rubber skin. To model the vinyl rubber requires accurate material characterization and code material model/type selection. In cases where code material model/type is unsuitable or unavailable, some code development in LS-DYNA3D [2] may be required.

This paper describes the development and validation of a deformable featureless headform using a viscoelastic material model. A brief review of material types available in LS-DYNA3D, which may be applicable to modeling the vinyl rubber skin of the featureless headform is described in Section II. Description of the featureless headform model is given in Section III. Experimental measurement of moments of inertia of featureless headforms is given in Section IV. Details of development/verification of the featureless headform model are given in Sections V and VI. Simulations of deformable headform responses are presented in Section VII and results are discussed in Section VIII. Parametric studies carried out to investigate the effects of various test conditions on HIC calculations are presented in Section IX as part of a Design of Experiments study of test-to-test variability of the interior head impact test facility. Finally, conclusions are drawn and recommendations made in Section X.

II. MATERIAL MODELS/TYPES AVAILABLE IN LS-DYNA3D

A sample of vinyl rubber skin was removed from a featureless headform and a static compression test was conducted to determine its characteristic. Figure 2.1 shows a uni-axial compressive stress-strain curve of the vinyl rubber skin material, indicating that the characteristic is of non-linear nature. The immediate task is to search for the material models/types available in the LS-DYNA3D material library that will accurately fit the vinyl rubber material characteristic. Feasible material models are briefly reviewed below.

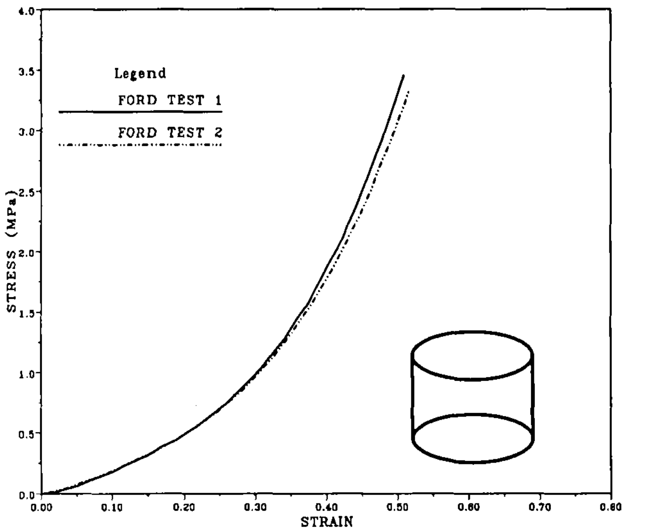


Figure 2.1 Stress-strain curves of uniaxial compression of rubber

Blatz-Ko Material Model:

This material model (material type #7) was developed by Blatz and Ko [3], and was originally intended for modeling the rubber materials. This material model/ type, with Poisson's Ratio being set to 0.463 internally, proved unsatisfactory for simulating the vinyl rubber.

Mooney-Rivlin Material Model:

The next attempt was to try a slightly compressible Mooney-Rivlin model (material type #27) [4], which uses the strain energy density to represent the rubber skin material properties. Mathematically, the Mooney-Rivlin model is expressed as:

$$W = A(I - 3) + B(II - 3) + C(III^{-2} - 1) + D(III - 1)^2 \qquad (1)$$

where W = strain energy density

$C = 0.5(A + B)$

$D = [A(5\nu - 2) + B(11\nu - 5)] / 2(1 - 2\nu)$

ν = Poisson's Ratio

$2(A + B)$ = shear modulus of linear elasticity

I, II, III = invariants of right Cauchy-Green Tensor

The determination of strain energy functions of rubbers can be found in the works of Kao et al [5], Morman [6] and Wineman [7]. A procedure for determining Mooney material constants for highly nonlinear isotropic incompressible materials under large elastic deformation was reported by Vossoughi [8]. A least-squared technique was used to fit the curve as shown in Figure 2.2 to determine the Mooney-Rivlin constants A and B in Eq. (1), resulting in A = 0.7769, B = 0.1548 and shear modulus = 1.8634 Mpa. Predicted headform response based on these constants did not correlate well with the head drop test corridor. When compared to the experimental data, the simulated response curve appeared to be wider in the time domain. It was noted that this material model did not take into consideration the energy dissipation observed in vinyl rubber materials. In fact, the energy dissipated by the vinyl rubber skin during impact is very difficult to quantify experimentally. The strain-rate dependency was also not incorporated in this material model.

All the above models encountered difficulties in simulating the vinyl rubber skin behavior in head drop tests in that all the simulated responses were of longer duration than that of the test, resulting in over-estimation of the HIC value. This indicates that some energy may not be dissipated, as should be in reality, when these material types are used in the simulation. In order to take energy loss of vinyl rubber into account, a viscoelastic material was investigated next.

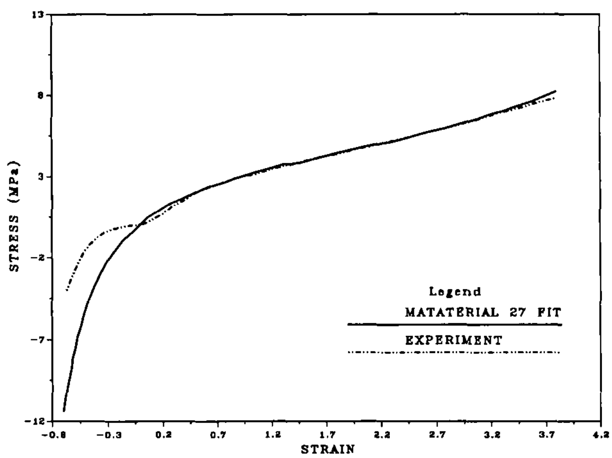


Figure 2.2 Experimental and fitted Money-Rivlin stress-strain curves of rubber

Viscoelastic Material Model:

Test results of some recent attempts to characterize the vinyl rubber skin showed that the mechanical response of this material is not only non-linear but also time dependent. Therefore, an appropriate constitutive equation(s), which take into account the large deformation and time dependency, can be expressed as, for uniaxial extension case:

$$\sigma(t) = g(\lambda(t), t) + \int h[[\lambda(t), \lambda(s), t-s]]ds \qquad (2)$$

where g and h are the material property functions. Detailed review of rubber viscoelasticity is given by Morman [6]. Use of this model requires extensive material testing. Some tests were conducted to derive property functions based on stress relaxations which were strain and time dependent. Test data so far were non-conclusive, and thus precluded establishment of these functions.

In order to take time-dependency into consideration, a linear viscoelastic model with material type #6 is used. This material model, based on shear relaxation behavior, is characterized by the following expression:

$$G(t) = G_{inf} + (G_0 - G_{inf})e^{-\beta t} \qquad (3)$$

where G_0 = short-time shear modulus,
G_{inf} = long-time shear modulus,
β = decay constant.

A literature review revealed that this material type was used by Khalil et al [9] in FEA Hybrid III dummy development and by Liu [10] in simulations of knee impact responses using LS-DYNA3D. Values of parameters used in these studies are listed in Table II.1. It is noted that values for the short-term and long-term shear moduli used by Kahlil et al. are much smaller (i.e. almost three orders of magnitude) than those used by Liu. Utilizations of these values by Khalil and Liu in the featureless headform model resulted in a softer and stiffer response, respectively, when compared with head drop calibration test data. Therefore, an appropriate set of parameters still need to be determined for deformable featureless headform model. In our study, G_0 is selected based on the value determined from the Mooney-Rivlin model presented above, and the other parametric values for model constants used in material type #6 are determined by fine tuning in such a way that the headform model using this material type is capable of simulating head drop responses at various velocities up to 6.71 m/s (15 mph).

Table II.1

Parametric constants used in various studies of vinyl rubber skin material

	bulk modulus K (MPa)	shear modulus G_0 (KPa)	shear modulus G_{inf} (KPa)	decay const sec^{-1}	density (kg/m^3)
Kahlil [9]	22.6	3.0	2.7	0.5	330
Liu [10]	100	5000	1000	2.0	437

III. DESCRIPTION OF FEATURELESS HEADFORM MODEL

III.1) Featureless Headform

The featureless headform is basically a Hybrid III head without a nose. It consists of a hollow cast aluminum thick shell of uniform thickness which approximates the skull exterior geometry. A drawing of the featureless headform is shown in Figure 3.1. The occipital portion of the shell is removed and replaced by a back plate for mounting to a propulsion shaft. The aluminum skull is covered with a vinyl rubber skin. The headform assembly is instrumented with a tri-axial accelerometer located at the headform center of gravity to measure its three-dimensional translational accelerations.

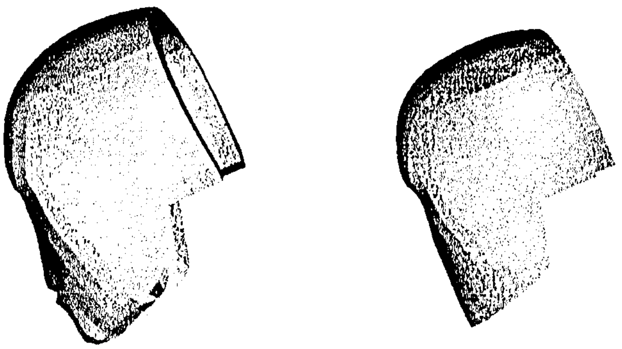
III. 2) Model Description

A featureless headform was scanned by the Dimensional Analysis Group of GTO to provide line data for generating the model. The model was created using Hypermesh [11] and/or FEMB [12] for LS-DYNA3D analysis.

Deformable Featureless Headform:

The deformable featureless headform FE model consists of two material models. The aluminum skull, back plate, ballast, and accelerometer fixture are represented by a rigid shell elements using rigid material type #20. The mass and moments of inertia of the rigid skull obtained from tests are input directly. The experimental measurement of moment of inertia of the headform is presented in Section IV. The vinyl rubber skin is modeled with 8-noded solid elements and viscoelastic material (material type #6). The

mass of the vinyl rubber skin is determined internally by the LS-DYNA3D code. The parameters required for the rubber skin model are determined based on data obtained from head drop tests at different velocities conducted by Ford's Core and Advanced Vehicle Systems Engineering organization(CAVSE).



(a). Rubber skin (b). Aluminum skull

Figure 3.1 Deformable featureless headform

Connected vs. Disconnected Models:

When the skull/back plate model and the vinyl rubber skin model are combined, two types of models result (i.e., connected and disconnected). In the connected model, the rubber skin and the rigid skull share common nodes, while in the disconnected model, these two are separated by an interface.

When the disconnected model is used, a very high friction coefficient needs to be prescribed to prevent the vinyl rubber skin model from sliding over the aluminum skull model. This friction should be regarded as a model parameter rather than an actual physical one. Likewise, in the rigid skull case, material parameters such as density, Young's Modulus and Poisson Ratio do not necessarily reflect their actual physical quantities, but are used for controlling time steps in the calculation processes.

For the connected model, care must be taken to ensure correct total mass and moments of inertia. Depending on the number of layers used in the rubber model, the total mass calculated is different from each other, because of the lumped mass algorithm used in the code. The connected deformable featureless headform model, which has one layer of rubber skin, is used throughout this study.

The advantages of the deformable headform model are that it:

- Simulates the actual headform in reality. No velocity reduction or compensation is required in the simulation.
- Overcomes the negative volume problem in some cases where the impacted material is too soft.
- Allows better simulations of headform impacting thin/soft foams.

The disadvantages are that the:

- Rubber material parameters must be carefully tuned when using a viscoelastic material model (material type #6).
- Mass and moments of inertia of the rubber skin as computed from finite element model may not exactly match experimental measurements and may need to be adjusted to match through iterations.

Rigid Featureless Headform:

A rigid headform results when the vinyl rubber skin is assumed to be rigid solid elements (material type #20). In this case, the following material properties are used:

- Density = 1.19E-09 ton/mm^3
- Young's Modulus = 950 Mpa
- Poisson's Ratio = 0.3

Again, it should be mentioned that these parameters prescribed in the input cards are primarily used for controlling the time step and do not necessarily relate to their actual physical properties. The total mass, location of the C.G., and moments of inertia are provided to the rigid body using LS-DYNA3D card #51 (Rigid Inertial Properties and Constraints). This allows assignment of precise mass, C. G. location, and the moments of inertia to the headform model, all of which are determined experimentally.

The advantages of using the rigid featureless headform in simulations are:

- The C.G. location, headform mass, and moments of inertia can be accurately specified, and
- It is easy to apply. In essence, users almost do not need to tune any of the parameters.

Some drawbacks in using the rigid headform can be mentioned. The use of a rigid headform may cause "negative" volume problems when it impacts a deformable body, such as soft foams. Additionally, when the rigid headform is used in the simulations, the impact velocity have to be reduced in order to compensate for the energy

dissipated by the vinyl rubber skin. Currently, a reduction factor of 0.935 is established. For example, a 6.79 m/s (15.2 mph) laboratory head impact test is simulated using a velocity of 6.35 m/s (14.2 mph=15.2 x 0.935).

Use of a rigid headform also creates a difficulty in simulating thin foam under a "bottomed-out" condition. When a foam is approaching 90 percent compression, the densification occurs with increasing stiffness, thus causing the foam to behave more rigidly. This creates a rigid-to-rigid interaction, which can not be simulated using currently available FEA codes.

IV. MEASUREMENT OF MOMENTS OF INERTIA

Values for the moments of inertia of a Hybrid III head are available in publications by Kaleps et al. [13] for occupant model simulations and by Kahlil [9] for FE analysis. These values are compared in Table IV.1. It is seen that these values vary somewhat and are not applicable to the featureless headform which has no nose and has a modified back plate for attachment to the propulsion shaft.

Table IV.1

Principal moments of inertia of Hybrid III head

	Principal Axis I_1 (ton-mm^2)	Principal Axis I_2 (ton-mm^2)	Principal Axis I_3 (ton-mm^2)
Kaleps [13]	24.04	22.10	15.91
Kahlil [9]	21.64	20.67	14.82

To provide accurate inputs to the featureless headform FE model, the weight, the center of gravity and moments of inertia of the headform were determined for a head with and without a vinyl rubber skin at the Bioengineering Center of Wayne State University. Three headforms were used in the measurements.

Each head was weighed on an O'Haus beam balance scale. Known precision weights were used to check the accuracy of the scale, which provided a resolution of better than 1 gram. The average weight of the headform with skin is found to be 4.77 kg (10.5 lbs).

The center of gravity (c.g.) of each headform was determined using a tri-filar pendulum as described in References [14,15] and the Appendix.

Based on the measurements, the moments of inertia are:

$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 18.25 & 0.00 & 0.02 \\ 0.01 & 21.48 & 0.00 \\ 0.02 & 0.00 & 18.62 \end{bmatrix}$$

The principal moments of inertia are found to be:

- I_{p1} = 22.91 ton-mm^2 (0.2028 in-lb-sec^2)
- I_{p2} = 21.45 ton-mm^2 (0.1899 in-lb-sec^2)
- I_{p3} = 14.91 ton-mm^2 (0.1320 in-lb-sec^2)

The C.G. location of the headform is at

x_{cg} = 71.2 mm (2.804")

y_{cg} = -0.3 mm (-0.010")

z_{cg} = -35.4 mm (-1.393")

relative to the reference point shown in Figure 4.1.

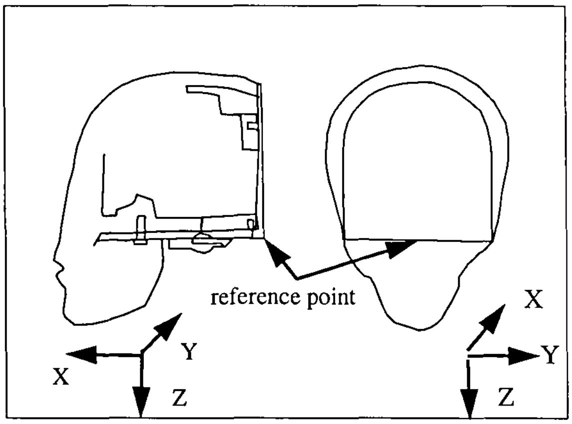


Figure 4.1 Reference point of headform measurement

V. HEAD DROP TESTS

a) Calibration Tests:

Prior to impact testing, the featureless headform needs to meet the calibration performance requirement specified by NHTSA. This calibration test will serve as a baseline for component validation of the FE featureless headform model.

In the calibration test, a headform must pass the standard Hybrid III head drop-test verification in order to be certified for testing. To perform the test, the headform is suspended 376 mm (14.8 inches) above a steel table such that the initial contact will occur at the forehead. The

headform is released, and the accelerations in the three major head axes are recorded. The peak resultant acceleration must not be less than 225 g, and not more that 275 g to pass [1].

A series of 30 headform drop tests were conducted. The performance responses are plotted as a function of time as shown in Figure 5.1. At each discrete time step, the maximum and minimum accelerations were determined from these curves to form the maximum and minimum envelopes. The mean and standard deviation were also computed. The corridor bounded by the maximum and minimum envelopes and the mean curve are shown in Figure 5.2. This corridor will be used for validating the prediction of the featureless FE model response.

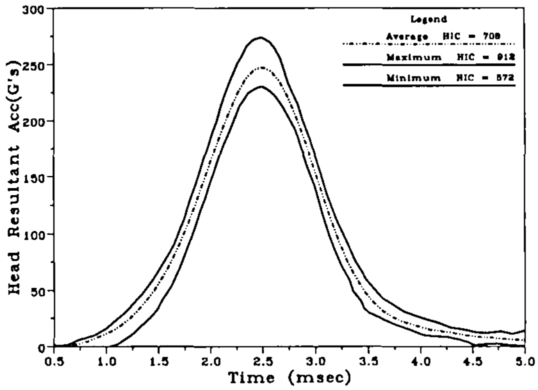


Figure 5.1 The performance responses of head drop test

b) High Velocity Head Drop Tests:

In most simulations using the deformable headform model, the impact velocities are in the proximity of 6.71 m/s (15 mph). It is felt that a headform model validated at 2.68 m/s (6 mph) in a standard drop test may not be adequate for simulating impact at a higher velocity. It is believed that the strain rate effect of the vinyl rubber material is different at the 6.71 m/s (15 mph) actual impact condition than at the 2.68 m/s (6 mph) head drop calibration test. Therefore, a series of higher velocity head drop tests were conducted by CAVSE at 4.02, 5.36 and 6.71 m/s (9, 12 and 15 mph). The resultant headform accelerations for these tests are shown in Figure 5.3.

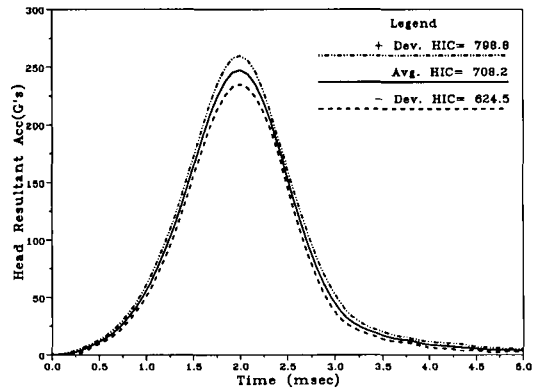


Figure 5.2 The standard deviation of head drop test

Headform responses obtained from the 2.68, 4.02 5.36 and 6.71 m/s (6, 9, 12, and 15 mph) head drop tests are used for selecting the material parameters in the development of the deformable headform model. The parametric values of the viscoelastic model were tuned in such a way that the simulated responses of the headform dropped at 2.68, 4.02, 5.36 and 6.71 m/s (6, 9, 12 and 15 mph) were in agreement with the test data. Parameters thus determined are considered as coefficients of a transfer function rather than constitutive values.

VI. VALIDATIONS AGAINST HEAD DROP TEST DATA

Validation studies of the deformable headform model are carried out by comparing the predicted results of the headform responses with data from the head drop tests at various velocities.

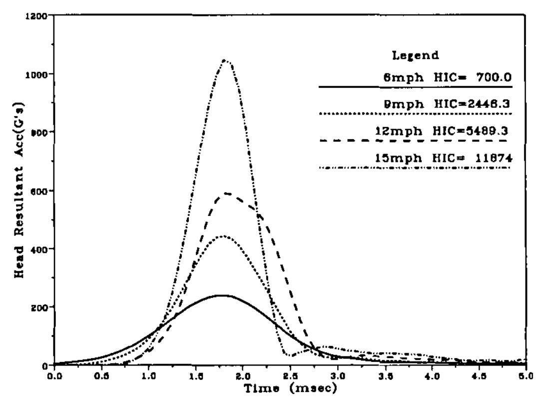


Figure 5.3 Head drop tests at different velocities

a) Simulation of headform drop calibration test:

To simulate the standard calibration test in the FE analysis, a rigid "stone" wall or a rigid body can be used to

represent the rigid plate against which the headform is impacted. A remark is made here that although the rigid body and rigid wall are similar in physical sense, the parameters of the headform may be chosen differently because of differences in computation algorithms used in the code. The headform is given an initial velocity of 6.3 mph (2.71 m/s), representing the impact velocity from a free fall at a height of 376 mm (14.8") toward the rigid wall. The effect of 1G gravitation is neglected in the analysis. The headform acceleration from simulation is compared with the calibration corridor as shown in Figure 6.1. It is seen that the predicted response lies within the corridor, thus exhibiting a good correlation with the test results. The total energy, kinetic energy, and internal energy-time histories are plotted in Figure 6.2, showing that with the exception of about 10% of hourglass energy, the total energy is essentially conserved.

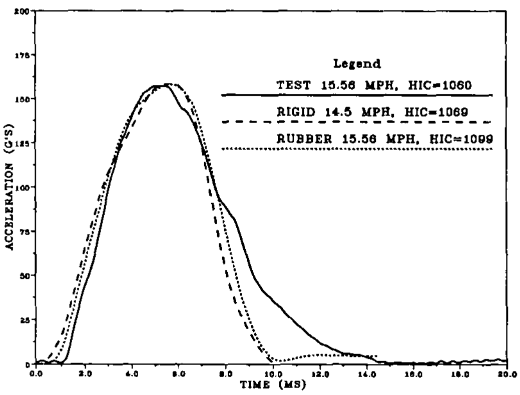


Figure 6.1 Featureless headform model validation

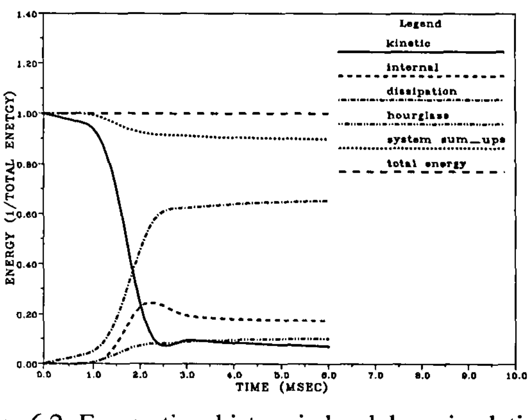


Figure 6.2 Energy time history in head drop simulation

b) Validation against higher velocity impact tests:

In the headform drop test simulation, only a small portion of the solid elements in the forehead is compressed against the rigid surface. When the headform is used to impact foam and/or sheet metal, the rubber skin may experience more compression over a larger region at a higher impact velocity. A comparison of headform responses between the simulation and tests at higher velocities is shown in Figure 6.3.

An examination of results shown in Figure 6.3 reveals that the deformable headform gives accurate predictive trends at 2.68, 4.02, and 6.71 m/s (6, 9, and 15 mph) test conditions. The largest discrepancy occurs at the 5.36 m/s (12 mph) simulation. By comparing the areas under the 5.36 m/s (12 mph) test and simulation curves, it is suspected that the actual test velocity in this case may be lower than the 5.36 m/s (12 mph) shown in the test report.

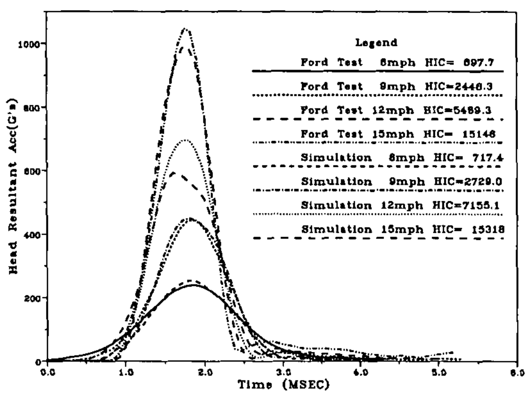


Figure 6.3 Head drop tests and simulations

c) Deformable spherical headform

The spherical headform was used earlier in Ford research activity for head interior impact testing and FEA analysis. Data generated in this phase of research can be used as additional references for validating the fidelity of the rubber material parameters. The viscoelastic material parameters were used in the FE deformable spherical headform model in the standard head drop test. The computer calibrated response is compared with the calibration corridor of the spherical headform in Figure 6.4. It is seen that the predicted spherical headform response also falls within the corridor.

Previous simulation using the rigid spherical headform was done at an impact velocity of 6.17 m/s (13.8 mph) for a 6.71 m/s (15.0 mph) impact test. A comparison of responses between the rigid and deformable spherical headforms impacting a block of foam is shown in Figure 6.5. Comparable results indicated that the estimation of the reduced velocity for the rigid spherical headform was also correct.

Based on results compared in Figures 6.1, 6.3, 6.4 and 6.5, it is concluded that use of the deformable headform model is possible to predict head impact response using the viscoelastic material model. This model will be further validated in sub-models including sheet metal and foams.

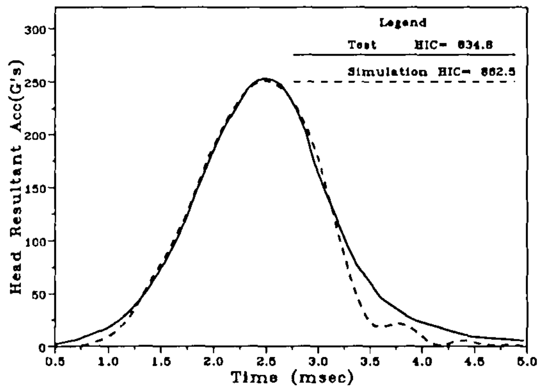


Figure 6.4 Spherical headform drop test and simulation, 6 MPH

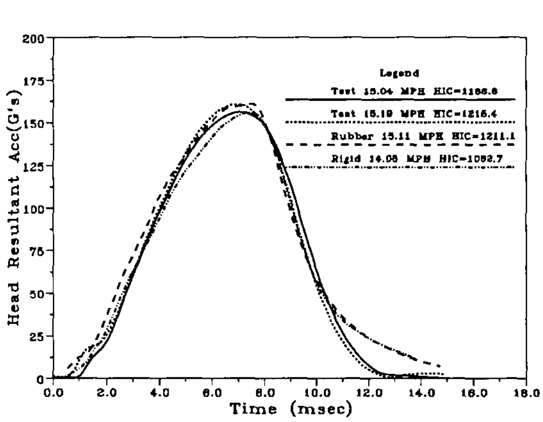


Figure 6.5 Spherical headform to foam impact

VII. SIMULATIONS OF HEADFORM RESPONSE

The validated featureless headform model was used to simulate its response upon impacting sub-models of bare sheet metal (S/M) pillar structure, foam alone, S/M with a foam padding, and an assemblage of these sub-models comprised of plastic trim panel, foam padding, and S/M pillar.

Simulation of Featureless Headform Impact with a Sheet Metal Part

The validated deformable headform was further verified by simulating its impact against a "B"-pillar of constant section. This pillar consists of three pieces: an outer panel, an inner panel, and a reinforcement panel between the outer and inner panels. It is 533.4 mm (21") long with both ends being welded to mounting plates which, in turn, are rigidly bolted on to the test fixture. The pillar was tilted about 15 degrees to ensure initial forehead contact and a nearly normal impact with the designed target point on the pillar. The actual impact velocity was 6.95 m/s (15.56 mph).

The pillar structure is modeled using shell elements in two mesh sizes: a finer mesh of 6 mm (0.24") is used for the impact region at the mid-section of the inner panel and 12 mm (0.47") meshes are used for the rest of the non-impacted panels. The welds on the flange are 50.8 mm (2") apart and are represented by rigid body links in the model. Material type #24 (piecewise linear isotropic plasticity) with SAE1010 material properties was used for mild steel in the model. The boundary conditions for the end nodes are fixed in all directions to represent the actual test conditions mentioned above.

In the simulation, the pillar was impacted with a rigid featureless headform and a deformable featureless headform at 6.48 m/s (14.5 mph) and 6.96 m/s (15.56 mph), respectively. The predicted results using the two different velocities are compared with the test data as shown in Figure 7.1, exhibiting good correlation. Close agreement between the deformable headform response and the test is indicative of a good viscoelastic material type used to simulate vinyl rubber response in the model. Results also show that a reduction ratio of 0.935 in impact velocity between the rigid headform and the one with a vinyl rubber fascia, established prior to the development of the deformable headform model, is correct.

Prediction of Featureless Headform-to-Foam Impact

Previously published foam models [16,17] were used to predict a featureless headform to foam impact. The test specimen was a resilient polyurethane foam with density of 96.1 kg/m3 (6.0 lb/ft3). The foam specimen dimension was 0.254 m x 0.254 m x 0.064 m (10" x 10" x 2.5"). The stress-strain characteristic of this foam is shown in Figure 7.2, and material type # 57 (low density urethane foam) was used for the foam model.

The actual test was run on a horizontal impact facility. The headform was mounted on a carriage which was propelled by a compressed nitrogen gas-driven actuator to 6.71 m/s (15 mph). The foam sample was mounted on a steel plate opposite the headform/carriage. Behind the steel plate was a load cell, which in turn, was attached to a stationary fixture. A copper foil contact switch was used to

sense the initial contact between the foam sample and the headform.

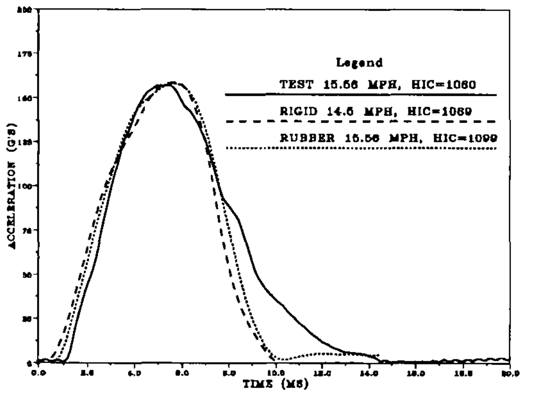


Figure 7.1 Featureless headform to b-pillar impact

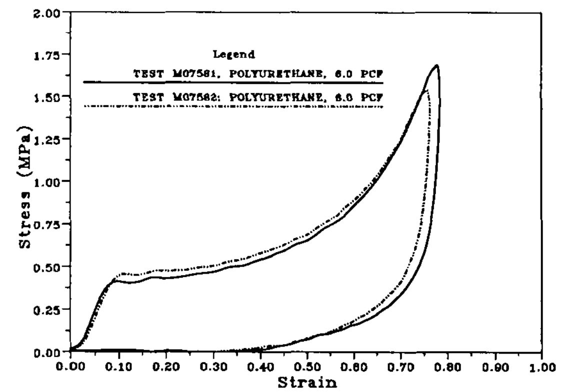


Figure 7.2 Dynamic stress-strain curves of polyurethane foam

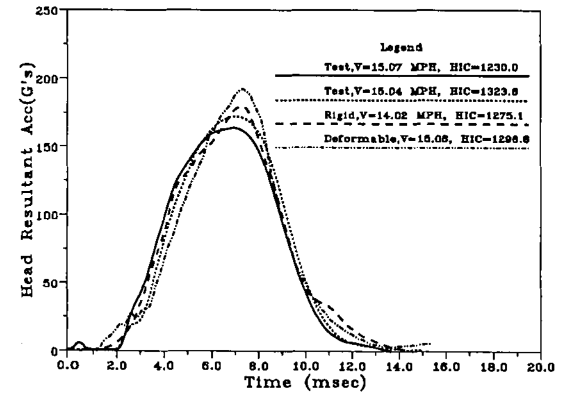


Figure 7.3 Featureless headform to foam impact

In the simulation, the initial and boundary conditions from the test were imposed upon the model to replicate the dynamic impact. The headform was given an initial velocity of 6.74 m/s (15.07 mph), and the foam was supported by a rigid wall. Figure 7.3 compares the prediction with the experimental result, indicating that the prediction is in close agreement with the test data.

An Integrated Trim/Foam/Sheet Metal Model

The trim modeling methodology, currently under development, includes dynamic trim material characterization and dynamic response correlation. A preliminary polypropylene (PP) trim model is available. When a trim sub-model is integrated into the foam/sheet metal model described above, an integrated trim/foam/sheet metal model is generated. This FEA model will be used for trend analysis here. No experimental data are available for correlation.

The trim is 2.5 mm thick and modeled with shell elements. The property of PP was characterized by tensile testing quasi-statically (12.7 mm/min or 0.5"/min) and dynamically at 4.47 m/s (10 mph) and 6.71 m/s (15 mph). The dynamic properties were used in the model via Material type #24. Node connectivity was used to tie trim nodes with those of the sheet metal along the flange.

Simulations of the integrated model were made with and without foam. Foam thickness was assumed to be 0.5" and 1". Two types of foam densities, i.e. 24.03 kg/m^3 (1.5 pcf) and 40.05 kg/m^3 (2.5 pcf), were used. Consequently, when the foam was not present in the structure, there was a gap of 12.7 mm (0.5") or 25.4 mm (1") between the trim and the sheet metal. The deformable featureless headform was used and the impact velocity was 6.71 m/s (15 mph).

Simulated results are discussed below:

•Effect of Foam Thickness (with Trim)

For a given trim, effects of foam thickness on headform responses are shown in Figure 7.4, along with HIC values tabulated in Table VII.1. Note that the HIC value from the baseline structure without foam and trim is 1129.9. Results show that, for a given foam density, the thicker foam yields a lower HIC value. Results also indicate that, for a given foam thickness, foams with a higher density give higher HIC values in headform response. Foams with higher densities normally exhibit higher stress levels. Therefore, foams having higher strength characteristics are expected to yield higher HICs.In this case study, the percentage in HIC reduction for 12.7 mm/24.03 kg^{m-3} (0.5"/1.5 pcf) foam is approximately 17.6% from 12.7 mm/40.05 kgm^{-3} (0.5"/2.5 pcf) foam.

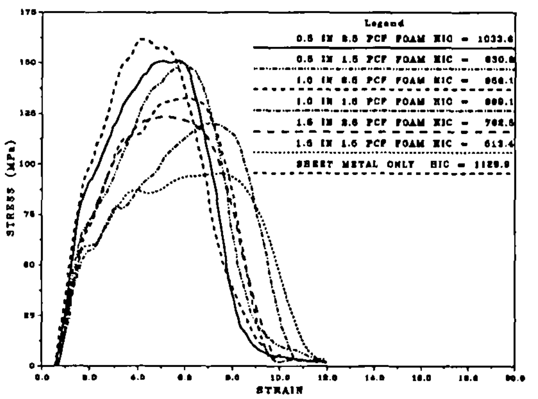


Figure 7.4 The effect of foam thickness on response

Table VII.1

Effect of foam thickness and density on HIC

Density (pcf)	Foam thickness		
	0.5"	1.0"	1.5"
1.5	930.6	699.1	513.4
2.5	1033.6	856.1	762.5

•Effect of Air Gap with Trim only

Removing the foam from the previous models results in trim/sheet metal models with air gaps. For simplicity, trim is modeled without ribs here. (Trim with ribs will be studied at a later date). In this example, three different gaps of 12.7, 25.4 and 38.1 mm (0.5", 1.0" and 1.5") are introduced to study their respective effects on the headform responses. The simulated results are shown in Figure 7.5 and Table 7.2. Curves shown in Figure 7.5 reveal that there are two distinct stages in the response curves. An initial flat portion is the response due to the trim, followed by a "typical" headform response. This phenomenon occurs when the air gap is closed and represents the headform response to impact against the sheet metal structure. The smaller the air gap, the earlier and the higher the peak headform acceleration, thus yielding larger HIC values. Results also show that the larger the gap, the lower the peaks of the acceleration. Model prediction of this trend appears to be correct, since the larger the air gap, the more headform stopping distance is available to dissipate the energy. A study on estimating the minimum space to meet federal interior head impact requirements is given by Lim and Chou, et al. [18].

If the thickness of the trim is double that of the baseline, the HIC values are reduced for a given gap. In the case of 25.4 mm (1.0") gap, the HIC value reduces from 792.2 to 605.9 when the trim thickness is doubled. Referring to Table VII.2, the maximum percentage reduction in HIC appears to occur at 25.4 mm (1.0") gap, which is about 23.5%. An optimal combination of gap and trim thickness may be found if a trim characteristic (or trim type) is given.

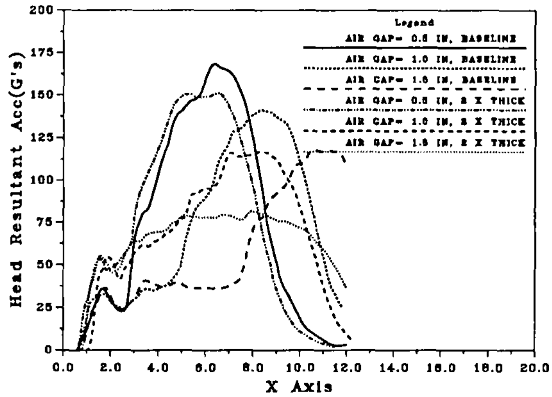


Figure 7.5 Effect of air gap between trim and sheet metal

Table VII.2

Effect of air gap on HIC

Trim thickness	Air gap		
	0.5"	1.0"	1.5"
Baseline	1106.9	792.2	519.5
2 x thickness	1004.6	605.9	416.7
HIC reduction (%)	9	23.5	17.8

"B"-pillar Foam Model

Figure 7.6 shows a featureless headform and a "B"-pillar foam pad, which was mounted on a rigid curved surface to simulate the contour surface of an actual "B"-pillar inner panel. This model was used to study the effect of foam thickness on head impact performance evaluation. This simulation was designed to evaluate the contribution of the foam pad alone without the compliance of a flexible pillar.

Figure 7.6 Featureless headform to B-pillar foam pad impact

An experimental program was conducted to characterize dynamically the stress-strain relationship of different foams with varying densities. Figure 7.7 shows some typical foam characteristics, which were used as inputs to the foam model. Here, both the thickness and the characteristics of foams were varied for head interior impact simulation at 6.71 m/s (15 mph) and their corresponding HIC were calculated.

Simulation results are shown in Figure 7.8, where HIC vs. 50 percent compression stress level for thicknesses ranging from 20 mm to 50 mm are plotted. For a given thickness, the response trend indicates that there is a stress level corresponding to an optimal HIC. As the thickness increases, the optimal stress level corresponding to their respective optimal HIC values decreases.

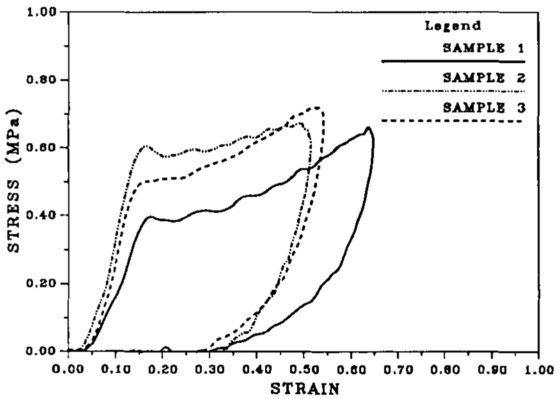


Figure 7.7 Typical foam stress-strain curves in dynamic compression

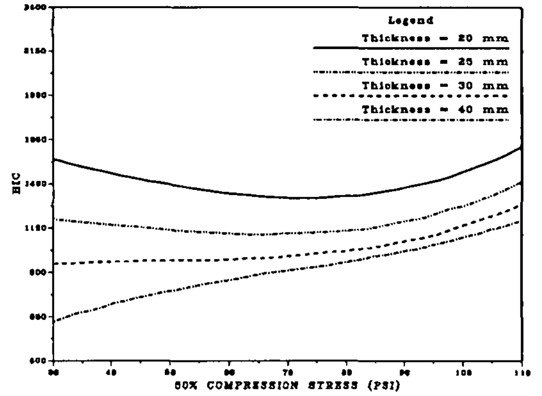


Figure 7.8 Effect of foam thickness and stiffness on HIC

VIII. DISCUSSION OF RESULTS

Comparisons of responses between the predicted and test results for headform impacts with a sheet metal structure and a foam block are shown in Figures 7.1 and 7.3, respectively. The simulated results are considered to be reasonably good.

In the trend analysis using the integrated trim/foam/ sheet metal model, results are quite promising in providing correct direction when various parameters are varied.

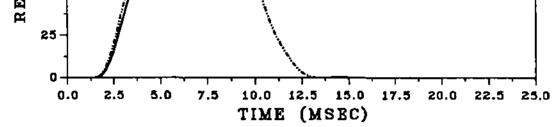


Figure 8.1 Simulation of headform to 6mm foam pad impact

As mentioned earlier, difficulty in simulating thin foam when approaching 90 percent compression was found when using a rigid headform. In general, when this bottomed-out condition occurs, the simulation will carry on for a long CPU time without yielding a solution. This case was re-studied with a deformable headform. The result is compared with test data as shown in Figure 8.1. Although the predicted HIC value is still higher than the test result,

the simulation run without being terminated is indeed an improvement of the deformable headform over the rigid counterpart. In this circumstance, the CPU time is shorter when using the deformable headform than the rigid headform.

Responses using the rigid and deformable headforms are compared with test data from impacting against sheet metal only structure sub-system, foam sub-system and trim/ foam combined sub-system. Comparisons of results for these cases are shown in Figures 8.2 to 8.4, indicating that all the simulated results using the rigid headform at reduced velocities agree very well with results from the deformable headform impact at actual velocities.

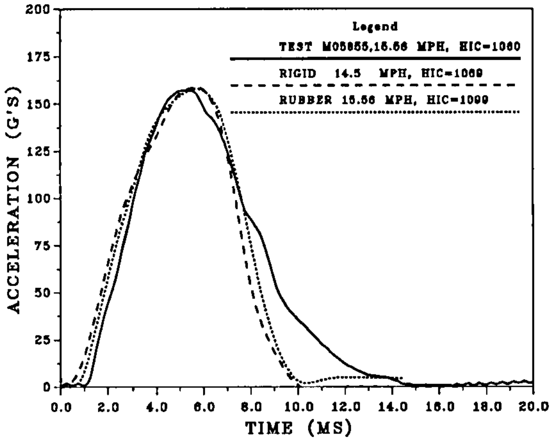


Figure 8.2 Featureless headform to sheet metal pillar impact

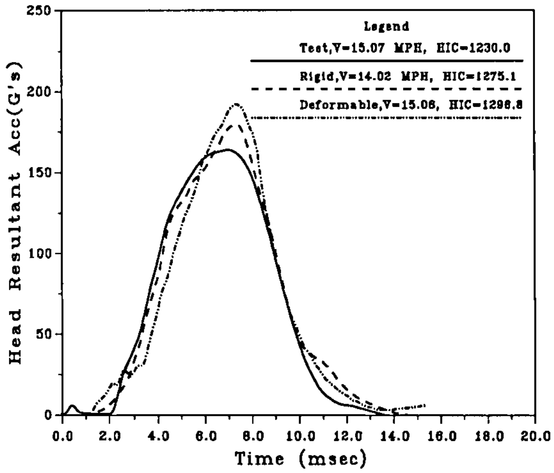


Figure 8.3 Featureless headform to foam pad impact

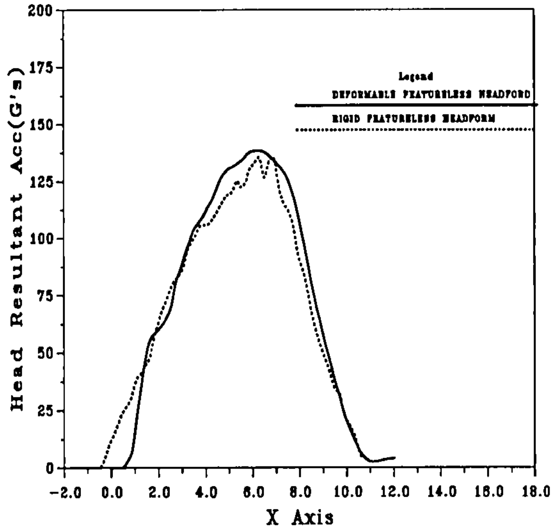


Figure 8.4 Featureless headform to pillar/foam/trim impact

IX. PARAMETRIC STUDIES

The deformable featureless headform thus validated can be used for variability study by carrying out through CAE analysis of parametric variations.

Results from various test conditions indicated that Head Injury Criterion (HIC) calculations obtained from interior impact testing with a free-motion featureless headform were influenced by many variables. Influence of system variables on interior head impact was reported by Amori and Chou et al. [19]. In this study, further variability study is performed including:

a) Headform Drop Tests with Different Contact Points

As mentioned above, the standard headform drop test procedure requires that the forehead must first contact the rigid steel plate prior to other parts of the headform. This parametric study is performed to investigate the sensitivity of headform response to contact points and its effect on the HIC value. Contact points are changed by varying the impact angle of the headform. Figure 9.1 shows the acceleration time histories of head drop tests impacting at two different contact points. Results show that when the contact point is one inch above the center of forehead, the HIC value is lower. This is due to a larger rotation taking place in this case, thus dissipating part of the energy through rotation.

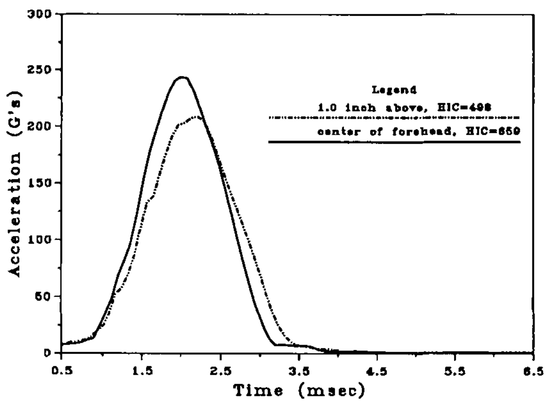


Figure 9.1 Simulation of head drop with different contact points

b) Headform Contact Point vs. Target Location (on Constant "B"-Pillar Section)

In interior impact tests, an "impact contact zone" is marked on the headform forehead measuring 101.6 mm (4.0") high by 127 mm (5.0") wide, into which all initial head impacts must occur. Typically, the headform is aimed such that the impact occurs as close to the headform centerline (mid-sagittal plane) as possible. Let us denote several points in the headform forehead zone by numbers from 1 to 4 as shown in Figure 9.2. When the headform bows 15 degree to the impact direction, the contact point on the forehead is denoted by the number 2, which also serves as the reference point of this study. The point numbered 1 is located 12.5 mm (0.5 inch) above the reference point, and the point 3 is located 12.7 mm (0.5 inch) below the reference point. Point 4 is one inch to the right of the reference. Parametric studies were then conducted to investigate the effect of the contact point on HIC calculations. The target location was defined on the center point of the 533.4 mm (21 inch) long constant section "B"-pillar described earlier.

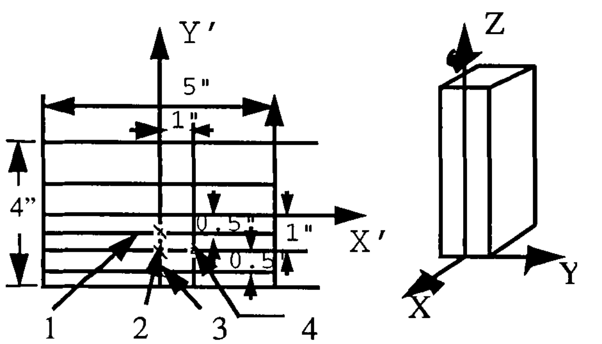


Figure 9.2 Featureless headform to "B"-pillar impact variation study

A series of simulation runs were made using various contact points on the forehead with the target location on the pillar. Results are tabulated in Table IX.1, indicating that the HIC value increases as the contact point changes from the top to the bottom of the forehead.

Table IX.1

Effect of headform contact point

contact location number	CAE predicted HIC (15.56 mph)	TEST	
		impact velocity (mph)	HIC
1	966	15.12	930
2	1099	15.04	1222
3	1291	15.91	1414
4	1039	15.01	1054

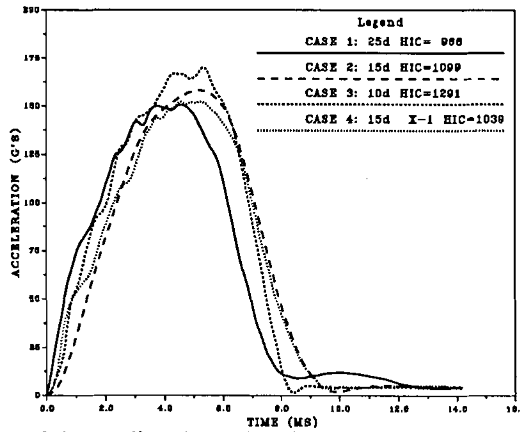


Figure 9.3 Predicted acceleration time history of different contact locations

c) "Roof Side Rail" Impact Locations (Horizontal "B"-pillar)

Simulations of a "roof side rail" impacted at various locations were conducted by rotating the axis of the constant "B"-pillar section by 90 degrees as shown in Figure 9.3. The featureless headform impacted the "roof side rail" at locations shown in Figure 9.4. Simulation results are shown in Table IX.2, indicating that the HIC values do not differ much. This is expected, since the sectional property of the constant section beam did not vary.

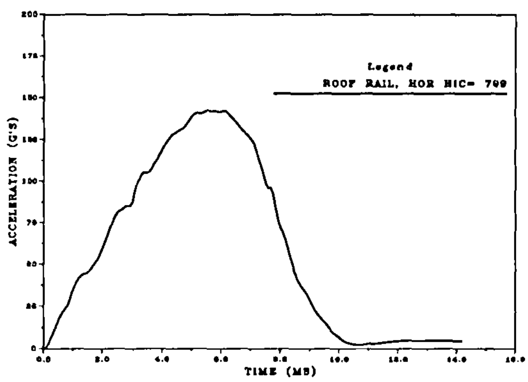


Figure 9.4 Featureless to roof rail impact

Table IX.2

Effect of target point

target point on roof rail	contact location number on headform	HIC
center point	2	799
1.0 inch left	2	784

X. CONCLUSIONS and RECOMMENDATIONS

A deformable featureless headform (DFH) model based on a viscoelastic material characteristic was developed. In the development process, parameters of this featureless headform model were established through comparisons of drop test simulations at various impact velocities with the test data. In addition, the DFH model was also validated for many featureless headform impacts with varying stiffness components, such as sheet metal, foam and trim. Applications of the DFH model to other structural component concept designs and trim model development have found that this model is quite robust. However, it may still not guarantee a "perfect" robustness in wide applications. Effects of complex element deformations, contact friction, scale factors, contact between two materials with varying stiffness, and hourglass control parameters should be further studied in an integrated model with trim/foam and structures. Further, it should be pointed out again that the viscoelasitc material parameters were determined based on the rubber skin modeled with one layer of solid elements. Effects of number of layers on material parameters and headform response need to be studied in the future.

Research should continue in characterization of the vinyl rubber and improvement of the current model or development of a new material model that closely simulates the vinyl dummy skin characteristic. Currently, plans are work closely with the University of Michigan on the material model development and validate it through further material testing.

It is recommended that the DFH model be used in future interior head impact CAE analysis. Further, a similar viscoelastic material model should be developed and implemented in FCRASH for enhancement of its simulation capabilities.

XI. ACKNOWLEDGEMENT

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XII. REFERENCES

1. Notice of Proposed Rulemaking to Amend 49 CFR Part 571, Standard 201 (Docket No. 92-28; Notice 2), 58 Fed. Reg. 7506, February 8, 1993.

2. J. O. Hallquist, "LS-DYNA3D User's Manual", Livermore Software Technology Cor-poration, April 1994.

3. P. J. Blatz and W. L. Ko, "Application of Finite Elastic to the Deformation of Rubber Material", Trans. Sco. Rheology, pp. 223-151, 1962.

4. R. S. Rivlin, "Large Elastic Deformations of Isotropic materials: IV. Further Development of the General Theory", Phi. Trans. Soc. London, Series A: Material and Physical Science, Vol. 241, pp. 379-397, 1948.

5. B. G. Kao and L. Razqunas, "On the Determination of Strain Energy Functions of Rubbers", SAE Paper 860816, 1986.

6. K. N. Morman, Jr., "Rubber Viscoelasticity - A Review of Current Understanding", Proceed-ings of 2nd Symposium on Analysis and Design of Rubber Parts, London, England, Batelle Institute, limited, January, 1985.

7. A. Wineman, "Some Modeling Consideration for Rubber-Like Materials in the Development of Software for Computer-Aided Design", proceedings of the sixth International Conference on Vehicle Structural Mechanics, pp. 119-125, 1986. SAE Paper No. 860812.

8. J. Vossoughi, "Determination of Mooney Material Constants for Highly Nonlinear Isotropic Incompressible Materials under Large Elastic Deformation", Experimental Techniques, March/April 1995, pp. 24-27.

9. T. B. Khalil and T. C. Lin, "Simulation of the Hybrid III Dummy Response to Impact by Non-linear Finite Element Analysis", The 38th Stapp Car Crash Conference Proceeding, SAE Publication P-279, pp. 325 - 343, 1994.

10. Dahsin Liu, "Simulation of Knee Response for Dummy Model", Progress Report under Ford University Research Grant, Department of Materials Science and Mechanics and Center for Composite Materials and Structures, Michigan State University, March 1995.

11. HyperMesh User's Manual, Version 1.40d, Altair Computing, Inc., 1994.

12. FEMB (Finite Element Model Builder) User's Manual, Version 26, Engineering Techniology Associates, Inc., 1994.

13. I. Kaleps and J. Whitestone, "Hybrid III Geometric and Inertia Properties", SAE Paper No. 880638, 1988.

14. K. W. Krieger, "Full Scale Experimental Simulation of Pedestrian-Vehicle Impacts", Chapter 7, Ph.D. dissertation, Wayne State University, 1976.

15. D. A. Wells, "Theories and Problems of Lagrangian Dynamics with Treatment of Euler's Equations of Motion, Hamilton's Equations and Hamilton's Principle" Schaum's Outline Series, McGraw-Hill Book Co. pp. 132-133

16. C. C. Chou, Y. Zhao, G. G. Lim, R. N. Patel, S. Shahab and P. Patel, " Comparative Analysis of Different Energy Absorbing Materials for Interior Head Impact", SAE Paper No. 950332, 1995.

17. C. C. Chou, Y. Zhao, L. Chai, J. Co, G. G. Lim and T. L. Lin, "Development of Foam Models using LSDYNA3D", The Second International LS-DYNA3D Conference held in San Francisco, September 20 -21, 1994. Paper No. 2IL-SD3D125.

18 G. G. Lim, C. C. Chou, et al., "Estimating Minimum Space to Meet Federal Interior Head Impact Requirements", SAE Paper No. 950333, 1995.

19. R. T. Amori, R. R. Armitage, C. C. Chou, G. G. Lim, R. N. Patel and S. A. Shahab, "Influence of System Variables on Interior Head impact", SAE Paper No. 950882, 1995.

APPENDIX

Determination of Headform C.G. and Moments of Inertia

The center of gravity (c.g.) of each headform was determined using a trifilar pendulum as described in Reference [14]. The headform was attached to a light weight frame which was then placed on the trifilar pendulum supported by three wires as shown in Figure 3.1. Each of the three wires of the pendulum was attached to a load cell. The sensitivity of each load cell was calibrated identically. The c.g. of the frame was moved to coincide with the c.g. of the pendulum by manually adjusting the position of the frame on the pendulum until all loads were equally distributed. A line was marked on the frame that passed through the center, establishing a plane passing the c.g. The frame was rotated to two other orientations using the aforementioned procedure, thus establishing three planes which all pass through the c.g. Proper choice of rotations would allow these planes to intersect at a point. Determining this point gave the location of the c.g. of the head and frame.

The weight and c.g. of the frame alone was also determined. The c.g. of the head alone can then be calculated from the following equation:

$$CG_h = [(W_h + W_f) * CG_{hf} - W_f * CG_f]/W_h \qquad \text{(A-1)}$$

where CG_h = c.g. position vector of the head

CG_{hf} = c.g position vector of the head and frame

CG_f = c.g. position vector of the frame

W_h = weight of the head
W_f = weight of the frame

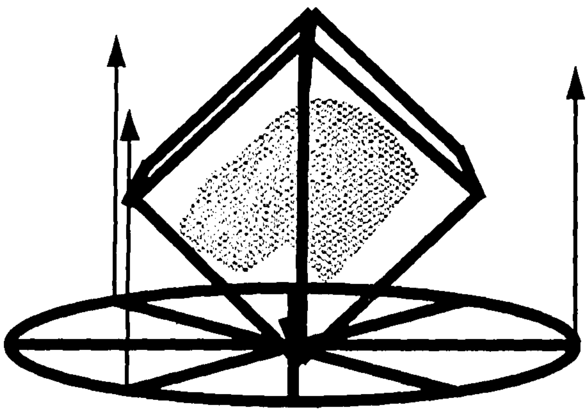

Figure A.1 Testing arrangement

The trifilar pendulum (with the frame and headform on it) was set into torsional oscillation by imposing a small angular rotation to it. The number of oscillations occurring over a long period time was measured with a photocell/ counter. The period of oscillation was calculated by dividing the total duration by the number of oscillations. Similarly, the period of oscillation was determined for the pendulum and the frame without the headform. The moment of inertia of each headform was determined from the period of trifilar pendulum oscillation from the following equation:

$$I = [T^2 * W * R^2]/[4 * ã * L] \qquad \text{(A-2)}$$

where I = moment of inertia
- T = period of oscillation
- W = weight of the oscillating mass including the headform, the pendulum disk and half the weight of the suspending wires
- R = radius of the pendulum disk
- L = length of the pendulum wire.

Eq. (A-2) gives the moment of inertia of the combined pendulum, frame, and the headform. The moment of inertia for the pendulum and frame without the headform can be obtained from Eq. (A-2) by substituting the appropriate T and W. Subtracting the moment of inertia of the pendulum and frame from the moment of inertia of the combined pendulum, frame, and headform yields the moment of inertia of the headform alone. A simple object such as a solid cylinder, for which the moment of inertia could be calculated theoretically, was tested on the pendulum to check the procedure prior the headform test. It was found that the measured value was in agreement with the theoretical value to within 5%.

To obtain the complete moment of inertia tensor, it is necessary to make measurements in at least two orientations. If the headform axes of interest are aligned to be coincident with the axis of rotation of the pendulum (i.e. the x-, y- and z-axes of the headform), then measurements must be done in the x, y, and z axes and also at 45 degrees to the x, y, and z axes. At least three timings of the period of oscillation were taken for each orientation. The empty frame was also measured in all six orientations so that its moment of inertia values could be subtracted from those the headform and frame to yield values for the headform alone. Off-diagonal terms or the products of inertia in the moment of inertia tensor were calculated from the following equations [15]:

$$I_{xy} = -I_{xym} + (I_{xx} + I_{yy})/2$$

$$I_{xz} = -I_{xzm} + (I_{xx} + I_{zz})2 \qquad \text{(A-3)}$$

$$I_{yz} = -I_{yzm} + (I_{yy} + I_{zz})/2$$

where I_{xym}, I_{xzm}, and I_{yzm} are the measured moments of inertial at 45 degree angles.

Principal moments of inertia were found by setting the following determinant to zero and solving for the three roots of I_p:

$$\begin{vmatrix} (I_{xx} - I_p) & I_{xy} & I_{xz} \\ I_{xy} & (I_{yy} - I_p) & I_{yz} \\ I_{xz} & I_{yz} & (I_{zz} - I_p) \end{vmatrix} = 0$$

Direction cosines for the principal moments of inertia were calculated.

Based on measurements, the principal moments of inertia are found to be:

I_{p1} = 22.91 ton-mm^2 (0.2028 in-lb-sec^2)
I_{p2} = 21.45 ton-mm2 (0.1899 in-lb-sec^2)
I_{p3} = 14.91 ton-mm2 (0.1320 in-lb-sec^2)

The C.G. location of the headform is at

x_{cg} = 71.2 mm (2.804")
y_{cg} =-0.3 mm (-0.010")
z_{cg} = -35.4 mm (-1.393")

relative to the reference point shown in Figure 4.1

SIDE IMPACT SIMULATION TECHNIQUES FOR COST EFFECTIVE AIRBAG AND TRIM DEVELOPMENT

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Paper Number 96-S8-O-09

ABSTRACT

A radical change has occurred in the organisation and planning of vehicle programmes in recent years. A number of systems within the vehicle are to be developed by Tier 1 suppliers in isolation from the vehicle platform. There is a need for a higher level of confidence in a system's performance before it is tried out on a full vehicle.

For side impact crashworthiness development the change in programme style has put a greater emphasis on advanced engineering at the concept and prototype stages. The need for increased confidence has required the development of physical test methods that do not need prototype bodyshells, but represent the environment experienced in full crash tests. The application of two sled based techniques, S.I.D.E and M-SIS, is described in relation to the modern vehicle programme with the advantage that:

- Side structure performance targets can be related to door velocity profiles and their effect on occupant response, before prototype vehicles are built.
- Structural and occupant computer models can be evaluated against a physical test method.
- Airbag and trim systems can be developed with a dynamic test without the need for destruction of many prototype parts.

INTRODUCTION

The automotive industry has undergone significant changes over the last ten years in the ways in which a vehicle programme has been constructed and executed. Most significantly the emphasis has moved away from the vehicle being designed by an engineering team from the vehicle manufacturer, to a vehicle that is made up of a number of systems from separate suppliers. Each system is carefully defined in advance of the programme by a series of performance targets. There is a further requirement for the systems to come together and to work correctly first time. This dictates that the designers of the systems have to have significantly higher levels of confidence in performance before they are tried out as part of the vehicle.

Side impact crashworthiness presents a complex problem, due mainly to the dynamic interaction between the occupant and the vehicle during the impact. This would tend to dictate that the 'occupant restraint system' cannot be considered separately from the 'crash pulse' as is generally the case with frontal impact. However the new design process requires the structure and the occupant restraint system to be developed apart. Clearly a new approach is required, with new tools and techniques, for the development of side impact.

CHANGE TO VEHICLE PROGRAMME

Traditional Programme

The way in which vehicle programmes used to be organised is shown in Figure 1. Each function within the company would perform their allotted task and pass the project on to the next group, often with little communication between the groups. One of the bad features of this type of programme was the serial process which could give rise to many programme delays from the initial concept to the point where the vehicle was available to be sold. This style of programme took a long time because it relied heavily on the building of prototype vehicles to identify and solve the design problems.

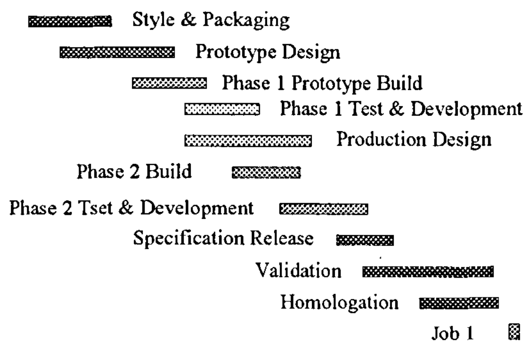

Figure 1 - Traditional Vehicle Programme

To compensate for the changes in customer expectation and allow for new technology developments, there was a general policy of keeping the design fluid. Thus,

late feature change was a common occurrence. This usually had knock on effects to all associated parts of the vehicle, which, in turn, led to delays and increased costs, particularly with tooling.

The Japanese auto makers started the change in Europe and America by bringing a number of new products to market that were not only better than the competition, but had been developed in a much shorter time.

Simultaneous Engineering

The response was to try to understand the way in which the Japanese were operating and to introduce an appropriate system that would allow the other countries to catch up. This led to the widespread development of techniques known as Simultaneous Engineering.

The concept behind Simultaneous Engineering was to carry out a number of activities in parallel, thus saving on the overall time to market. This was achieved by getting all groups involved in the design and production of the vehicle, together at the earliest possible stage. Thus, if a change to the design of a feature was suggested, there was opportunity for suppliers, manufacturing and other feature groups to comment on the feasibility and implications of that change.

The first programmes that were attempted with this process operated at a much higher risk level than had been experienced previously. The programme starting point was still the same with the styling and concept stages. Here the requirements of the marketing group were interpreted. Since old habits die hard, there was still a tendency to try to keep the design flexible. Very little 'advanced engineering' was carried out and there was still a great reliance on using prototype vehicles to solve problems.

The overall time to market reduced, but the risks associated with the programmes increased due to the possibility of getting the initial specification wrong and parts of the vehicle not being right first time.

Modern Programmes

The current approach which has been developed by vehicle manufacturers is to keep research and development separate. Thus, a new concept or system has to be proved before it is committed to a vehicle programme[1]. If new technology is introduced at the same time as a new design, there is an increased risk that the programme will not be on time and within cost.

The new vehicle programme is split into two major parts, not necessarily of equal value or duration. The first phase is Definition, and the second Implementation (Figure 2).

The overall approach is to do as much early engineering as possible to increase confidence in the design concept before committing to the detail design. This is achieved by setting a series of targets for the design of the whole vehicle. In theory it is possible to set 'high level' whole vehicle targets. These in turn are made up of a series of system targets, which are, it turn made up of a series of sub-system targets and so on. If the sub-system targets are all met then the system target is met. If the system targets are met then the vehicle target is also met. The great advantage of this method is that is gives very clear goals for each design team to work towards. If all targets have been set correctly and achieved then the design should be right first time.

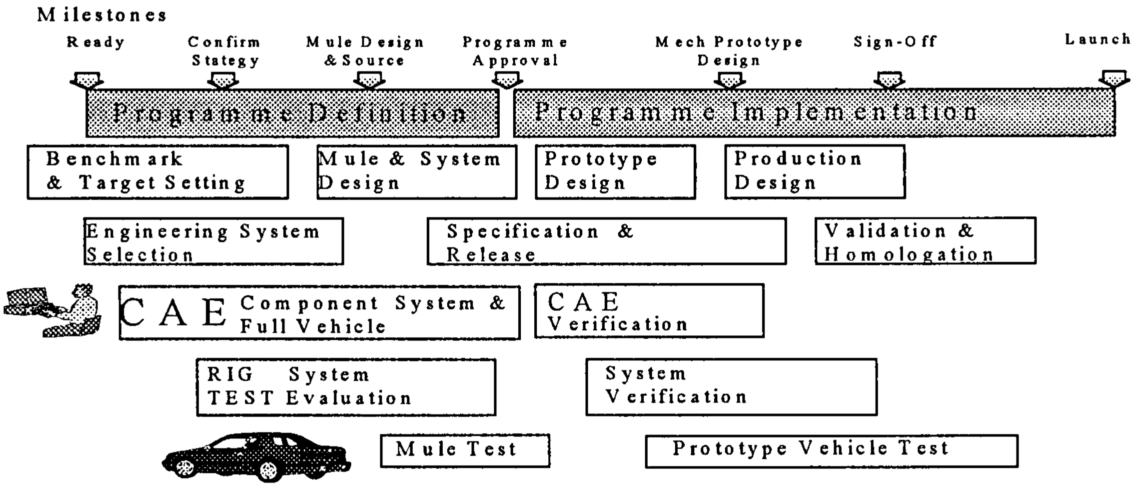

Figure 2 - Modern Vehicle Programme

There is an objective to keep the prototype vehicle work to a minimum and use these as much as possible for verification rather than as a necessary part of the development process.

The development of this style of programme has occurred at a time when safety has a significant influence in the buying process. The demands of customers, consumer groups and today's legislation means that safety is a dominant influence when the vehicle is specified and designed. Within safety engineering, one of the growing areas for development is side impact, where there are new levels of legislation to meet, and customer demands for greater safety. Within the boundaries of the modern programme there are opportunities for improvement in the specification and development process which will increase the confidence in achieving a competitive safe product.

SIDE IMPACT DEVELOPMENT

Before looking in detail at how side impact performance can be achieved within the modern vehicle programme, it is worth reviewing the tools and methods available for front impact development.

In general there are four levels of verification available to the front impact/occupant restraint engineer. These are shown below.

Level 1	Computer Models
Level 2	Component Test
Level 3	Sled Test Techniques
Level 4	Full Vehicle Crash Test

As the design for each part of the restraint system progresses; it can be evaluated at a first level by a computer model. This can be Finite Element Analysis (FEA) for the structure or steering column, and MADYMO for the occupant kinematics. However, one of the key weaknesses of computer models is the quality of the component data that is used to establish datasets. This moves the process to the next level of verification; component testing. For the FEA model; this can take the form of a load-deflection curve for a specific joint or a simple material property stress-strain test. For the MADYMO model; it is more likely to take the form of seat belt elongation data or a seat characterisation study.

At this stage of development it is possible to move to the third level of verification, dynamic sled tests which provide a physical simulation of the impact. There is a requirement for a number of prototype parts, but the part count is still low compared with the ultimate verification of using a full vehicle crash test.

For the side impact engineer there are the same requirements for the four levels of verification. However, until recently there has been a need to fill the role performed by the frontal sled test.

Two techniques have been developed by MIRA to fulfill this requirement. The first is the S.I.D.E. procedure [2][3]. This technique was developed to evaluate the collapse of the vehicle side structure and to evaluate dummy injury levels. The technique is based on a HyGe and aims to simulate the full vehicle side impact by mounting the bodyshell on one sled and a mobile deformable barrier (MDB) on a second sled. The HyGe gun fires the MDB on the first sled into the bodyshell on the second. The S.I.D.E. technique was developed and correlated to full scale side impact crash tests for both FMVSS 214 and ECE 95. The advantage of this technique is that it only requires the bodyshell and hardware local to the occupant.

The increase in importance of side trim and, more recently, side airbags highlighted the need for a second technique that concentrated on the interaction of the dummy and the side door, thus removing the variability of the structural collapse. To accommodate this, MIRA has developed a further technique called M-SIS (MIRA Side Impact Simulation). The detail of the technique and the level of correlation achieved with full vehicle impact have been presented in previous papers[4][5].

The overall aim of the M-SIS technique is to recreate the contact that occurs in the crash test between the door and the dummy, without having to incur any structural collapse. These two techniques, S.I.D.E. and M-SIS, fill the gap in the side impact development process.

SIDE IMPACT PROGRAMME

Setting Targets

As can be seen in the typical safety section of a modern vehicle programme (Figure 3), the first stage of the process is to benchmark and set targets. As with all design projects it is essential that clear objectives and constraints are set at the start. These would typically include performance and cost objectives, packaging constraints and requirements to use existing components depending on the product life cycle.

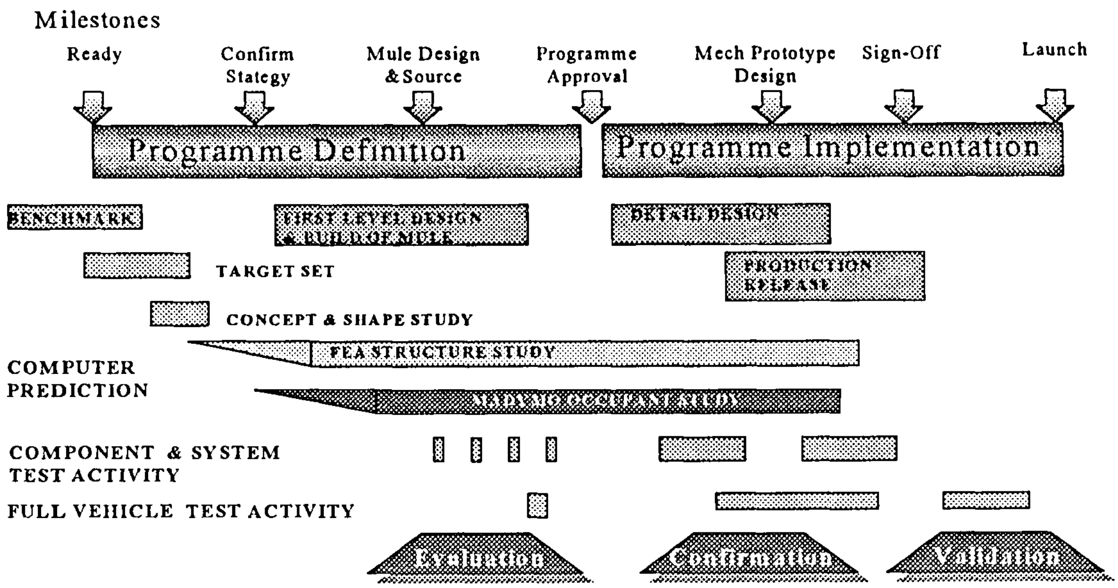

Figure 3 Side Impact Programme based on Modern Programme

For the vehicle manufacturer there are a number of factors that have to be taken into consideration in arriving at the design objectives for the safety systems on a vehicle [6].

- Accident surveys
- Export markets - legislation
- Product liability
- Consumer / media pressure
- Marketing issues
- Future legislation changes
- Competitor performance
- Corporate safety strategy

Taking those into account, the high level vehicle safety target will be set which, for side impact, will probably be expressed as dummy injury criteria and structural intrusion. These high level targets need to be cascaded to targets for sub-systems. Therefore the occupant injury target is, in turn, made up of a performance for the structure, the trim and, if specified, the airbag. Computer modelling and physical simulation techniques like M-SIS can guide the setting of these lower level targets through parametric studies.

One of the problems associated with the development of computer model predictive techniques for side impact has been the need to combine a number of complex systems. At a high level, these are the mobile deformable barrier used on the striking vehicle, the vehicle structure with all its complexities, the side trim/airbag and finally the dummy. Since there are variables and approximations in any computer model, a technique that can reduce the model by using established test data will be an advantage. The M-SIS technique fulfils this role and can be used to evaluate a series of crash pulses in order to arrive at the optimum.

The approach here would be to establish the overall dimensions of the vehicle package and the seating position. Once this is known, a computer model can be generated using an occupant modelling package like MADYMO. The model will be able to evaluate a series of crash pulses through a DOE (Design of Experiment) analysis, with the aim of arriving at the 'optimum' pulse for minimum occupant injury. The crash pulses that show the best results can then be verified by conducting tests on the M-SIS rig.

The combination of the computer model and the physical test enable the effect of the variables to be explored. Thus the structural engineers will not only have a target that they can have confidence in, but they will also know the sensitivity of occupant injury to change in their predicted pulse. If a concern arises during the predictive studies that the pulse is likely to be significantly different to the target, it can be evaluated using either the MADYMO model or physically tested on the M-SIS rig.

Early Trim/Airbag Studies

The philosophy of the modern programme is to set targets for all parts, to enable each element to be developed before the full vehicle is constructed. Once the target has been set for the door intrusion velocity pulse, it can be used to support early trim and airbag studies before the first full structure has been built. Again, the combination of MADYMO and physical test on M-SIS can be used.

Structural Evaluation

Before full commitment is made to the implementation of the vehicle programme, the structure will require evaluation to both FMVSS 214 and ECE 95. These tests can either be performed as a full vehicle, or as a S.I.D.E. test depending on the level of prototype parts available. These tests should enable the confidence of achieving the required target to be increased. They will also provide a more definitive pulse for the further airbag and trim studies.

Side Airbag Sensor Studies

Front impact sensors are developed by conducting a series of tests at different speeds on the full vehicle. These are based on the fire and no-fire conditions. There are a further series of evaluations based on worst case scenarios which are termed abuse tests. These latter tests are based around misuse of the vehicle in activities like kerb strike and pole impact.

Side impact airbags have a similar requirement for sensor development. One of the first side airbags installed into the market was on the Volvo 850. This airbag uses a percussion cap mounted on the seat to trigger the inflator. Current systems under development use electronic sensors that are based on either pressure, acceleration, or radar. The latter devices are aimed at predicting the onset of an impact. All of these are likely to be housed in the door or the 'B' post. It has been suggested that, ultimately, the side airbag sensor will be housed at the same location as the front sensor. This would save on complexity, but may require the frontal sensor to move to the side of the vehicle.

There will be a need to conduct a series of tests to ensure that the side airbag sensor is registering the appropriate information. Traditionally this would have been done on full vehicles, but another of the physical techniques developed by MIRA can be utilised for this purpose. The S.I.D.E procedure was aimed at the development of the structure so it can also be used for the development of the sensor. Clearly the advantages of being able to accurately reproduce an impact condition help to tune a sensor. By taking a close look at the requirement for triggering the side airbag it is seen that the sensor has to fire within the first 10 ms after contact, probably 5 ms for a 30 mile/h impact. Hence, when developing the sensor response, it is only necessary to reproduce the first 8 - 10 ms of the impact (Figure 4). Looking closely at the structural collapse, it is seen that only the sill, 'B' post, front and rear door are involved. If these parts are assembled onto a frame and a S.I.D.E style test conducted, the required information for sensor development can be derived with only a minimal outlay of prototype material.

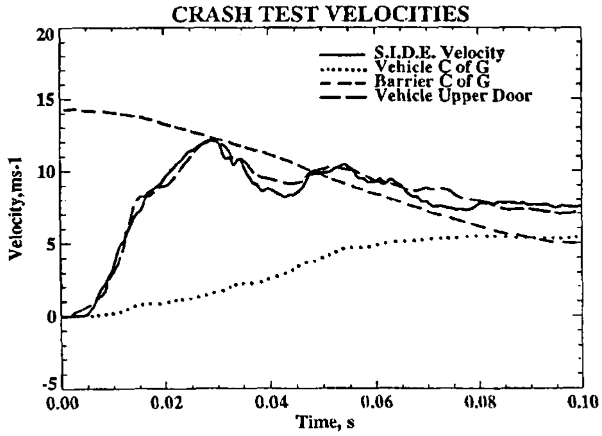

Figure 4 Comparison of Velocity Trace for Crash and S.I.D.E

Side Airbag and Trim Development

As the programme progresses, the airbag and trim will require further development once the first crash pulse becomes available. There will also be a need to conduct an investigation into occupant out-of-position and extremes of temperature on restraint system performance. The tests involving out-of-position occupant and rearmost location of the front seat where contact can occur with the 'B' post can all be conducted on M-SIS. The extremes of temperature testing prove to be more difficult to conduct because of the close proximity of the dummy and the airbag module.

For front impact testing, it is relatively easy to have the full test buck ready on a sled, with dummies in position, prior to fitting of an airbag module which has been conditioned in a climatic chamber. Practically, there is still a requirement to take less than seven minutes from the time the module is taken out of the chamber to the test being fired. Side airbags that are seat mounted are a problem. The module has to be fitted to the seat and the dummy positioned which can take up to forty minutes, and the temperature conditioned module will have either cooled or warmed significantly.

The solution here is to re-evaluate the purpose of this test activity. The extreme temperature test is conducted to

ensure that the system still performs satisfactorily. The two keys aims are to ensure that the gas generator has consistent characteristics, and the deployment 'doors' function in a similar fashion to the ambient temperature test. For high and low temperature test it is possible to perform static deployment in a climatic chamber using a ballast dummy as a reaction load. Confidence in the system can be gained by taking pressure traces and analysing the high speed film of deployment.

CONCLUSIONS

Today's automotive engineers are faced with many demanding requirements for the crash and occupant protection performance of their cars. As well as the obvious need to comply with legislative markets for the vehicle, product liability and consumer pressure are extending the envelope of performance for these safety systems. Competitive pressure is also pushing up standards and reducing new vehicle development cycles at the same time which means that a systematic approach is needed to be effective.

Side impact development has been enhanced with two new sled test techniques, S.I.D.E and M-SIS, which are making significant contributions to modern vehicle programmes.

REFERENCES

[1] HOPTON J R, Development of Modern Vehicle Programmes, Seminar Brazil 1993

[2] STEPHENS V M and BACON D G C, The Development of a Method for Dynamic Simulation of Side Impacts Using a HyGe Acceleration - The S.I.D.E. Procedure, 13th ESV Conference

[3] STEPHENS V M, CORY G and HOPTON J R, Developing Side Impact Crashworthiness Through Advanced Experimental Techniques, SAE 951064

[4] HOPTON J R and PAYNE A R, Faster Side Impact Development using MIRA's Side Impact Simulation (M-SIS) Technique, Autotech England1995

[5] HOPTON J R, PAYNE A R and BACON D G C, Comparison Study of EuroSID, USSID and BioSID Performance Using MIRA's New M-SIS Side Impact Simulation Technique, SAE 960103

[6] BACON D G C, Component Development for Automotive Interior Safety, Interauto Paris 1995

EXAMPLES OF EVALUATION METHODS OF ENERGY-ABSORBING PROPERTIES FOR UPPER INTERIOR HEAD PROTECTION

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1. ABSTRACT

Various types of samples, including plastic foams, elastomers, and hollow-shaped plastics, are evaluated by both high-speed impact tests and the static compression tests. We found that the high-speed impact tests together with proper data analyses are very effective in evaluating Energy-Absorbing(E/A) properties of various materials. Analyses from the data obtained from those tests, estimation of E/A properties for different types of samples from the compression data should be avoided and the compression data are effective only among the same type of samples. With the high-speed impact tests, plastic foams and hollow-shaped plastics showed excellent head protection properties. Foamed plastics, which can be easily applied to interior trim parts, are focused on and some typical plastic foams are additionally tested under various conditions. Comparison of those test results to actual vehicle tests, design guidelines in applying plastic foams to head protection trims are introduced as final conclusion.

2. INTRODUCTION 1),2)

Base concepts of Isuzu product development are 'safety and reliability' and 'practical, timeless, sound-quality'. In order to materialize these concepts, Isuzu Materials Development Department has been conducting activities based on those concepts. For instance, quality assurance by estimating degradation lives of materials for airbag parts has been done, and, in order to reduce an occupant's head injury level, FMVSS 201 is applied for instrument panels of all Isuzu vehicles whether regulations require or not. This paper deals with safety in an accident such as rollover, overturning and side impact, where airbags do not function, but impact E/A materials work to reduce the level of an occupant's head injury due to hit against the interior structural parts.

Major interior structural parts are roof rails, and A, B, and C pillars. E/A materials are used on the inboard side of the structural parts. Especially, stiff pillars have been demanded as structural parts, to prevent a roof from being crushed in the case of overturning. Also, all the pillars should be as slim as possible to secure a driver's view. Slim and stiff pillars, however, will increase head injury level. Therefore, the use of E/A materials is one of major issues concerning to reduce head injury level, as well as to save space, to secure a driver's view, and to improve the total safety of a vehicle.

This paper reports the summary of test results for E/A materials jointly evaluated by the materials and the vehicle test departments in order to provide guidelines for selecting the optimum E/A material and design. This paper also explains the points of the material selection guidelines considering the stiffness of the vehicle body.

3. TEST SPECIMENS

Table 1 shows a list of sampled test specimens. Actually more than 5 times the specimens with different specifications have been tested including those tested under various temperature levels and after heat/humidity-aged. Table 1 shows the sizes of test specimens only for part of the specimens used in the tests.

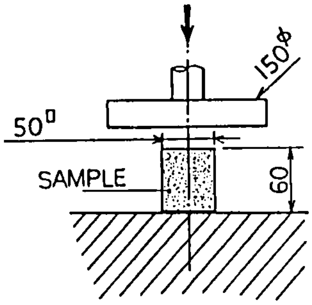

Fig.1 Static Compression Test

Table 1 Test Specimens

Mat'l	Structure	Dens. kg/m3	Sample Size b×h×t (mm) Static	Impact	Notes
PUR	Foam	100			×11
PP	Foam	60	50	200	×15
PE	Foam	200	×	×	×5
PET	Fiber	170	50	100	Felt
NR	Solid	950	×	×	40HsA
V/SIS	Solid	1200	60	20	Gel
PP	Hollow	250			BlowMold

4. TEST METHOD & EQUIPMENT

4.1 Static Compression Test

Static compression tests are what materials engineers normally do in analyzing material. Polygonal prism samples (See Table 1) are compressed at a constant speed by using a universal compression tester to obtain the relationship between compressive strain and stress (load deviled by sectional area). In Fig.1, compression speed is 10 mm/min., or a strain speed of 17 %/min., and the maximum compression distance is 50 mm, or a maximum strain of 83 %.

Static compression test has been generally performed because the reaction force of a material in response to a compressive input can be readily measured with reasonable accuracy. Material characteristics data obtained in the static compression test have been used as input data for CAE analysis and in such cases as estimating dynamic compressive E/A characteristics and screening materials.

However, the physical properties of polymer compounds have been known to depend on strain speed. Moreover, the upper limit of the compression speed of the static compression tester is 60 m/hour, far lower than the actual impact speed, 30,000 to 40,000 m/hour. For these reasons, static test results are used based on the assumption shown in Fig.2, in an extreme case, or for information only.

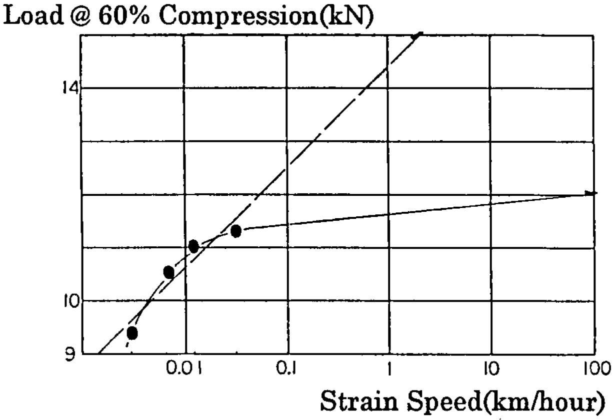

Fig.2 Dependence of Physical Properties of E/A Material on Strain Speed

Conventionally, materials engineers run the static tests on test piece to present data to design engineers, and in the next step, vehicle test engineers perform vehicle tests. In most cases, the static test results fail to be properly correlated with the vehicle test results. Therefore, there is no other way to achieve the performance target than repeating the vehicle tests by trial and error, which is nowadays considered as one of the standard procedures.

4.2 Impact test

In order to improve the reliability on the static test data, and to roughly narrow down the E/A materials to be used in the HIC vehicle tests, authors ran high-speed impact tests on test pieces.

These high-speed impact tests were performed by striking a head-form impactor, weighing 6.8 kg, with its top in a 165.1 mm diameter sphere, against the test specimen made from the E/A material in a certain shape at a certain speed by using an air cylinder to measure displacement, time, acceleration, and load (Fig.3).

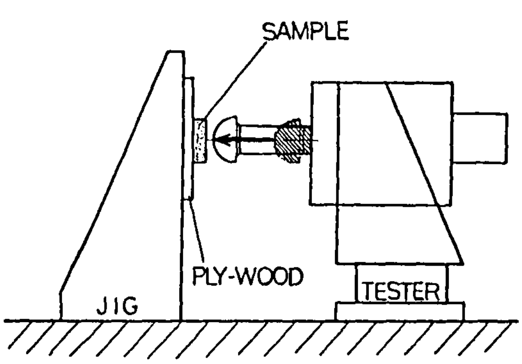

Fig.3 Impact Test

In this test, energy absorption (displacement x load) and head injury criterion (HIC) values are calculated by the following equation:

$$HIC = MAX \left[\frac{1}{(t2 - t1)} \int_{t1}^{t2} a \cdot dt \right]^{2.5} (t2 - t1)$$

where 'a' is the resultant acceleration, and (t2-t1) is the period of time which gives maximum HIC.

Performance of the E/A materials is evaluated by comparing the HIC values with and without the E/A material. Low HIC value is considered as a slight injury to a head.

This impact test is based on the revised FMVSS 201 HIC vehicle test using a free head-form, and has been performed for the first time to confirm the possibility of accurately evaluating the E/A characteristics of the materials in a simple way, and obtaining feedback information about safety by analyzing the test results and comparing them with those of the HIC vehicle test.

4.3 HIC Vehicle Test

HIC vehicle tests were performed in accordance with the revised FMVSS 201, with displacement, acceleration and load measured in the same way as the impact test mentioned in section 4.2 herein, and with the HIC value calculated.

First, the vehicle test was performed without attaching the E/A materials to the rigid vehicle body. The purpose of this test is to study the effects of the stiffness of the structural parts of the vehicle body on the HIC value. Then, HIC values were measured with the E/A materials attached.

5. TEST RESULTS

5.1 Static Compression Test Results

Fig.4 shows relationship between the compressive strain and the load (compressive stress), and Table 2 shows major physical properties. In the case of foamed polyurethane (hereinafter referred to as 'PUR') which has hysteresis characteristics, the specimen buckles, and as a result, 60 to 70 % of the deformation remains as permanent set.

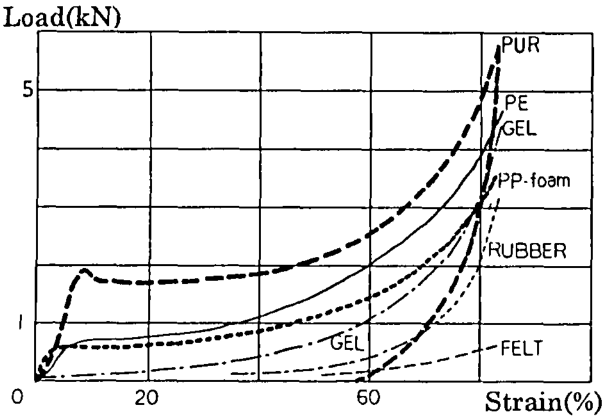

Fig.4 Static Compression Test Results

Table 2 Static Compression Test Results

Mat'l	Structure	Dens. kg/m3	Compression Test Results (MPa)		
			Elasticity	Stress @ Proportionality Limit	Max. Stress @83%
PUR	Foam	100	3.58	0.65	1.24
PP	Foam	60	1.00	0.17	1.26
PE	Foam	200	0.81	0.19	1.80
PET	Fiber	170	0.05	0.05	0.24
NR	Solid	950	0.30	0.39	11.80
V/SIS	Solid	1200	0.07	0.06	1.80
PP	Hollow	250	0.29	0.63	1.57

5.2 Impact Test Results

Fig.5 shows relationship between displacement (strain) and load (stress) in comparison with Fig.4. As seen from these figures, the dynamic compression behavior is totally different from the static one, which indicates that the E/A performance of the specimens cannot be evaluated only with the static and impact test results,. Quantitative relationship between the static and impact test results, however, has been confirmed among the specimens with the same structure, such as foamed material, which can give us a definite answer to how to use the static test results.

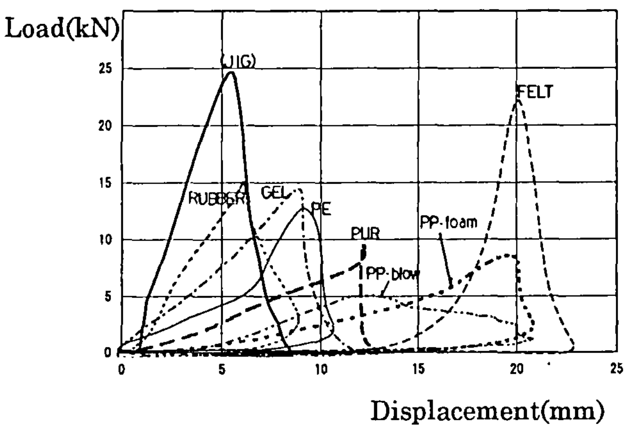

Fig.5 Impact Test Results

Main characteristics are shown in Table 3. Values in this table are calculated except for the peak accelerations, or max. 'a'. The impact energy damping ratios are defined as the quotient of the peak deceleration with the E/A material divided by that without the material. Attachment of the E/A material to such rigid surface as pillars, can reduce the HIC value. Also, even a 20 mm thick E/A material, if properly selected, can reduce the HIC value by 80 % (to 20 % of the HIC value without the E/A material).

Table 3 Impact Test Results

Mat'l	Structure	Dens. kg/m3	Impact Test Results					
			Elasticity (N/mm)	HIC	Reduction of HIC (%)	Max. 'a' (G)	Impact Energy Damping Ratio (%)
*	*		5000	2965	0	485	0
PUR	Foam	100	600	740	75	146	70
PP	Foam	60	300	614	79	131	73
PE	Foam	200	1000	901	69	199	59
PET	Fiber	170	20	2187	26	391	19
NR	Solid	950	2600	1429	52	234	52
V/SIS	Solid	1200	1700	1171	61	228	53
PP	Hollow	250	400	431	85	85	82

*: when a head directly hits vehicle body

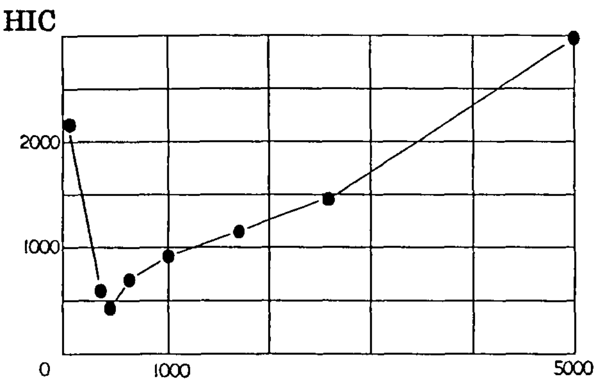

Fig.6 Impact Elasticity vs. HIC

The HIC values and the impact elasticities in Table 3 are compared in Fig.6 as E/A materials are required to reduce HIC value. If impact elasticity is too low (e.g. the displacement-vs.-load curve rises too leisurely), a head comes into contact with the rigid vehicle body before impact energy is absorbed, which means that the material does not absorb enough energy. On the other hand, if impact elasticity is too high, impact energy cannot be properly damped. Accordingly, the material with the local minimum of the HIC value as seen in the curve of Fig.6, the material has such a proper balance between hardness and softness that impact energy is absorbed without a head hitting against the rigid vehicle body.

5.3 HIC Vehicle Test Results

The foamed PUR was use as a representative E/A material in this test. Table 4 shows the results of HIC values at 5 locations of the rigid vehicle body without E/A material, HIC values with the E/A material, and HIC reduction effect. As the vehicle body stiffness increases, so does HIC value, as well as HIC reduction effect.

Table 4 HIC Vehicle Test Results

Parts where a head hits against	w/o E/A	with PUR E/A	
**: Impact Test Results	HIC	HIC	HIC(%) Reduction
A Pillar Upper	1643	697	58
Roof Side rail FRT-1	1418	625	56
Roof Side rail FRT-2	1058	541	49
Roof Side rail RR-1	1081	564	48
Roof Side rail RR-2	1024	488	52
**	2557	501	80

6. CONCLUSIONS

As a result of discussing the most effective way to reduce head injury level in a traffic accident where airbags do not work and a head hits interior structural parts, the following conclusions have been reached:

1) It is effective to mount proper E/A material on the surface of the structural parts, in order to reduce HIC value.

2) The E/A material should be hard enough to prevent a head from directly hitting the structural parts, and at the same time, soft enough to sufficiently absorb impact energy.

Also, the following knowledge has been acquired in studying evaluation methods:

3) E/A characteristics of the materials with different structures and specifications cannot be compared based only on the static test results.

4) Impact elasticity obtained in the impact test can be an indicator of E/A performance.

Material selection guidelines have been drawn up based on these ideas by quantitatively comparing the impact elasticity test results with those of the HIC vehicle test. Fig.7 shows plots of ratios of HIC value reductions in the impact test and the HIC vehicle test with the PUR E/A material from those without the material. As seen from this figure, effect of adding the E/A material is more significant as the HIC value without the E/A material is larger. In addition, this figure suggests such a positive correlation between the reductions of HIC values in the impact test and HIC vehicle test enables us to quantitatively compare the characteristics of different E/A materials.

Also, the thickness of the PUR E/A material required to reduce the level of HIC value to target values are shown in Fig.8, which has been

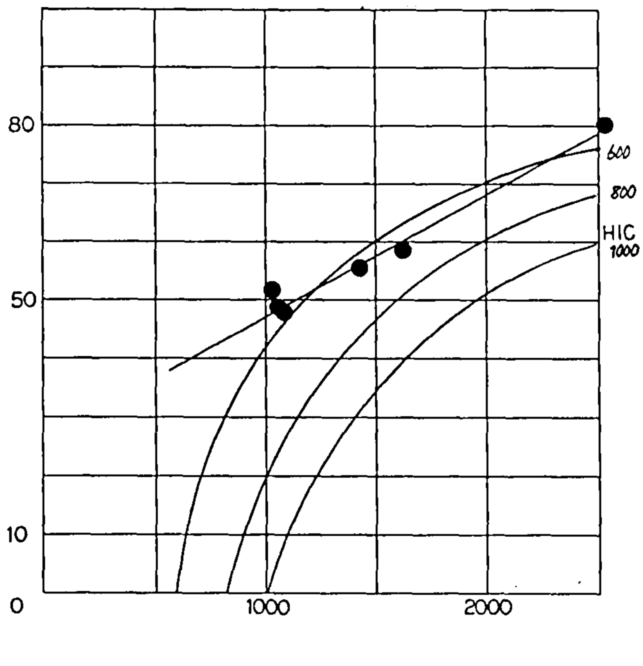

Fig.7 Effects of E/A material in Reducing HIC

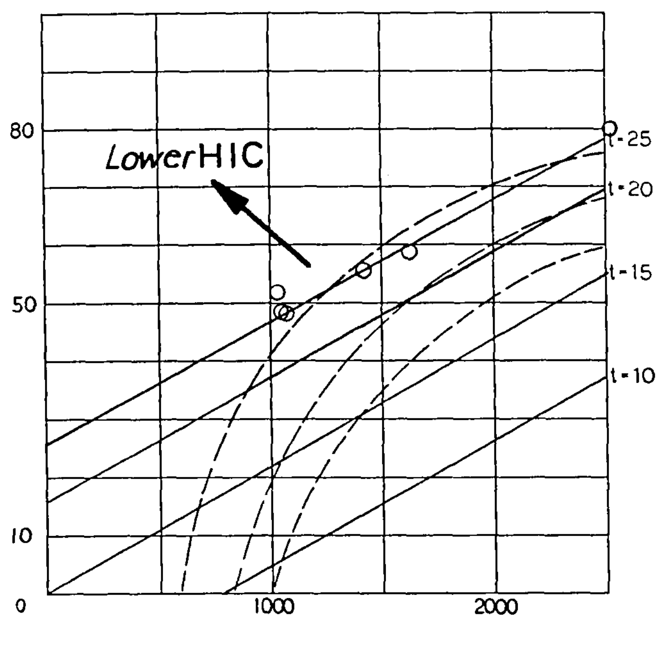

Fig.8 Material Selection and Design Guidelines

obtained for each vehicle part by conducting the impact test and the HIC vehicle test with the material thickness varied. Though only one material is dealt with in this figure, similar relationships can be obtained for the other E/A materials because the impact test results almost fully correspond with the HIC vehicle test results. This indicates that the impact test is very effective for quantitative evaluation of E/A performance of various materials.

Moreover, E/A performance of the materials which have undergo different aging tests and temperature dependence tests can be accurately estimated for each vehicle part. As a result, maintaining a low HIC value is possible not only for the initial materials but also for those which have undergo aging tests and temperature dependence tests, that is more than regulated by the revised FMVSS 201.

7. AFTERWARDS

The authors consider the impact test as the first step of breaking down the stereotype of materials experiment, with which researchers normally evaluate the E/A performance of the materials on the basis of the static compression test.

The materials engineers' knowledge acquired by running the impact tests has been developed into the design guidelines for occupant protection by comparing the test results with those of the HIC vehicle test from different points of view. As in this case where safety is improved, necessity for materials engineers to collect data which they conventionally do not deal with, and to contribute to the improvement of vehicle quality, will increase in the future. Also, from an opposite point of view, the authors have strongly felt the necessity for vehicle test engineers to analyze vehicle quality and suggest requirements through keeping close contact with materials engineers, and exchanging the most up-to-date information because the authors have been reminded of the necessity of the interaction between materials engineers and vehicle test engineers.

The authors believe that materials engineering is an elementary technology playing an inconspicuous but vital role in the vehicle development. Therefore, we will continue to make efforts to contribute to the vehicle development, hoping that someday results of our activities are spotlighted.

REFERENCES

1) J.Kasai, "A New Stage of Development in Automotive Plastics and Environmental Technology - Interior Parts", Plastics Vol.46, No.3, page 27 to 32, 1995

2) S. D. Barbat et al, "Finite Element Modeling of Structural Foam and Head Impact Interaction with Vehicle Upper Interior", SAE 950885, 1995

DEVELOPMENT OF A FINITE ELEMENT MODEL OF THE SIDE IMPACT DUMMY AND APPLICATION FOR THE SIDE IMPACT PROTECTION

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ABSTRACT

In occupant safety assessment, numerical simulations of automotive crash provide a valuable tool for the engineers. A large number of numerical models of dummies have been proposed to date to help engineers to assess with numerical simulation tools the level of injury on occupants in automobile crashes.

In side impacts, the phenomena are more complicated than in other crash configurations such the frontal and rear-end collision. The dummy and the car structural parts, such as side-door panels, interact strongly during the side impacts. In order to accurately predict the phenomena in such situations, a detailed 3 D finite element model of the DOT-SID dummy was developed [Ref.1 and 2]. In the present model, based on the SID dummy, we carried out the combined simulation and experimental verification of the dynamic and pseudo-static characteristics of different materials such as foam, rubber, composites and so forth.

The SID finite element model has been validated first at the individual segment level, then by using rigid surface impactor tests on dummy sub-assemblies, and finally based on the SID performance verification impact tests on the complete dummy assembly.

Furthermore, the SID finite element model was also validated in padded surface impactor situations providing similar effects as the real configuration of passenger car side impacts. A parametric study was carried out on this configuration to reduce the level of injury parameters.

The paper presents the results from these validation steps.

INTRODUCTION

The energy absorbing space between the occupant and environment in car-to-car side impact accident is relatively small compared with that of frontal or rear-end accidents, and for the occupant injury reduction measures, it is found to be generally more difficult in side impact accident. In this regard, manufactures and research laboratories have been carrying out extensive side impact tests on actual vehicles, and evaluations and reviews on technologies for the development of countermeasures are being conducted in energetic manners.

Side impact phenomena, however, involves many factors, such as

(1) the stiffness of the front portion of the striking vehicle,
(2) the stiffness of side portions of the struck vehicle,
(3) behavior of occupants, etc.

The development of countermeasures is thus a time-consuming process.

Under these circumstances, a variety of numerical simulations by modeling said factors have been conducted in order to identify the mechanism that tend to cause occupant injuries.

Results of such studies have been used in extensive parameter studies, taking into account of the impact speed, the weight of the striking car among other parameters to develop proper guidelines for the establishment of injury reduction measures.

These occupant models can be broadly grouped in two groups:

(i) rigid bodies of ellipsoids connected by springs, i.e., mass spring models and
(ii) elastic/plastic bodies representing accurate material stiffness and geometrical shapes connected together with springs and joints.

The rigid mass-spring dynamic models have a lot of merits such as requesting very low computational times and are widely used in frontal crash simulations.

The authors have also been carrying out side impact simulations using a simple mass-spring model of the SID for side impact analysis [Ref.3]. However, it is very difficult to represent the real 3 D geometries of the SID by using the ellipsoid. Such ellipsoidal models fail to represent the detailed 3-D contact mechanism which is extremely important in side impact situations, such as strong interaction between dummy and complex geometric side-door panels.

On the other hand, the real 3 D shapes and the real material properties of each SID part based on finite element modeling technique are capable of predicting very complicated and local responses such as the deformations or the contact forces which can hardly be measured experimentally. We developed a SID model by using the nonlinear Finite Element product PAM-CRASH [Ref.4]. The details of this model are described in the following sections.

SID FEM Model Description

The overall geometry of SID FEM model is depicted in Figure 1. The detailed FEM model of upper and lower torso parts are shown in Appendices.

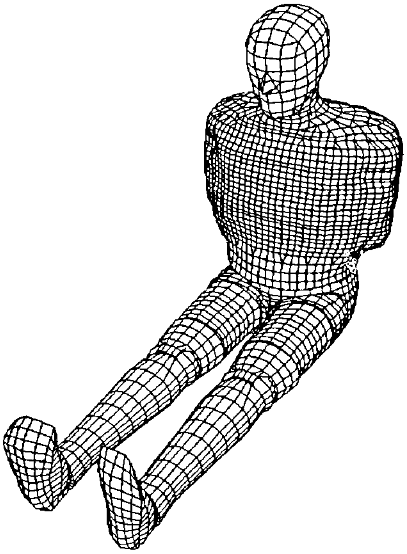


Fig 1. SID FEM model

The present model consists of solid, thin shell, beam and spring elements. The total number of elements in SID model is about 20,000 and contains approximately 9,400 shell elements, 10,700 brick elements and 23 other elements including beam, bar and joint. The spine box, head, pelvic bone, femur bone and the lower portion of the leg are modeled as rigid bodies to reduce the calculation time.

(1) Mass Distribution of SID model

The mass distribution of individual components plays an important role in predicting the total movement of the dummy. The mass and inertia properties of each individual component was measured accurately and it properly incorporated into the model by adjusting the densities and mass distributions.

Table 1 in Appendices summarizes the mass distribution of the SID model. The total mass is 75.8 kg.

(2) Validation of SID Individual Segment Test

The SID dummy is composed of a variety of foam materials. It is very important to represent the foam material properties for the accurate SID model response.

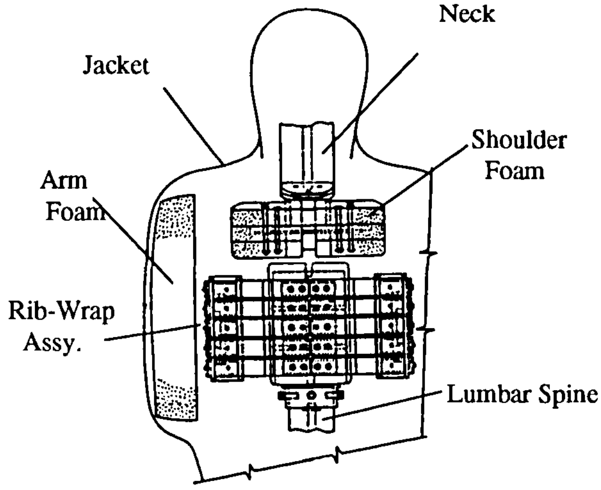
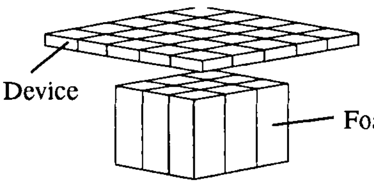


Fig 2. Example of Foam and Rubber Material of SID

To develop the present model, the following items were checked and modified to match the experimental and numerical results. To calibrate the parameters of the material, accurate tests on samples of said material must be carried out. As such samples could not be readily available, foam test samples were cut from actual SID components. Foam samples from arm segment, pelvic segment, abdominal inserts, etc. of the SID dummy were tested to find out the force - displacement characteristics under different compression conditions including quasi-static and dynamic loading using the test setup depicted on Figure 3.

Loading Device



Foam

Fig 3. Compression of Foam

Most foam materials showed to have a volumetric strain rate dependency effect. When accurate numerical results could not be obtained by using the existing constitutive law of foam material, new constitutive laws, based on experimental results, needed to be developed and implemented in collaboration with the software house.

(a) Pelvic Foam

The pelvic and abdomen part of the SID model are used with sophisticated porous foam material model . The test samples of the pelvic foam were cut out from the pelvic flesh of an actual SID dummy, so they had uneven shapes.

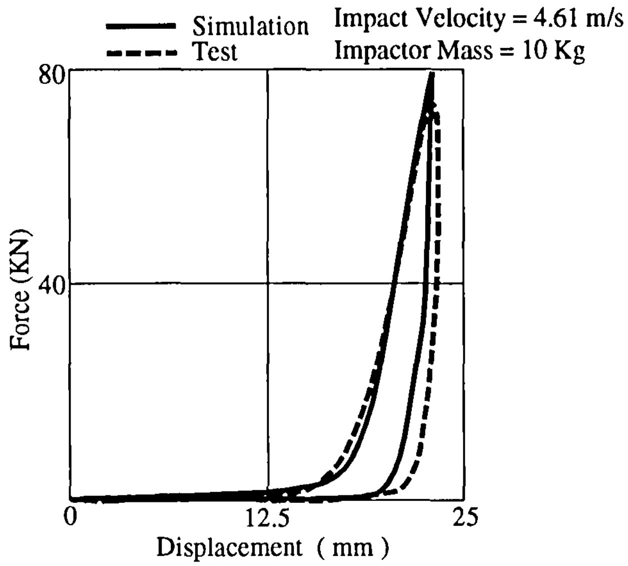


Fig 4. Force-Displacement of Pelvic Foam

To fix the force - displacement characteristics, the pelvic foam samples were tested under different compression conditions. Figure 4 shows the comparison of test and simulated results

<u>(b) Lumbar Spine</u>

Since the lumbar spine connects the pelvis at its bottom extremity and the neck and head of the dummy through the spine box at its top, a proper modeling of this segment is important for simulating the global kinematics of the SID dummy. The lumbar spine has a strong influences on ribs , pelvic and especially lower spine accelerations.

The lumbar spine is made of rubber and has a steel wire-cable inside it as shown in Figure 5. The height of lumbar spine is adjusted to about 131 mm through twisting of the steel wire-cable. The estimated compressive initial load of the lumbar spine is 225 Kg. While PAM-CRASH product has a new function for the pre-straining, it was not used because of some oscillations at the beginning of the computation.

The verification of the modeling approximation was

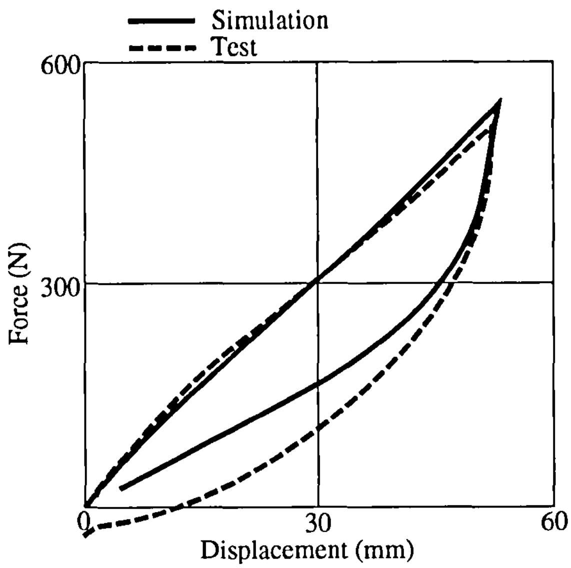


Fig 7. Bending Characteristics of Lumbar Spine

performed by simulating numerically the bending test of the lumbar spine as shown in Figure 6 and 7. Good agreement on the loading phase of bending characteristics can be seen in these figures. It is however also important to approximate the unloading curve because of the need to accurately predict the second peak of acceleration at the lower spine. For this unloading phase, further developments are needed to improve the accuracy between simulation and test results.

<u>(c) Rib Hinge</u>

The rib hinge is composite structure made of five sandwich layers of the rubber and fiber. The rib accelerations are very sensitive to the response of the damper inside the thorax and to rib-hinge deformations. Under a direct impact over the thorax, at first, the rib hinge between the spine box and the rib cage undergoes compression and then large rotational deformation

A first model, made of shell elements, could not produce similar Young's modulus in the bending, torsional, compression and tensile tests carried out on a sample rib hinge.

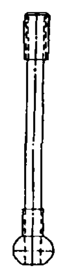


Fig 5. Wire Cable

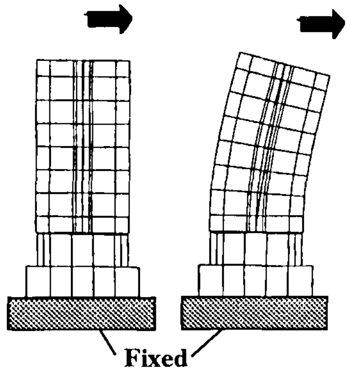
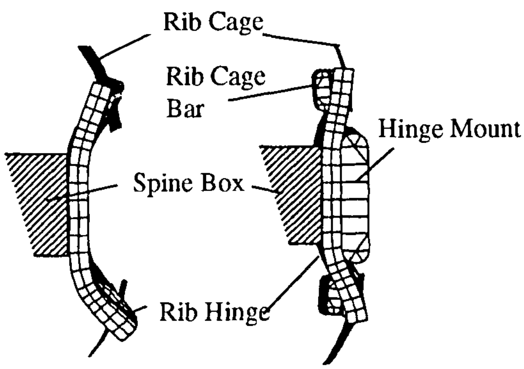


Fig 6. Lumbar Spine Bending



Before Modification After Modification

Fig 8. Rib Hinge Deformation

A model of the rib hinge made of solid elements could not be fixed to avoid overly large deformations causing an abnormal end of the computation. Finally, a more detailed model of the connection between rib and hinge, and between hinge and hinge mount was prepared. With this model, the hinge produced a similar S-shape deformation as during the impact tests on the thorax sub-assembly. This final model is depicted in Figure 8 showing the deformed shape of the hinge model.

(d) Damping Mechanism of Thoracic Damper

The damper inside the thorax has a 3-link mechanisms including two revolute joints and a spherical joint and controls deformation of chest. Accurate modeling of this part is extremely important to simulate the exact deformation characteristics.

First, the structure of the damper was reviewed. Figure 9 shows the sectional view of the damper. The internal parts of the damper have the following characteristics:

- four orifices on the cylinder wall.
- a spring which is initially compressed by 18 mm.
- hydraulic damping characteristics changing with the speed of impact and the instantaneous position of the damper's piston head with respect to the orifice position.

The second step was to characterize the damper by means of fluid mechanism. Based on the law of continuity, the oil flow velocity can read as:

$$V_O = \frac{S_O}{n * S_P} * V_P \text{ ------- } (1)$$

where V_O: velocity at orifice
V_P: piston velocity
S_O: area of piston
S_P: area of orifice (Each orifice has same area)
n : number of orifices available for the oil flow

In general, the damping force generated by orifices is given as

$$F = C * V_O^2 \text{ -------------- } (2)$$

where F : damping force
C : constant value

The third step was to carry out a series of damper impact tests on the damper for the validation of the damper model, as shown in Figure 10. Impact velocities were varied in the range of 3 to 6 m/s. Figure 11 illustrates the complexity of the damper reaction with the damper force rising up due to the series of orifices, even if the overall velocity of the damper's piston slows down. Further simulations have shown that the response of the thorax is complexified by this fluid flow through the orifices.

The present model was validated by experiment results as shown in Figure 11 and 12 showing good correlations with the experimental results obtained with this model.

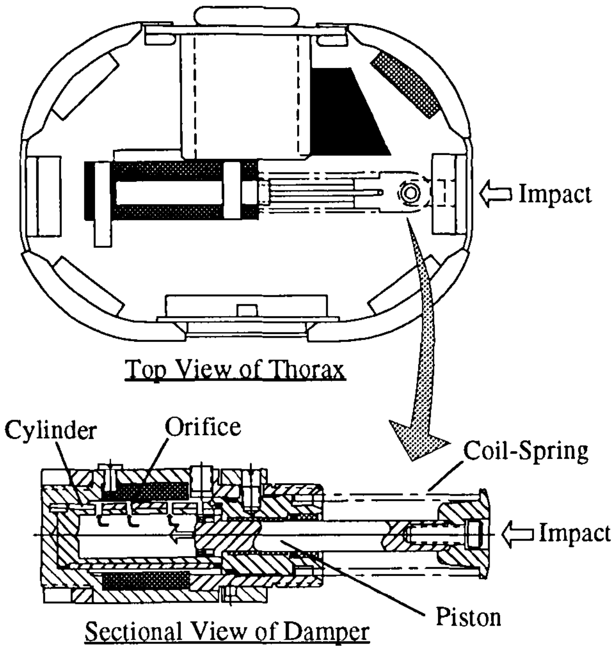


Fig 9. Structure of Damper

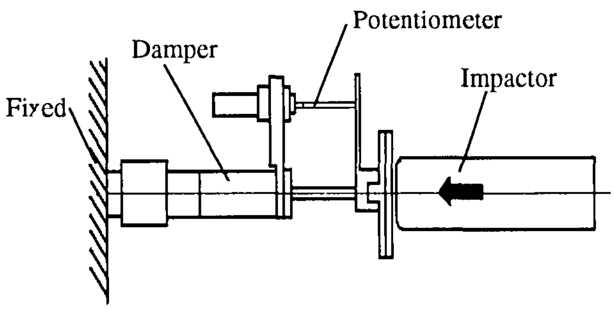


Fig 10. Damper Unit Impact Test

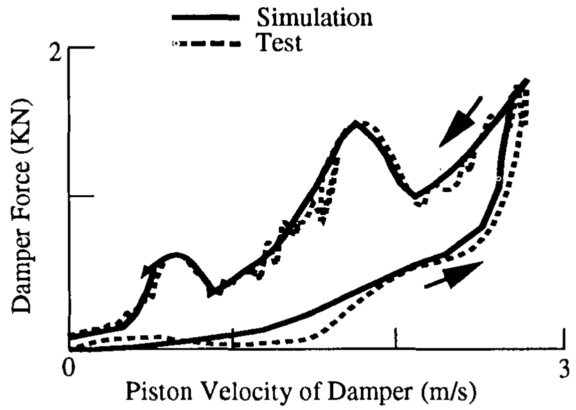


Fig 11. Force-Velocity Characteristics of Damper

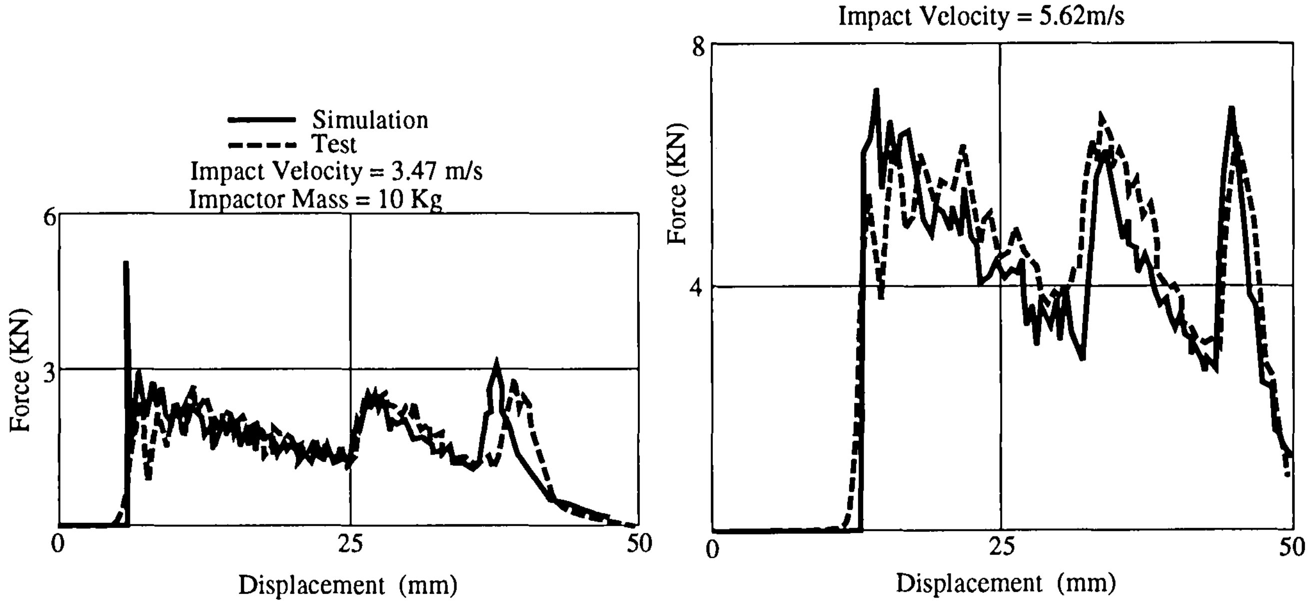


Fig 12. Force-Displacement of Damper

(e) Arm Foam

The porous foam material is used for modeling the arm foam . The arm foam is very soft, but its accurate modeling is important to control the timing of the rib peak acceleration. It is so soft that it is very prone to developing hourglass modes during large deformation as shown in Figure 13. An impactor drop test was carried out for the validation of the arm foam. The impact velocity is 0.51 m/s and impactor mass is 25 Kg. Figure 14 shows the good correlation between tests and simulated results.

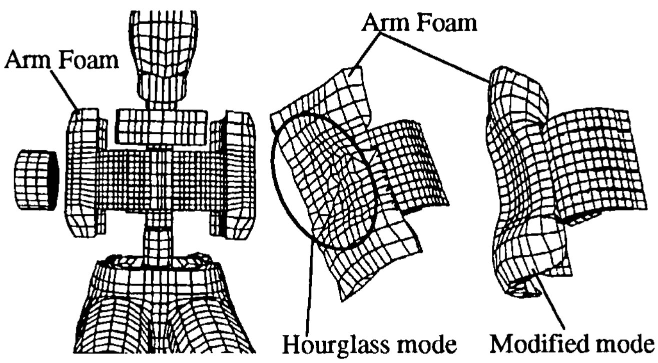


Fig 13. Deformation of Arm Foam

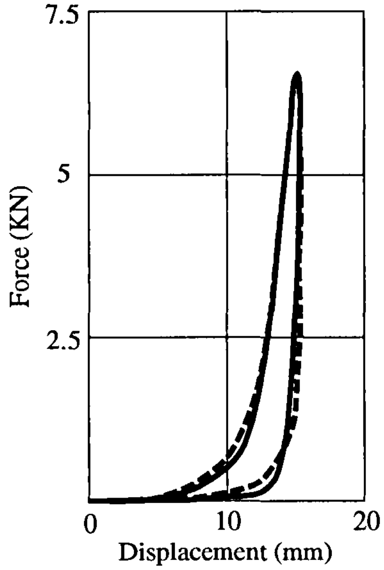
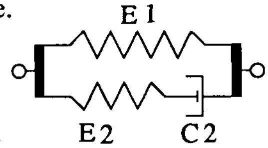


Fig 14. Force-Displacement of Arm Foam

(f) Rib Damping Material

It is very important for predicting the damping of the steel rib to represent the damping and hysteresis of this material as accurately as other foam materials. A nonlinear viscous-elastic material model is used for the modeling of the rib damping material. The unknown material characteristics of the nonlinear material were determined using an iterative optimization procedure.



$$E_1 = E_{10} * (V/V_0)^{-n1}$$
$$E_2 = E_{20} \qquad \text{--------(3)}$$
$$C_2 = C_{20} * [|1-(V/V_0)|]^{n2}$$

where $V=V(t)$: deformed volume

V_0 : undeformed volume

Fig 15. Non-Linear Visco-Damping Model

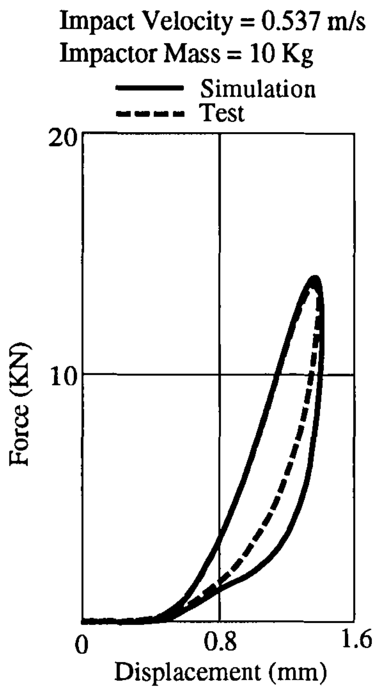


Fig 16. Force-Displacement of Rib Damping Material

Figure 16 shows the comparison between numerical and experimental results for a drop test. The simulation result are aver absorbing to some extent in the unloading phase.

<u>(3) Validation of SID Sub-Assemblies</u>

For the sake of efficiency, it was deemed that a detailed calibration of critical SID segments was essential before carrying out validation tests of the complete model. Impact tests on the SID thoracic and pelvic sub-assemblies were carried out by using a rigid surface impactor as shown in Figure 17 and 18, before the FMVSS 214 validation of the SID complete model.

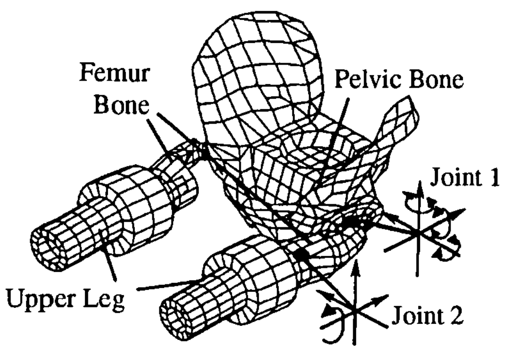


Fig 19. Bone Modeling

It is important to prepare an accurate 3 D model of the pelvic and femur bones as shown in Figure 19. Because of the very complex geometry of the pelvic bone, the thickness of the pelvic foam varies at every position and it has very strong influence on the pelvic acceleration. A good prediction of these accelerations calls for an accurate model. The model prepared shows very good correlations with respect to test results as shown on Figure 20 and 21 for both peak values of rib and pelvic accelerations.

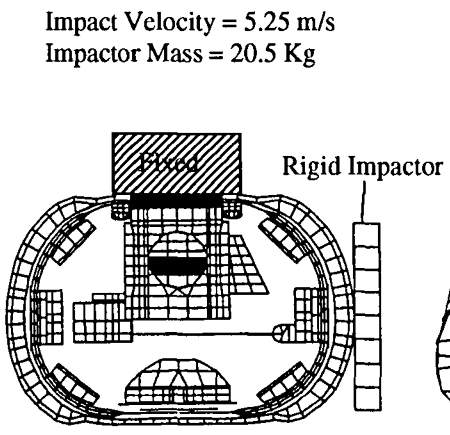


Fig 17. Thorax Sub-Assy.

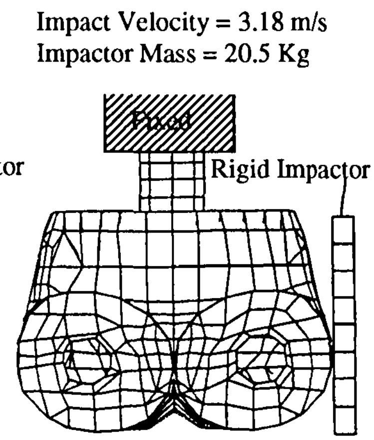


Fig 18. Pelvic Sub-Assy.

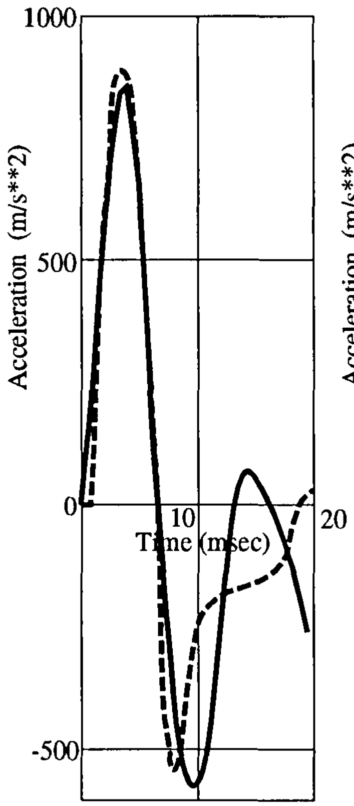


Fig 20. Upper Rib Acceleration Time History of Sub-Assy.

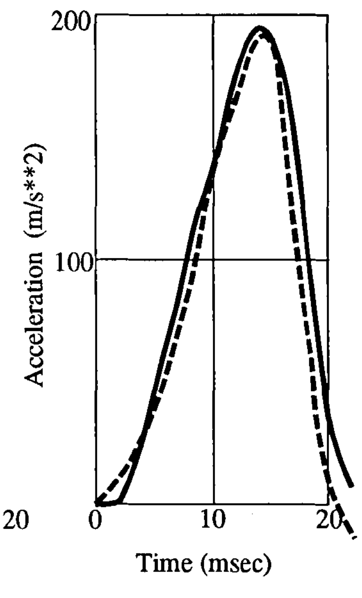


Fig 21. Pelvic Acceleration Time History of Sub-Assy.

(4) Complete SID Model Validation

Impact Performance Verification Test

This test is based on the SID Performance Verification Testing [Ref.5] for the thorax and pelvis impacts. The objective of this test is to measure the dynamic response of the thorax and pelvis to lateral hard faced pendulum impacts. Figure 22 shows the thorax impact test configuration. The impactor used to impact has a 152.4 mm diameter flat, rigid face and has an chamfering edge of 9 mm. The impactor mass is 23.4 Kg. The thorax and pelvis are to be impacted at about 4.3 m/s. And the results are filtered with a FIR filter. The measurement points of the accelerations for calculating the injury criteria are shown in Figure 23.

The acceleration at the upper and lower ribs and lower spine need to have responses that are within the following ranges:

Upper rib (Impact-direction) 37-46 g
Lower rib (Impact-direction) 37-46 g
Lower spine (Impact-direction) 15-22 g

The SID model showed good correlation between simulation and experimental results and satisfied each the impact performance specifications as shown in Figure 24.

It can be concluded that

- comparing the peak values and the timing of rib and spine accelerations, very good correlation is achieved.
- the lower spine and thorax potentiometer responses after the peak acceleration show some deviation with respect to experimental results.
- good correlation is achieved for the damper response of the displacement by the potentiometer.

Damper force in the impact tests usually cannot be measured, but , from the displacement-time history of the damper potentiometer, it seems that a good correlation was obtained.

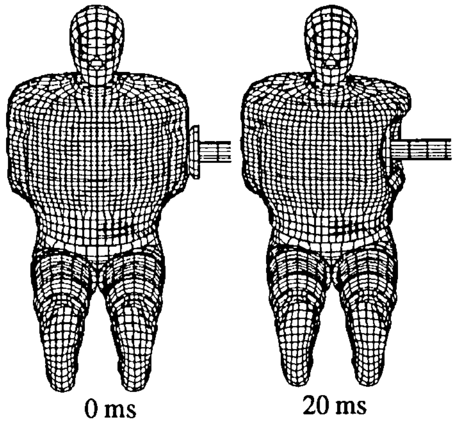


Fig 22. Thoracic Behavior

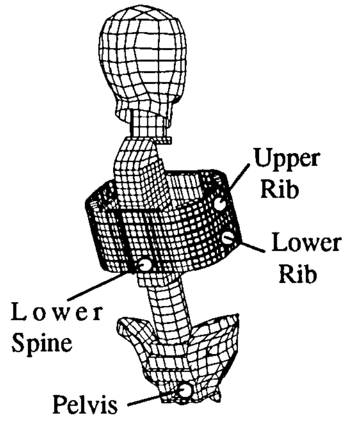


Fig 23. Calculation Point of Acceleration

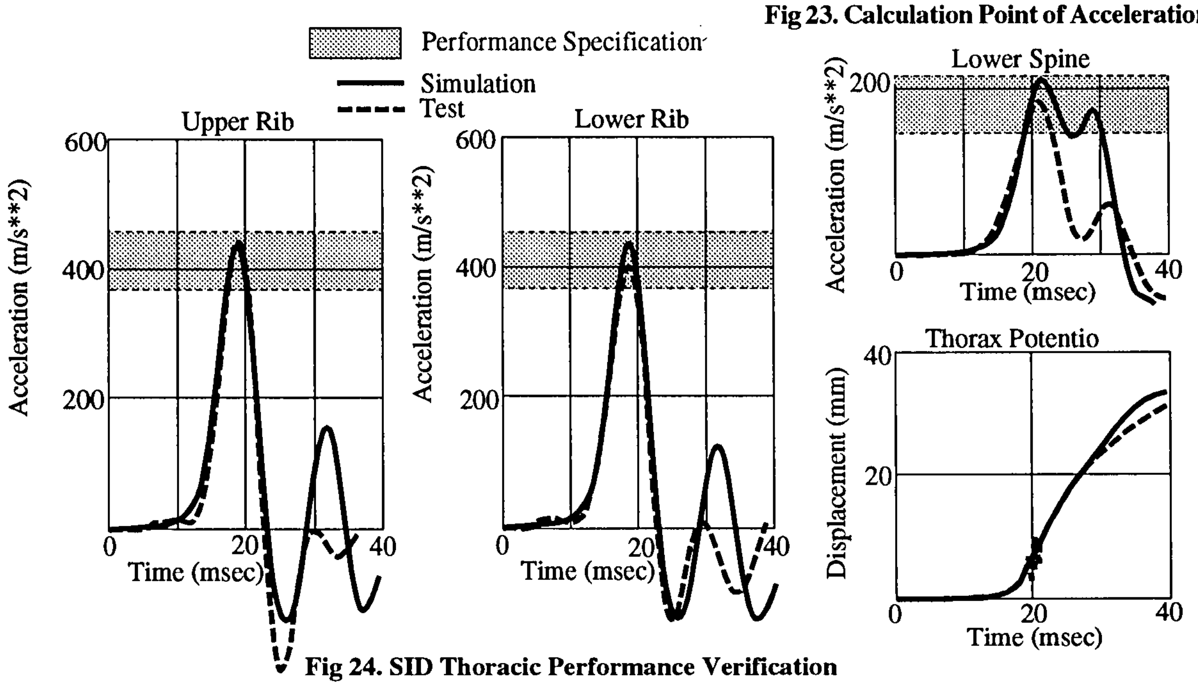


Fig 24. SID Thoracic Performance Verification

Figure 25 shows the pelvic impact test configuration and SID response at 20 ms after impact. The acceleration at the pelvis need to have responses within the following ranges:

Pelvis (Impact-direction)40-60 g

Figure 26 shows that the pelvic flesh is crushed to material bottoming between impactor and femur bone. The comparison between simulation and experimental results is shown in Figure 27 and the SID model satisfies the pelvic impact performance specifications. It can be concluded that very good correlation is achieved for the peak values and the timing of pelvic accelerations.

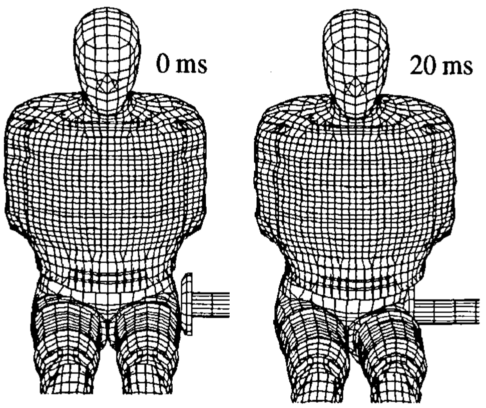


Fig 25. Pelvic Behavior

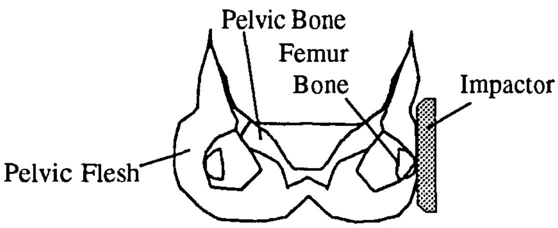


Fig 26. Sectional View during Pelvic Impact

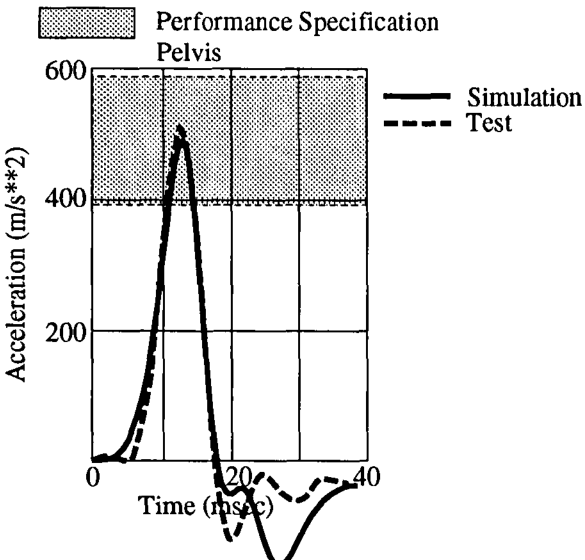


Fig 27. SID Pelvic Performance Verification

<u>(5) SID Complete Model Validation by the Padded Surface Impactor</u>

Before carrying out a parametric investigation on the thorax, padded surface impactor tests were conducted as shown in Figure 28. In this configuration, the interaction between dummy and vehicle side structures, such as side door, was approximated. The size of chest, pelvis and thigh padding was respectively 270*100mm, about 180~300*250 mm and 150*150mm. All padding thickness is 200 mm. The same characteristics were used for the thigh padding and the pelvic padding. The Impact speed was 6 m/s and the impactor mass including the padding was 565 Kg. As shown in Figure 28, the SID was on a rigid seat with a torso angle 25 degrees.

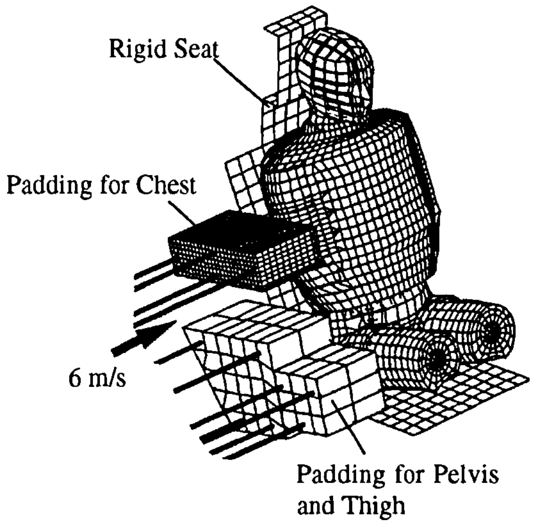


Fig 28. Padded Surface Impact Configuration

In such impact configuration, it is very important to represent the volumetric strain-rate effect of the padding. In the numerical impact simulations, foam material models must be calibrated against experimental results obtained with approximately the same impact velocity as the test on the complete model. The available material models could not provide accurate predictions of the deformation rate effect on the foam materials. A collaboration with Engineering Systems International (ESI) aimed at the development of new material model including the strain rate-dependency effect on foam materials based on experimental results. Though it is generally very difficult to conduct tests on foam materials under constant strain-rate condition during impact, many impact drop tests for various foam materials were carried out as shown in Figure 29.

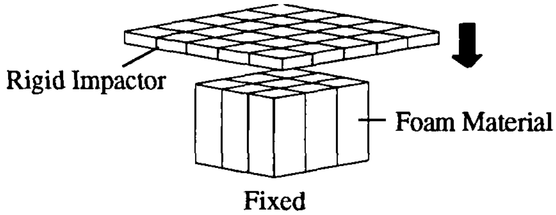


Fig 29. Drop simulation of Foam Material

Impact velocities varied from 3 to 6 m/s. Material models were calibrated by simulating the drop tests under the same conditions. The prediction of the strain rate effect up to a certain level is shown in Figures 30 to 33 below.

Figure 30 shows the force-displacement curve under the test with an impactor mass of 10 kg on the open-cell foam type used for the chest padding. Each graph shows a double line for the static test, a broken line for the dynamic test and a solid line for the simulation result. Due to the strain rate effect, the padding shows approximately two times the force at the same strain. Figure 31 shows the force-displacement curve under the test with an impactor mass of 30 kg on the closed cell type foam type used for the pelvic and thigh padding. Due to the strain rate effect, the padding has different volumetric strain-rate effect. In the case of the open-cell type, it seems that the pressure in the air trapped inside the foam is essential.

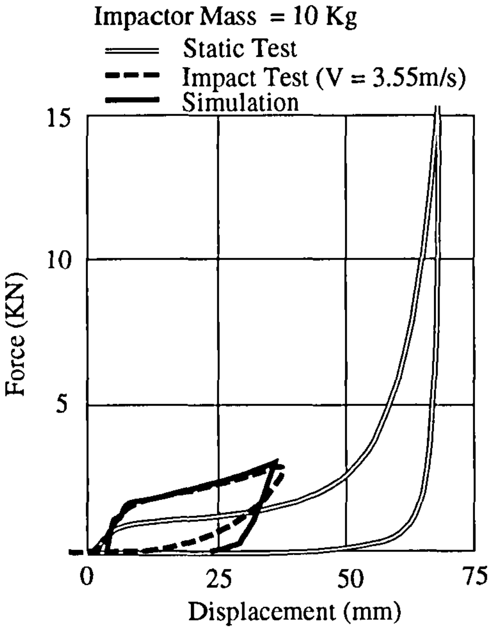


Fig 30. Padding Characteristics for Thorax

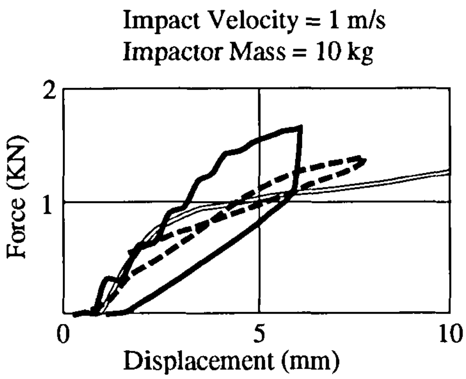


Fig 32. Padding Characteristics for Thorax

On the other hand, in the case of the closed-cell type foam, strain rate effect of the polymer skeleton itself seems to play an important role. Figure 32 and 33 also show the force-displacement of the same foam materials in the case of different impact velocities and impactor masses. In the case of a lower impact velocity, the pressure in the air inside the open-cell foam seems to have little influence because the air flows out slowly under the compression.
Therefore, the pressure inside cells may be overestimated for the lower velocity range. In the case of the closed-cell type, both has a clear yielding point as shown in Figures 31 and 33. It seems that the strength of polymer skeleton is bigger than the pressure inside the closed-cell. The strain rate effect seems to be predictable to some extent in wider generality. Strain rate dependency function are not yet used for a number of SID foam materials. Mostly because impact tests of the regular-size foam samples such as arm foam, pelvic foam, etc. could not be carried out. When foam is compressed up to its bottoming, a modeling of the failure phenomenon of the material might rove necessary in the near future.

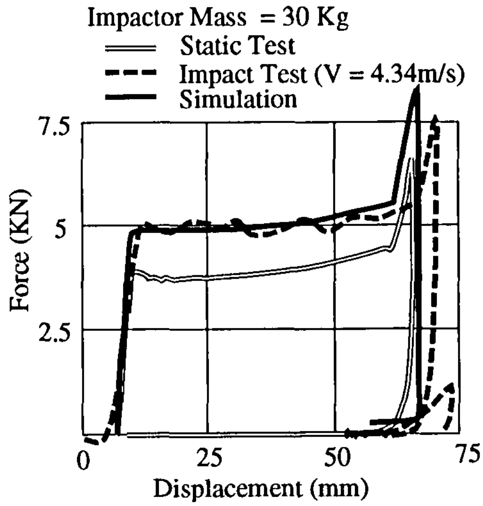


Fig 31. Padding Characteristics for Pelvis & Thigh

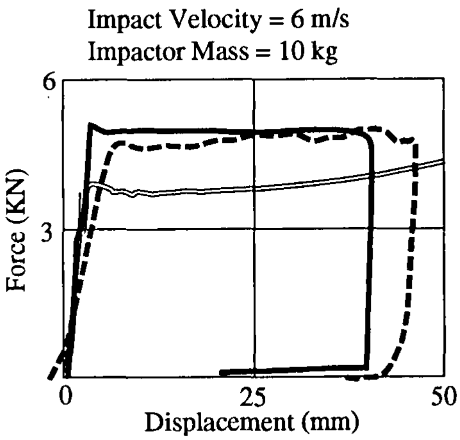


Fig 33. Padding Characteristics for Thorax

The comparison between simulation and experimental results for the padded surface impactor is shown in Figure 34 with a good correlation, because we can find out that the rib response has a wavy mode with two principal peaks in the acceleration-time history. This is a typical response of the real dummy in full vehicle side impact.

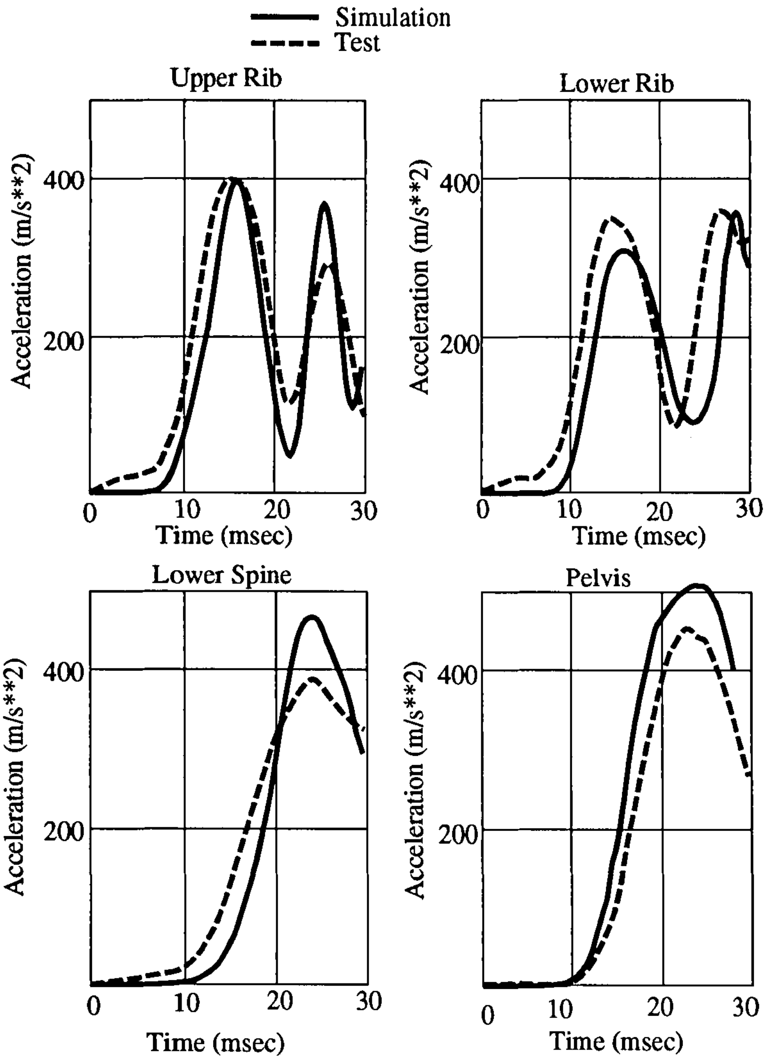


Fig 34. Comparison between Test and Simulation

Figure 35 shows the relation between the thorax acceleration and the force transmitted to the spine. The force on the rib hinge is bigger than the force on the thorax damper. It is also demonstrated by the experimental spine load of the thorax impact test in [Ref. 6], as shown in Figure 36 and 37. That is similar to the FMVSS 214 verification thorax impact test, but with an impact velocity of 10 m/s. The abbreviated notation such as for example R-S-S load means the load transmitted from the rib to the spine through the rib hinge.

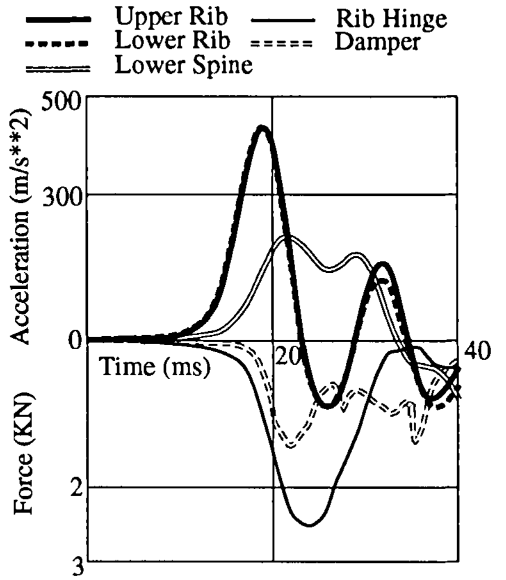


Fig 35. Transmitted Force of Spine by simulation

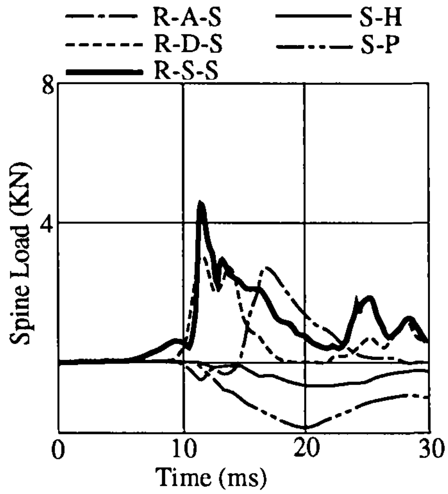


Fig 36. Spine Load by the thorax impact test

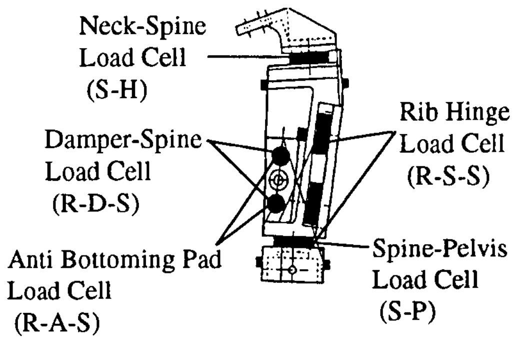


Fig 37. Load-Cell for Spine

(6) Thoracic Impact Parametric Study

The parametric investigations were carried out for the padded surface impact condition. The study focused on the thoracic padding characteristics. The SID response to the parameter variation has been evaluated with the TTI(d). For the assessment of the padding characteristics, the stress-volumetric strain curve of the thoracic padding used are those shown in Figure 38. Three levels of the padding crush strength were considered as shown by the solid lines of Figure 38. The double-line on the graph of Figure 38 depicts the static data. The density of the foam material was modified with the crush strength. So, the pressure by the air trapped inside the foam produced different responses, but no considerations about this influence was analyzed. The Young's Modulus of the three padding characteristics are 1.97, 8.33 and 15.2 N/mm**2, respectively. The padding thickness was fixed at 200 mm and a bottomig effect of the padding was represented by a tangent modulus of 12.4 N/mm**2. And the tangent modulus of the padding crush zone is 0.129 N/mm**2. The bottoming effect was set at approximately 73% of the strain.
Other parameters, i.e., the characteristics of the pelvic and thigh padding used, impact speed (6 m/s) and impactor mass (565 Kg) have been kept constant throughout the parametric studies. Figure 39 shows the example of the simulation results in the case of the Young's Modulus = 8.33 N/mm**2. In the these parametric studies, the pelvic peak acceleration was almost constant. The less the thoracic padding crush strength was, the more the lower spine peak acceleration was controlled under the pelvic responses..

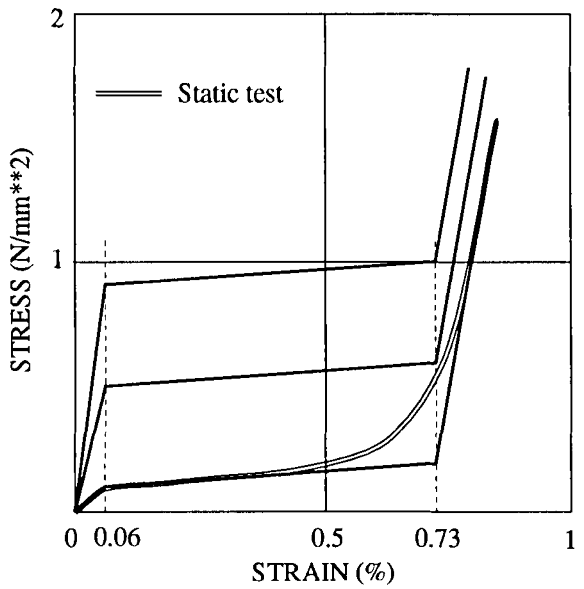


Fig 38. Stress-Strain Curve for Thoracic Padding

Figure 40 shows the normalized TTI(d) based on the thoracic injury criterion of 85 g for 4 door sedan. The relation between the thoracic padding crush strength and TTI(d) is non-linear as shown in Figure 40. For the optimal padding crush strength of the lower thoracic injury, more numerical investigations in the wide range of impact velocity and mass should be carried out with the padding variations including the characteristics and the bottoming effect of the padding.

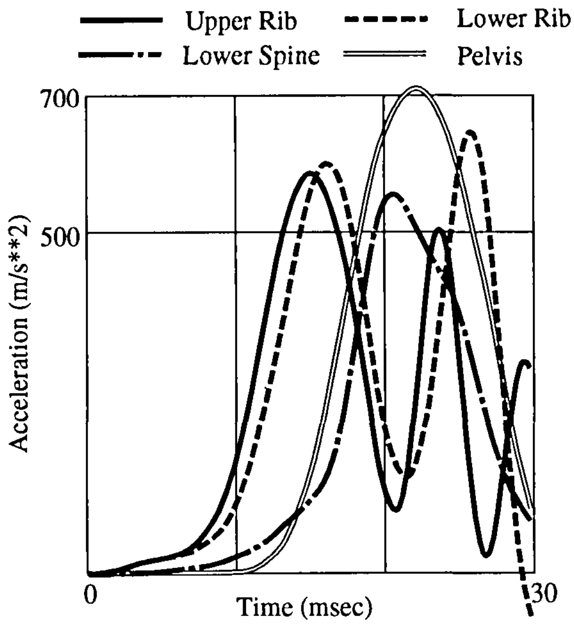


Fig 39. Example of Simulation Results
*(Young's Modulus=8.33 N/mm**2)*

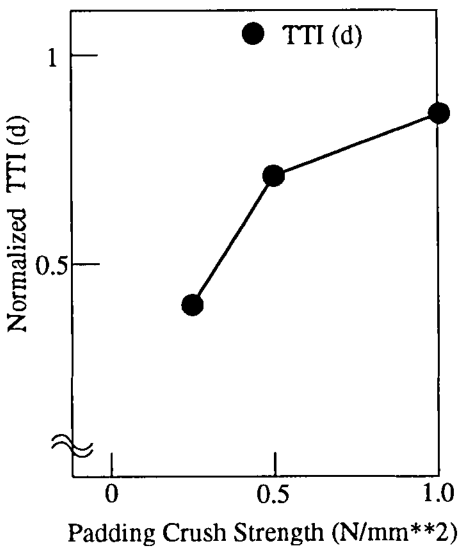


Fig 40. TTI vs Padding Crush Strength

CONCLUSION

The SID model was verified through dynamic and pseudo-static tests of the individual dummy segments, the sub-assemblies impact tests and FMVSS 214 thoracic and pelvic verification impact tests.
An accurate and complete model of the SID satisfying the thoracic and pelvic performance specifications has been developed.

1) The SID model has been developed by means of the following;
  - modeling of real 3 D SID geometries such as rib, pelvic bone, femur bone, thigh bone; and
  - modeling of characteristics of the highly compressible low density foams materials such as arm-foam, rib wrap assembly, pelvic foam, abdominal inserts, etc;
  - modeling approach based on real rib-hinge response and the mechanism of occurrence of damper damping force
2) The volumetric strain rate effect of the foam materials was validated with new material model of the crash analysis product. With the currently available material laws, mechanical behavior is derived from uniaxial data only, which can lead to severe errors in load prediction under biaxial or triaxial loading. A more powerful material law will increase the reliability and predictive capability of this part of the model in the near future.
3) Using this SID model, a parametric studies has been carried out to relate the tendency of the thoracic injury severity to the simulated struck vehicle side stiffness.

Finally, a better understanding of the injury mechanism can be expected from impact simulation analyses using the SID model presented here and efforts will be continued for further improvements of this SID model. The understanding of the dummy brought on by analyses of the type suggested here should lead to increased understanding of the use of these instruments to measure injury criteria. Combined with improved measurements of human impact response and injury, these analyses should lead to improved utilization of existing dummies and new dummy types.

ACKNOWLEDGMENTS

The authors thank Engineering Systems International for providing the coding developments of new material constitutive law for the SID model. The contributions of Toyota System Research INC., Cybernet Systems Co., LTD and CRAY RESEARCH JAPAN LTD. to this project are also appreciated.

REFERENCES

(1) S. W. Kirkpatrick, B. S. Holmes, W. T. Hollowell, H. C. Gabler, " Finite Element Modeling of the Side Impact Dummy (SID) " SAE Paper No. 930104

(2) D. E. Midoun, E. Abramoski, M. K. Rao, R. Kalidindi, " Development of a Finite Element Based Model of the Side Impact Dummy " SAE Paper No. 930444

(3) J. Hasegawa, T. Fukatsu, T. Katsumata, " Side Impact Simulation Analysis Using an Improved Occupant Model " The 12th Int'l Technical Conf. On Experimental Safety Vehicles

(4) PAM-CRASH User's Manuals, Version 12.0, ESI, France

(5) Side Impact Dummy (SID) User's Manuals, NHTSA, July 1990

(6) K. Taneda, Y. Tamura, " Study on the shock propagation characteristics at the chest of the US-SID dummy " JSAE Proceeding, 1994-5

(7) H. Maki, A. Osakada, " Plastic Foam Handbook ", Nikkan Kohgyo Shinbunsha ,1973

(8) ACE Industrial Shock Absorber Catalogue, 1992-9

Table 1. Mass Properties of the SID model

SID Part	Mass (kg)
Head	4.57
Neck	1.37
Lumbar Spine Assembly	1.31
Total Ribs	2.02
Rib Wrap Assembly	0.66
Front Rib Ballast	2.56
2 Side Rib Ballast	1.09 each
4 Corner Rib Ballast	1.08 each
Thoracic Spine Assembly (with damper)	10.89
Jacket	5.59
Abdominal Insert	1.34
Ilium with Lower Spine Adaptor	5.74
Pelvis Skin / Foam	5.01
2 Femur Assemblies	6.42 each
2 Upper Legs, Foam and Skin	1.26 each
2 Knees	1.40 each

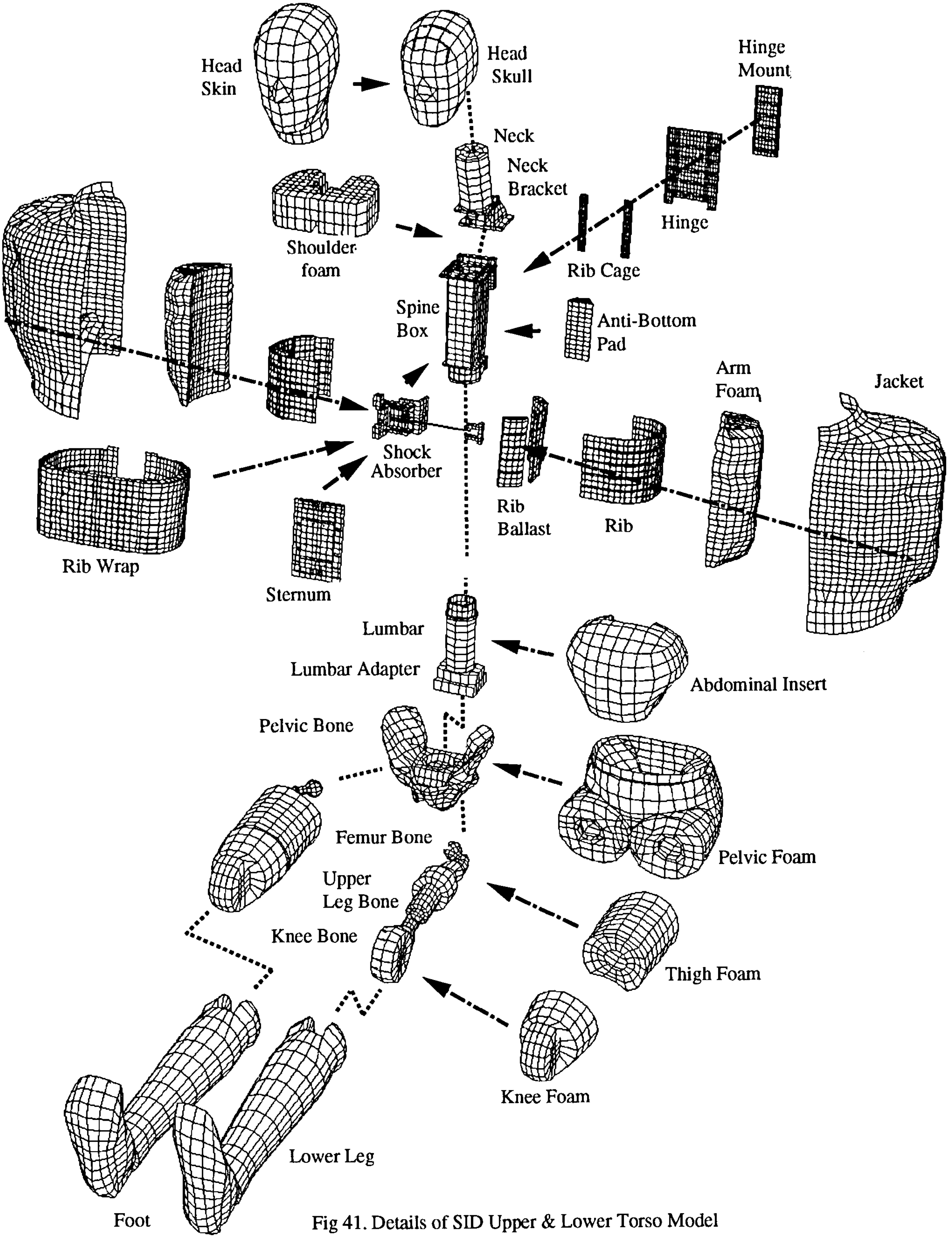


Fig 41. Details of SID Upper & Lower Torso Model

Development of Finite Element Side Impact Dummy (SID) Model Based on Dynamic Behavior

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Paper Number 96-S8-O-13

ABSTRACT

More stringent safety regulations worldwide have made the development of a vehicle a difficult process. The automotive industry has been working hard over the last decade in searching for new methods and processes to develop new models to meet the market timing and the safety standard requirements. Consequently, various computer aided engineering tools have been integrated in the design process of vehicles and have become key elements in reducing the development cycle time and number of prototypes required for new vehicles. In side-crash phenomena, finite element modeling becomes essential in investigating the occupant's post-impact dynamic behaviors after contact with the door panels. Almost all automobile companies in developed countries are actively involved in developing dummy models to meet the stipulated occupant safety regulations. These models are either developed in-house or in collaboration with national organizations in the respective countries. In the present model, based on the initial NHTSA model, a number of modifications are made based on combined simulation and experimental verifications of dynamic and pseudo-static characteristics of different materials such as foam, rubber, composites and so forth. This report illustrates how the modified material and structural modeling improve the accuracy of the overall dynamic behavior. Numerical simulation is validated by a number of experiments which also include oblique impacts to incorporate the effects on the rear dummy on driver's side.

INTRODUCTION

Two major side impact test procedures are used for verifying the ability of a vehicle to protect the occupants in a side impact. The proposed European Experimental Vehicles Committee (EEVC) procedure is based on the injury level of a driver measured with the EUROSID-I dummy, and in the National Highway Traffic Safety Administration (NHTSA) procedure, the injury level of the driver and that of the rear driver's side passenger are measured using two SID dummies. As full-scale side impact tests are expensive and time-consuming, they are supplemented with sled tests and extensive computer simulations. There are two types of simulations that can be carried out. In the early stages of development, a simple mass-spring type of simulation is extremely useful, and once the design has been developed, it is possible to create a more detailed model for obtaining more accurate prediction results. Numerical simulation techniques are commonly used to assess the crash performance of automobiles and guide their design during the development stage. Mathematical models of vehicle structures, restraint systems, and dummies are developed and verified under different conditions to ensure effective usage. Several analytical dummy models have been developed to simulate occupant responses in front and side impact phenomena. These models can be broadly classified in two groups (i) rigid bodies of ellipsoids connected by springs i.e. mass spring models and (ii) elastic/plastic bodies of proper material strength and geometrical shapes connected together with or without springs and joints. Although rigid mass-spring dynamic models are widely used in frontal crash simulations because of ease of modeling, they can only capture 2-D gross movements. Such ellipsoidal models fail to represent the actual 3-D contact mechanism which is extremely important in side impact phenomena. However, the recent versions of some of the numerical codes, such as MADYMO, CAL3D and DYNAMAN, based on mass-spring model, added some extra features to simulate and visualize more realistic crash phenomena. On the other hand, the later approach based on finite element technique is capable of predicting very complex and complicated responses such as deformation, contact force and so forth which can hardly be measured experimentally.

This paper describes the development and validation of SID model. The model is verified in standard thorax impact tests at three different rigid impactor speeds of 4.3, 6.7 and 9.0 m/sec. The explicit finite element code RADIOSS is used for the present numerical solution and some of the basic modifications that are incorporated to improve the degree of accuracy of the model are described.

FINITE ELEMENT MODEL

The overall geometry of the different parts of the present model are shown in Figure 1. It is originally based on NHTSA model and it consists of solid brick, thin shell and 6 degrees of freedom spring elements. The spine box, head and the lower portion of legs below the hip are treated as rigid bodies to reduce the computational time by eliminating the extra degrees of freedom for unimportant part. However, care has to be taken to represent the 3D shape of each of them for fairly accurate estimation of contact forces. To improve the degree of accuracy of the present model, the following items have been checked and modified to obtain good correlation between the experimental and numerical results.

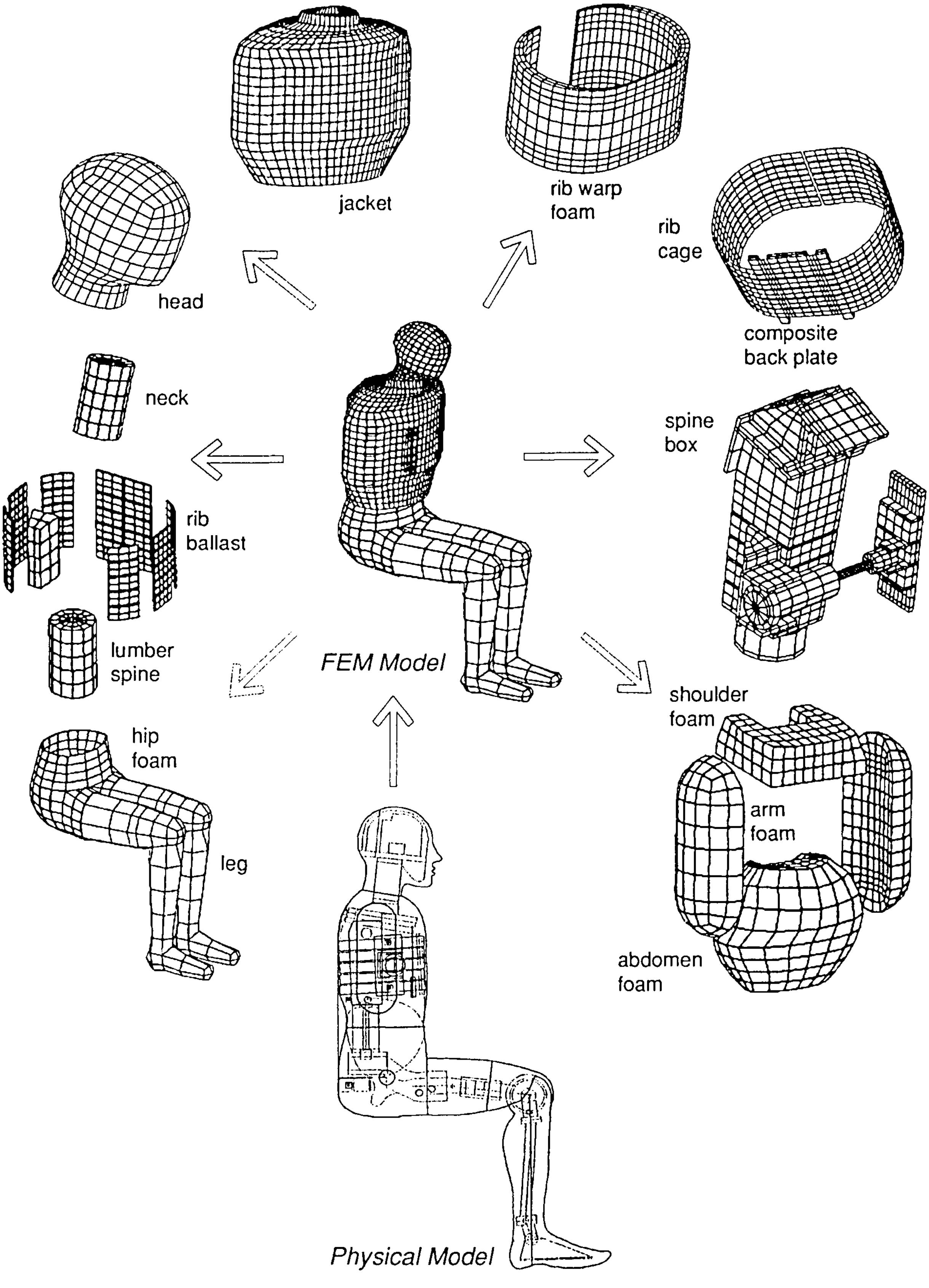


Figure 1 Different Parts of SID Dummy Model.

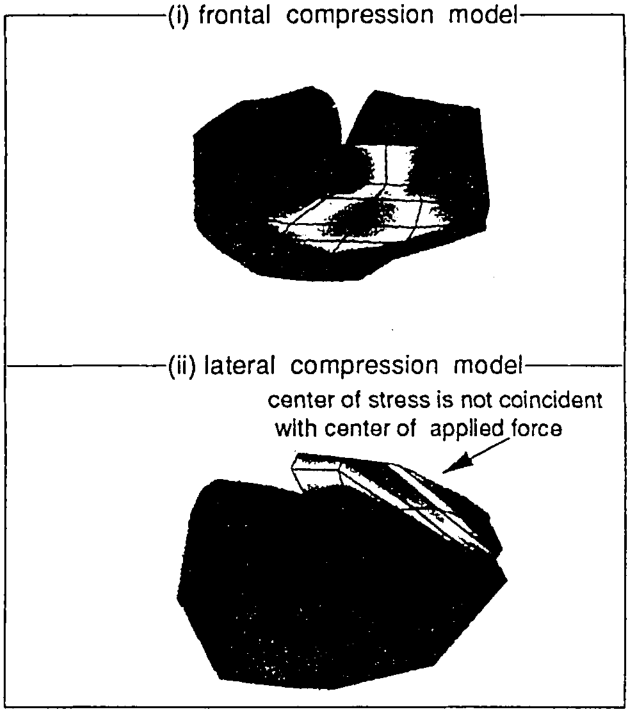


Figure 3a Deformation Mode of Abdomen near Impactor Displacement of 60mm (A-A).

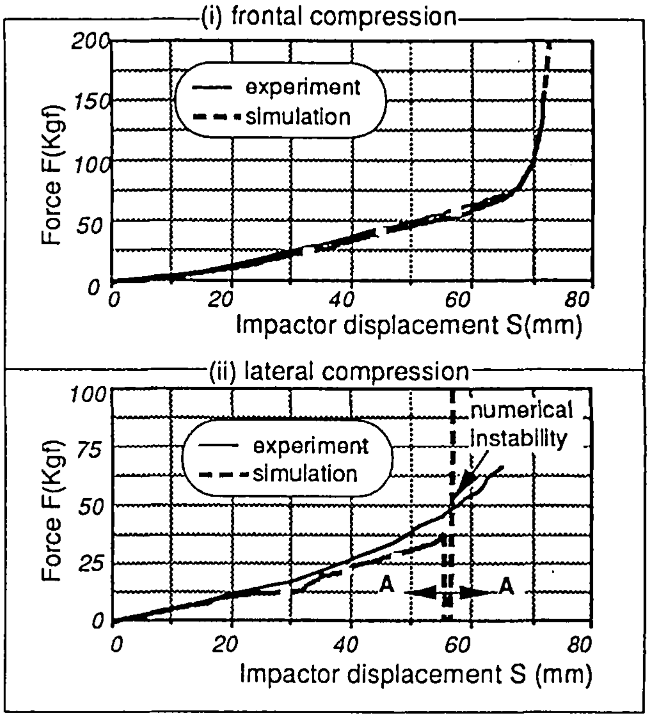


Figure 3b Comparison of Force - Displacement Identification (Simulation Results for Lateral Compression are based on Material Identification of Frontal Compression.

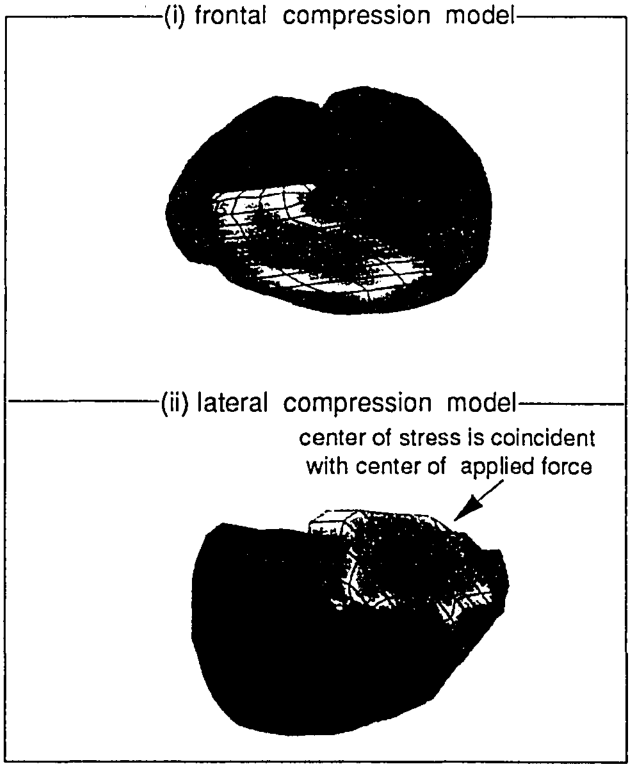


Figure 3c Deformation Mode of Abdomen near Impactor Displacement of 60mm (A-A).

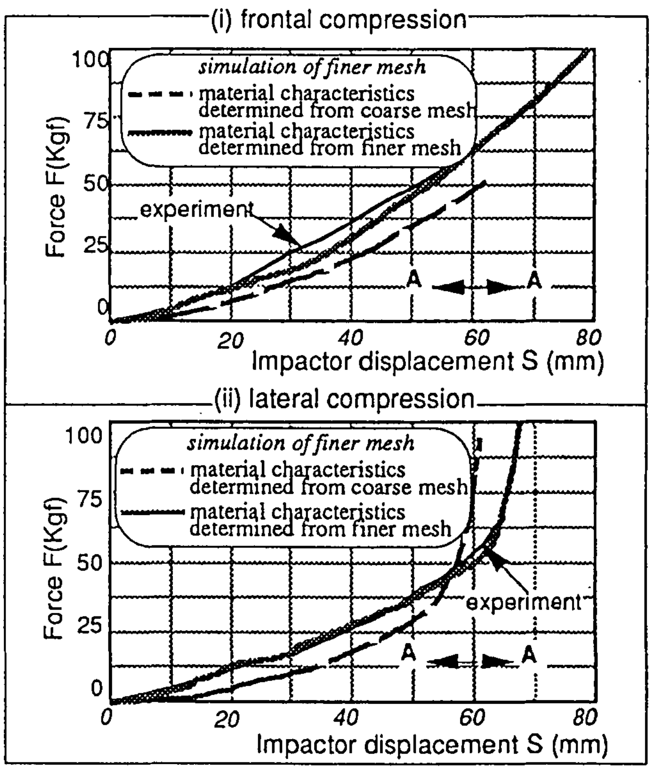


Figure 3d Compassion of Force-Displacement Identification (Simulation Results for Lateral Compression are Based on Material Identification of Frontal Compression.

Figure 3 Material Characteristics Identification of Abdomen Foam Based on Experiment.

(1) Weight Distribution

The mass distribution of individual items plays an important role in predicting the overall movement and the dynamic response of the dummy. Each individual item was measured and properly incorporated in the model by adjusting the density and its distribution.

(2) Nonlinear Characteristics of Hip and Abdomen Foam

The hip and abdomen part of the original NHTSA model have been replaced with sophisticated porous foam material. However, to set the parameters of the material requires accurate tests of a sample of the same material. Further, it is to be noted that these parts are made air tight with a thin outer polyvinyl rubber completely covering the inside core foam (Figure 2a). Since the in-plane membrane stiffness of the outer rubber skin and the shape of the individual item greatly affect the overall equivalent compression characteristics of the item, a simple material test of the inner core material will not truly represent the actual compression behavior. Hence, as an alternative, direct compression tests of the relevant part, say the hip of the SID dummy, were conducted to find the equivalent stress-strain relationship from the measured force-displacement characteristic under different compression conditions, the details of which are described below. The unknown material characteristics of the nonlinear foam material were determined by an iterative optimization procedure based on the concept of pseudo-static simulation performed by explicit nonlinear finite element codes. Figures 2b-2c show the process of evaluating the equivalent volumetric stress-strain characteristics. For example, in the case of the abdomen, it was initially tested in a frontal compression and the material characteristics are identified by the above mentioned procedure. Using these material characteristics, it is then tested in a lateral compression to check the validity of the previous stress-strain characteristics. Figures 3a and 3b show the effect of the initial coarse mesh on material identification. Numerical instability is observed at large strain. It is also observed that the center of maximum pressure is not coincident to the center of applied force of the impactor due to the discontinuity of stress at the corner. Based on these observations, the original coarse finite element mesh was remeshed again with more of elements at the corner. The consequent results of the modified mesh are shown in Figures 3c and 3d. The stress contour and numerical compression characteristics show no sign of numerical instability at large strain. Comparison of the test and the final simulated results indicates fairly accurate identification of the nonlinear characteristics of the foam material.

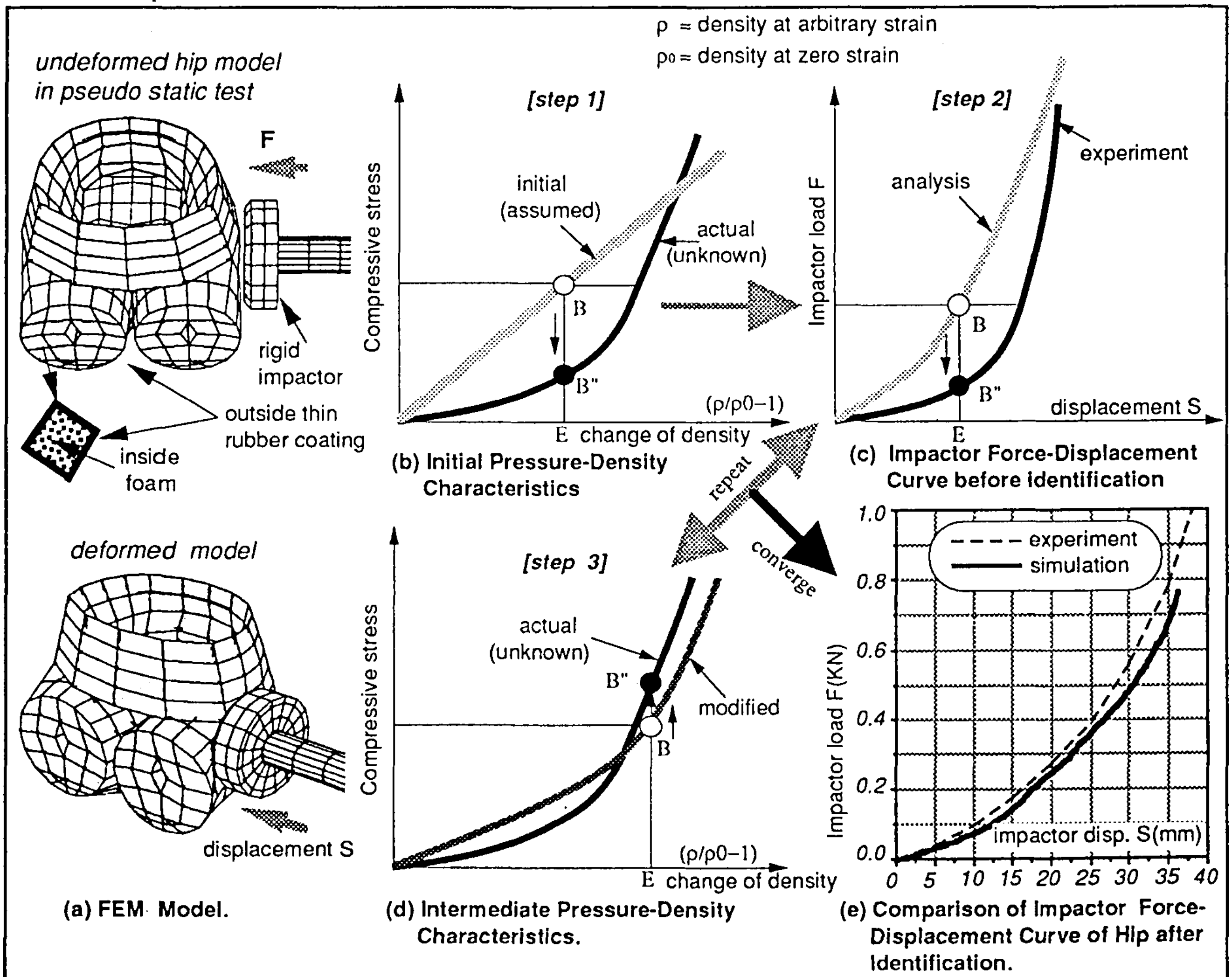


Figure 2. Material Characteristics Identification of Hip Foam Based on Experiment.

(3) Nonlinear Dynamic and Static Characteristics of Lumber Spine and Neck

Since the lumber spine and the neck connect the hip and the head of the dummy with the spine box at the bottom and at the top of the spine, both of them behave as cantilever beams. With the help of simple beam theory, the equivalent Young's modulus was determined from bending test results. Verification of the present assumption was performed by numerical simulation of the bending test as shown in Figures 4a and 4b. It shows good agreement of static bending characteristics. The pendulum test of the same lumber spine was carried out to determine the dynamic characteristics. A number of tests were conducted by varying the height Ha and mass Ma of the impactor head. Using the above-mentioned equivalent Young's modulus as determined from the static test, the first peak values of the experiment and the numerical simulation were of same order of magnitude (Figure 5b). However, the simple linear solid model failed to identify the non-linear damping characteristics. Hence, a non-linear solid material modeling (material 35 of RADIOSS) was chosen. It is based on the Maxwell-Kelvin-Voigt viscosity model as shown in Figure 5c. Compared with the linear model, the nonlinear model, as shown in Figure 5d, has better accuracy. The robustness of the present model was verified in 6 different pendulum tests.

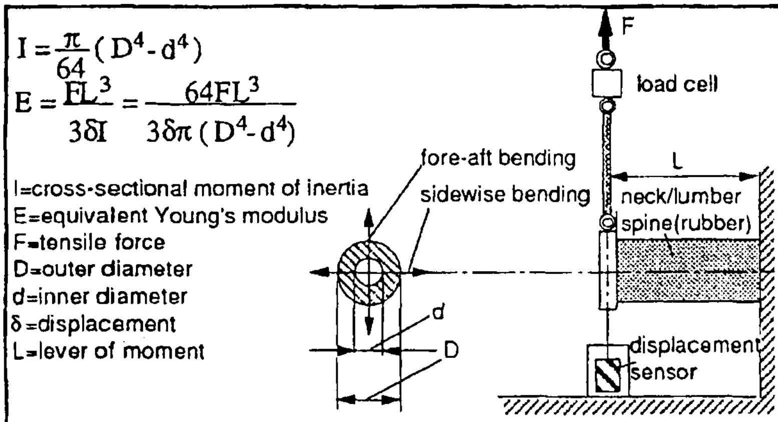


Figure 4a Experimental Set-up.

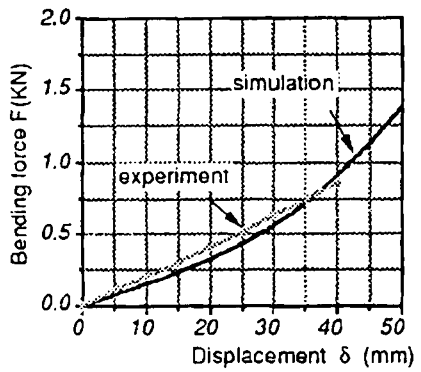


Figure 4b Identification of Bending Characteristics of Neck/Lumber Spine

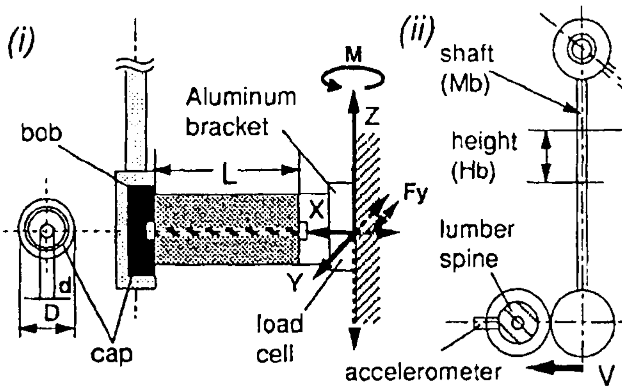


Figure 5a Experimental Set-up of Pendulum Test.

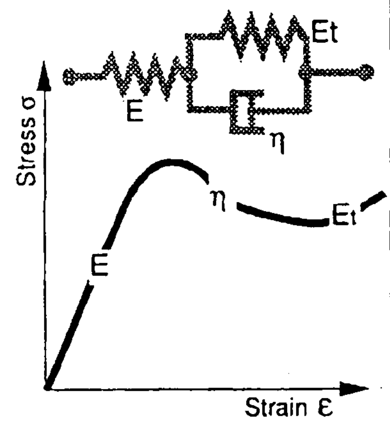


Figure 5c Nonlinear Damping Material Model.

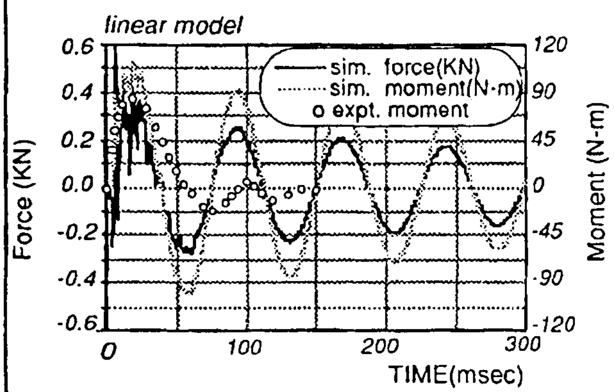


Figure 5b Dynamic Response of Linear Model.

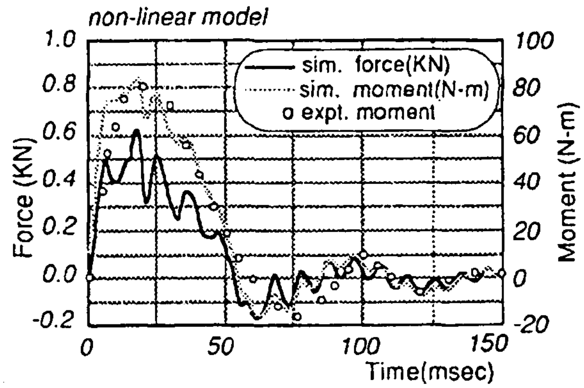


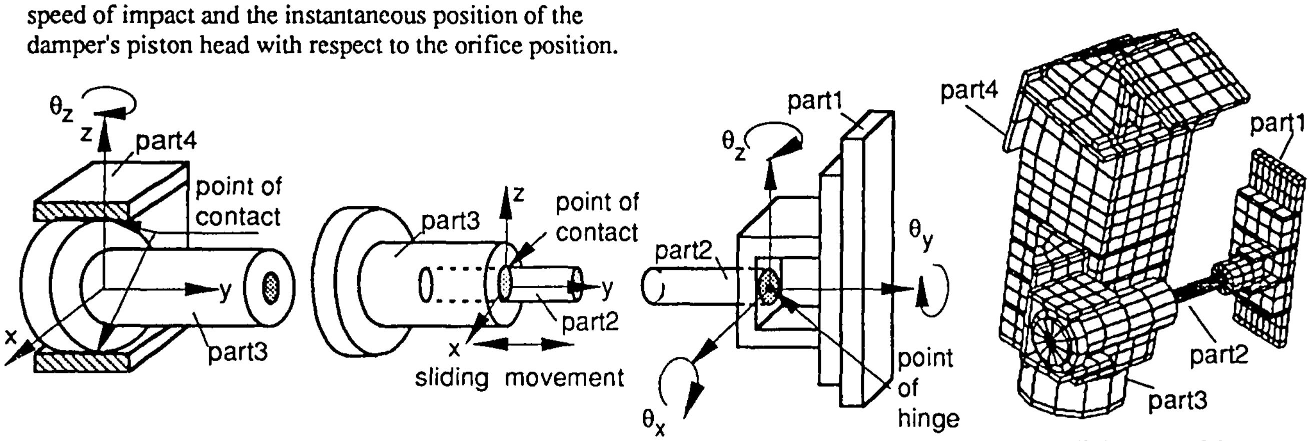
Figure 5d Dynamic Response of Nonlinear Model.

(4) Link Mechanism of Thorax

A 3-link revolute joint, cylindrical joint and spherical joint mechanism (Figure 6a) inside the thorax control the deformation of the chest. Accurate modeling of this part is extremely important to simulate the exact deformation characteristics such as the damper stroke length for an oblique impact as seen in rear dummy which are normally hit by the rear door panel at an angle in a side crash. The spring-damper module inside has the following characteristics:

- The spring is initially compressed by 23 mm.
- It has four orifices.
- The hydraulic damping characteristics change with the speed of impact and the instantaneous position of the damper's piston head with respect to the orifice position.

A sectional view of the damper as shown in Figure 5a is modeled with four discrete dampers instead of one. The typical damping force is shown in Figure 5b which clearly shows the change in reaction force as the piston head passes through each orifice. The present mathematical model was validated by experiment as shown in Figure 5c. The experimental time history of the damper force strongly supports the present concept. It clearly indicates that the damping force not only increases with the increasing speed of impact but also depends on the position of the piston head which determines the number of available orifices.



(i) revolute joint (ii) cylindrical joint (iii) spherical joint (iv) assembly

Figure 6a Link Mechanism of Thorax.

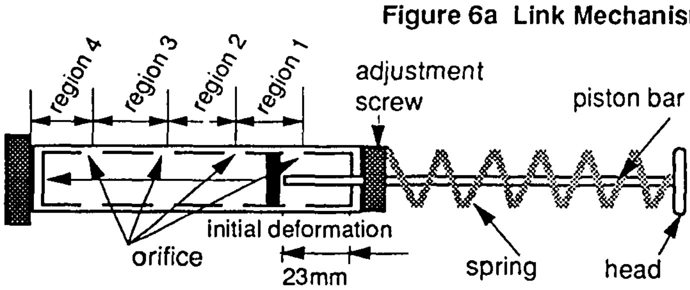


Figure 6b Assembly of Spring and Damper in Cylindrical Joint.

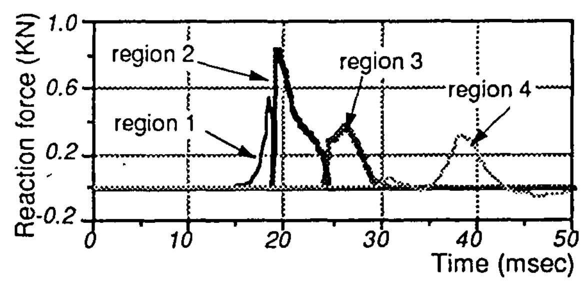


Figure 6c Discrete Damper Force of Simulation.

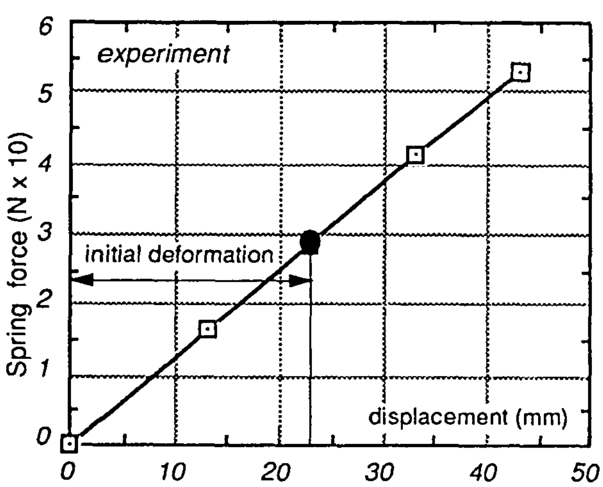


Figure 6d Stiffness of Spring.

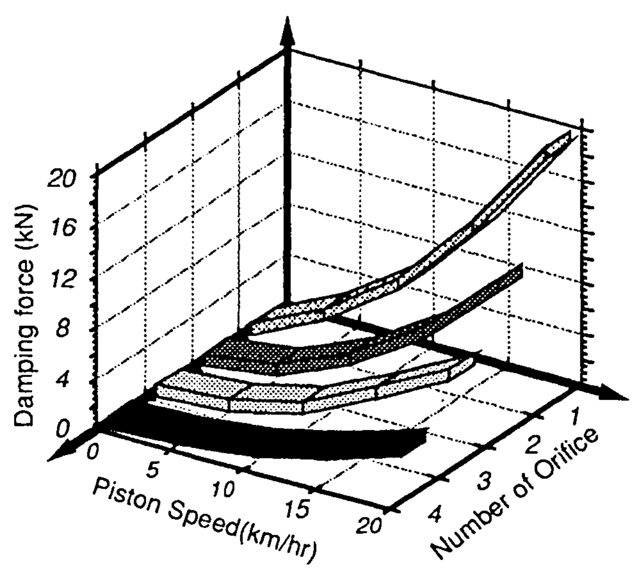


Figure 6e Damping Characteristics (experiment).

(5) Orthotropic Characteristics of the Composite Spine Back Plate

The composite spine back plate connection between the spine box and the rib cage undergoes large rotational deformation at impact speeds of 30 km/hr and above. The solid elements of the original NHTSA model fail to simulate such large deformations due to their limited bending characteristics. They have been replaced by a 3-layer composite shell elements not only to enhance the bending characteristics but also to incorporate the damping characteristics of the material. The in-plane damping of the individual layers away from the neutral axis contributes to the damping in the bending mode. The basic concept is explained in Figures 4a and 4b, showing the differences between the original and the modified structure.

(6) Bottoming of Arm Foam

The arms consist of very soft foam trapped between the rib cage and the rubber jacket. The original rubber material modeling of the arm foam of NHTSA the model has been replaced by porous foam material. The deformation shape of the rubber arm hardly shows any bottoming effect. By only varying the Poisson ratio of rubber, it would be difficult to adjust the time lag of transfer of force from the impactor to the rib cage. The speed of transfer of force changes the initial gradient of the rib acceleration curve for different impact speeds of impact. A higher Poisson ratio, η=0.48 and above, sometimes enhances the appearance of hour glass modes during large deformation. Figure 8 shows the comparison of the deformation shapes of the original and the modified foam model. Identification of the bottoming effect is extremely important for predicting the exact timing of peak values after the onset of impact.

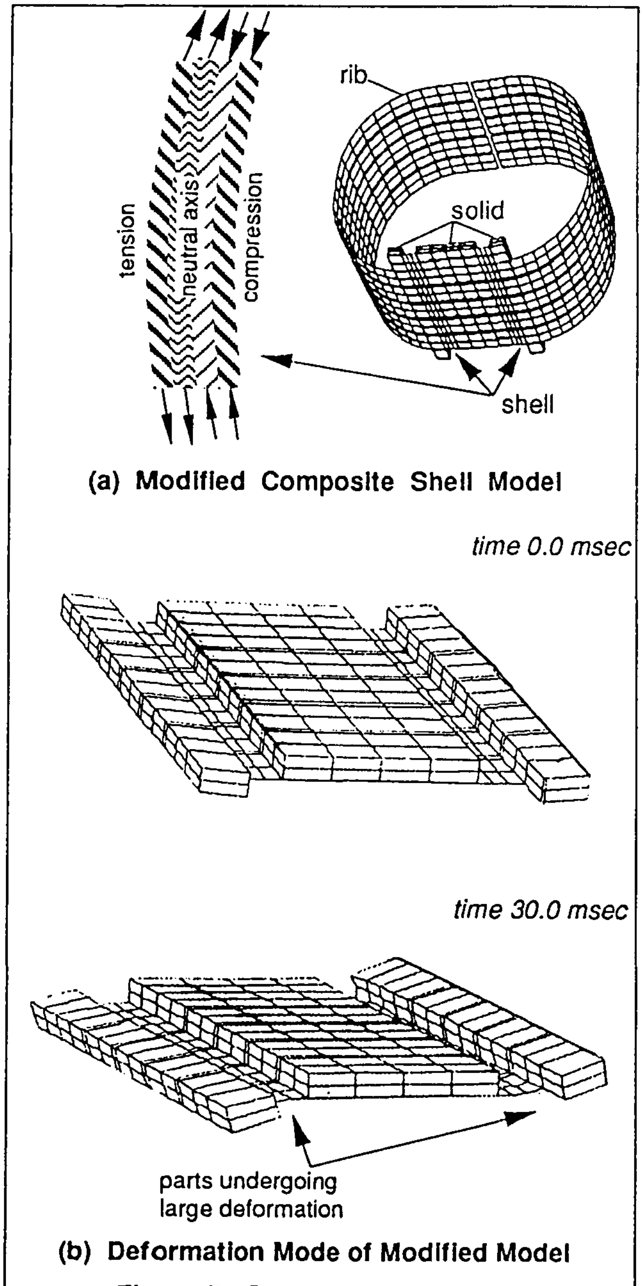


Figure 7 Composite Back Plate

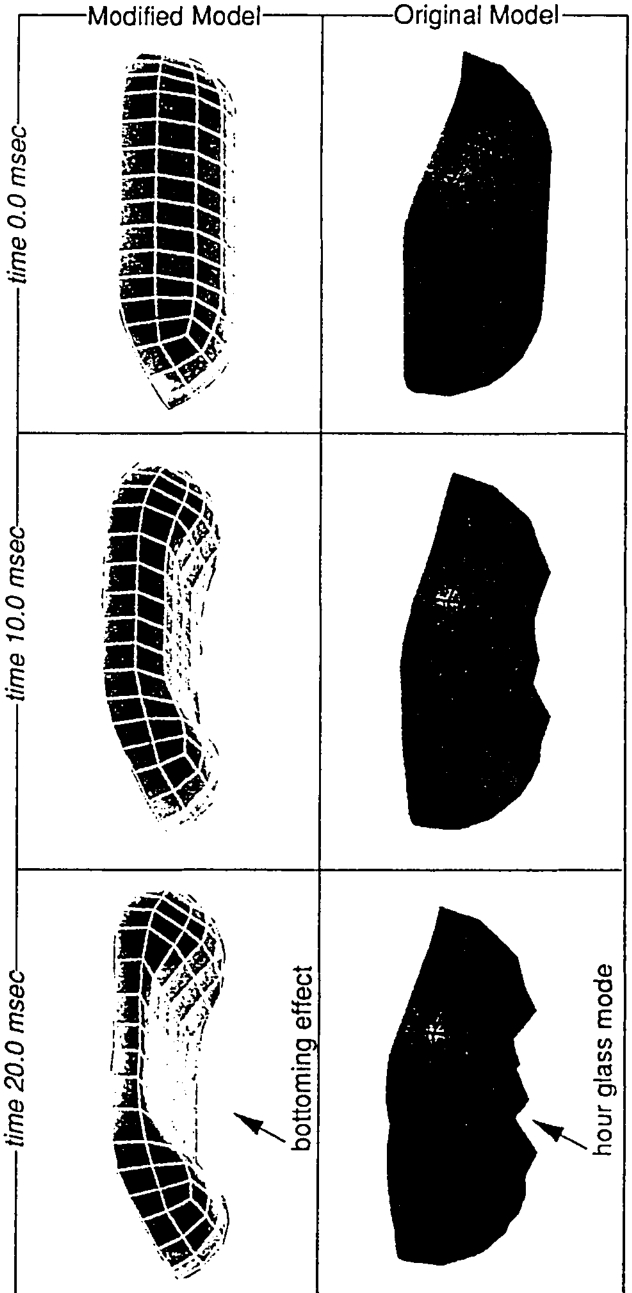


Figure 8 Deformation Mode of Arm Foam.

SIMULATION MODEL VALIDATION

Figure 9 shows the test configuration for a thorax impact with a standard 24 kg rigid impactor. Typical simulation and experimental results are shown in Figures 10-14. Figure10a shows the effect of the link mechanism of the chest on the oblique impact response. Without a detailed link mechanism, as illustrated in Figure10b, the predicted response of lateral acceleration will be very low compared to experimental values. Based on these simulations and experimental verifications, it following conclusions can be drawn.

- Comparing the peak values of rib acceleration, impactor deceleration, chest damper displacement for different velocities and angles of impact, a satisfactory level of correlation can be achieved with the present FEM model for studying the dynamic behavior of the SID dummy.
- The above results indicate that proper modifications of material modeling lead to better representation of bottoming of the arm pad, rib deformation mechanism and lumber spine bending characteristics, all of which are very important in analyzing the distribution of the load path from the rib to the spine.
- Oblique impacts were studied to investigate the effect of impact angle of the door on the injury level of the rear occupant on the driver's side. For the SID dummy with thorax impact, maximum rib acceleration occurs around a 20 degree angle of impact.

DISCUSSION

This paper has focused on the basic dynamic behavior of SID dummy and the corresponding modification of FEM modeling. Only the response of the upper portion of the dummy was tested and verified in rigid impact tests. Further study is under way to verify the cross correlation of the hip-thorax input-output relation and vice-versa. A series of multiple sled tests with simultaneous impact at the chest, abdomen and hip is also under investigation to further improve the degree of accuracy of the dynamic response of the present FEM model.

REFERENCE

1. Radioss User's Manual, Version 2.3, MECALOG, France.

2. Side Impact Dummy User's Manual, NHTSA, July 1990.

3. Midoun, D., Abramoski, E., Rao, M., and Kalidindi, R., *Development of a Finite Element Based Model of the Side Impact Dummy*, SAE International Congress and Exposition, SAE Paper No. 930444 , March 1993.

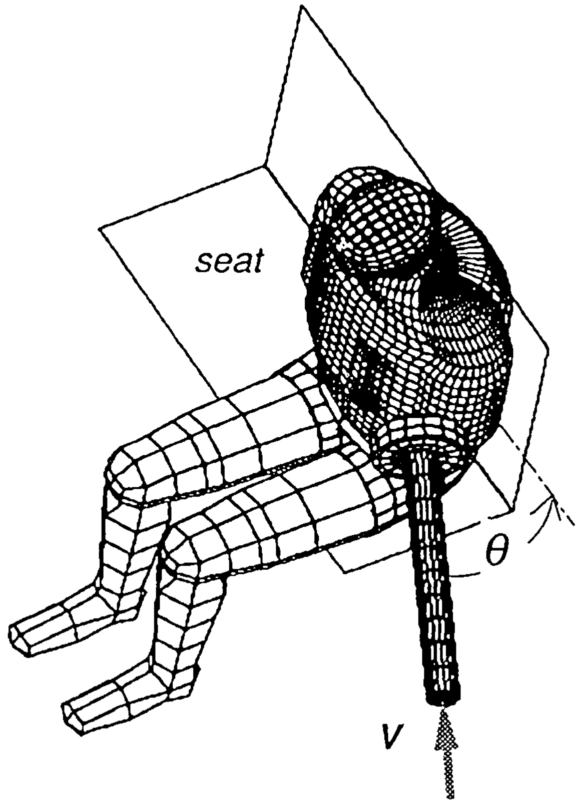


Figure 9 Oblique Impact.

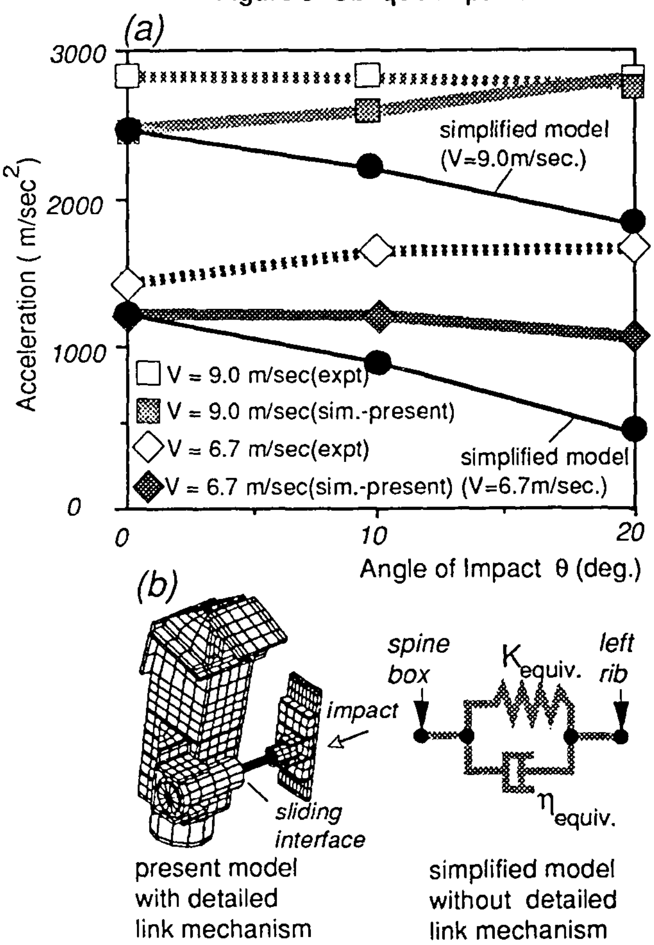


Figure 10 (a) Variation in Upper Rib Acceleration (b) Comparison of Simplified and Detailed Present Chest Model.

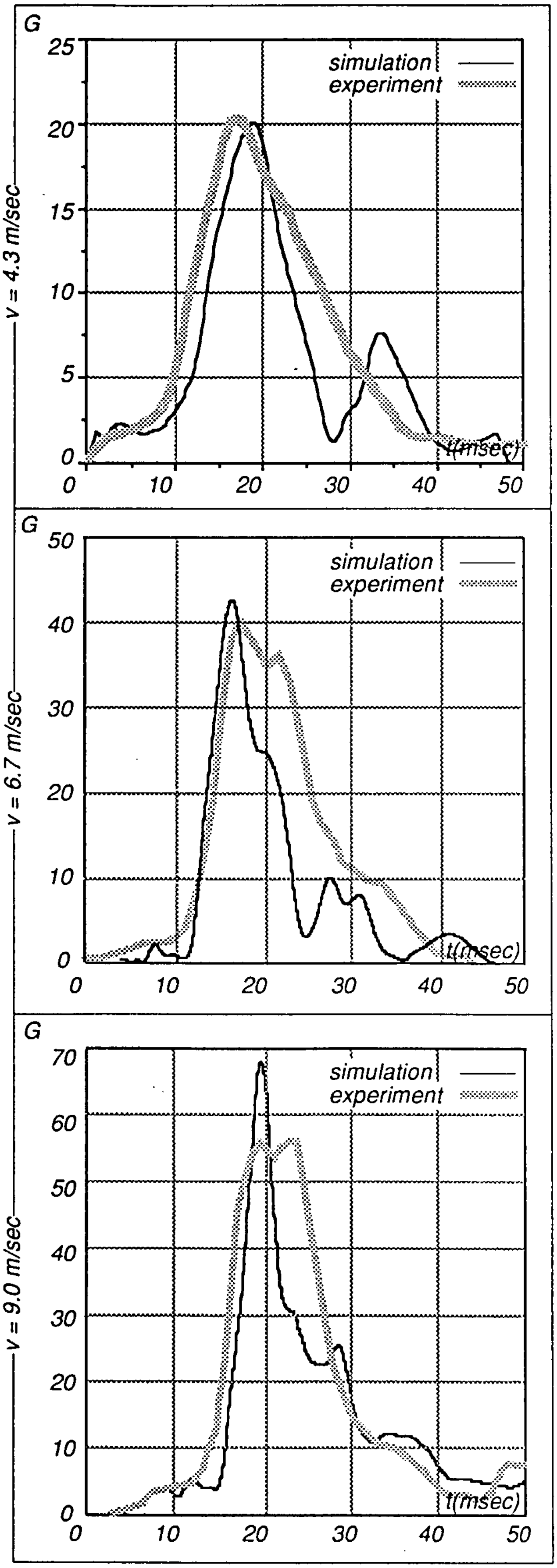


Figure 11 Impactor Deceleration (Impact Velocity V=4.3, 6.7, 9.0 m/sec and Angle of Impact θ=0 deg.).

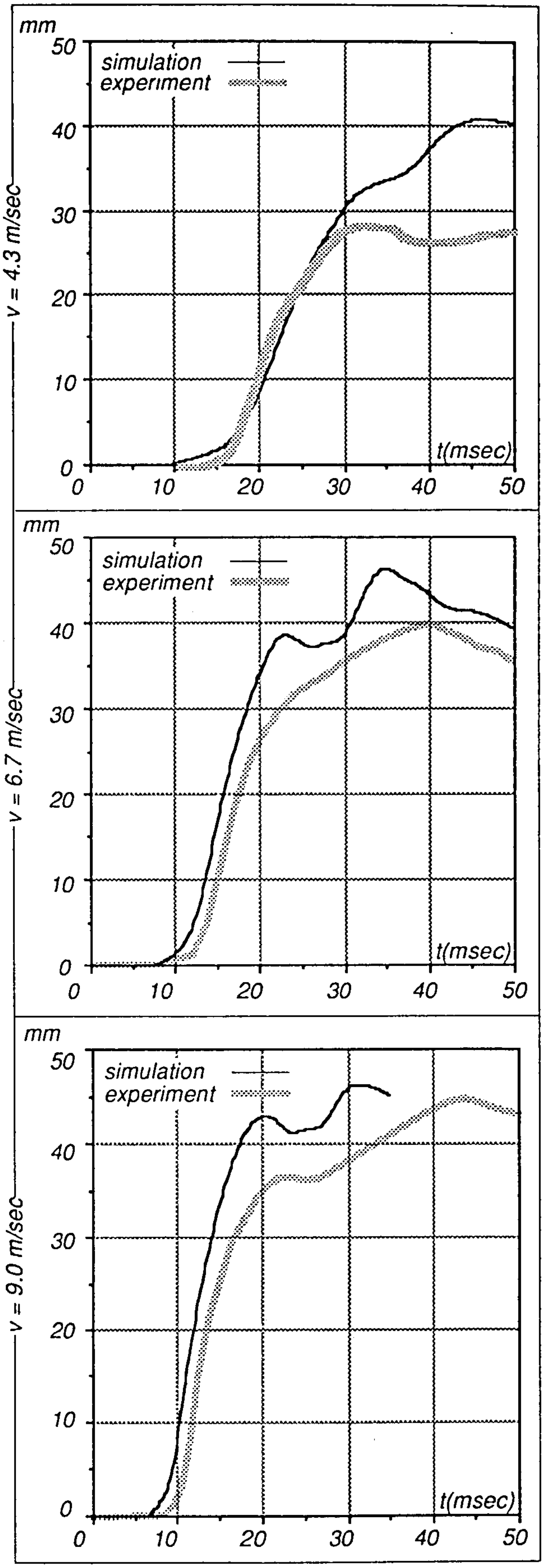


Figure 12 Chest Displacement (Impact Velocity V=4.3, 6.7, 9.0 m/sec and Angle of Impact θ=0 deg.).

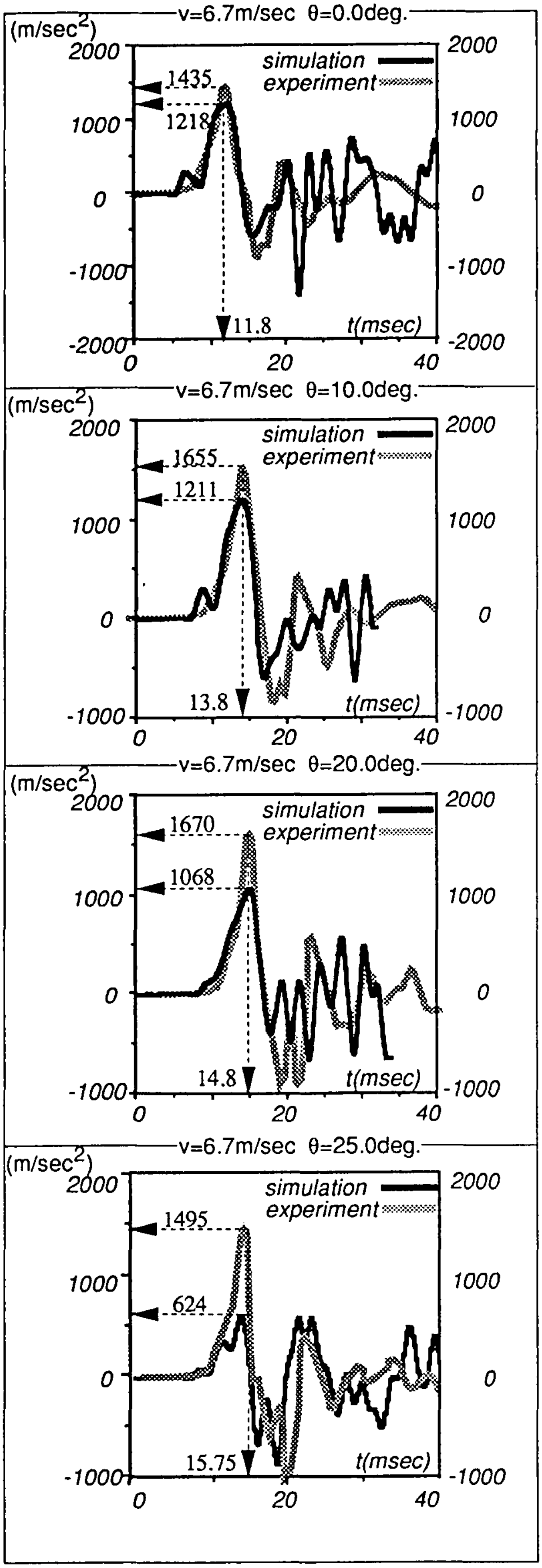


Figure 13 Upper Rib Acceleration with Impact Velocity V=6.7m/sec and Angle of Impact θ=0, 10 20, 25 deg.

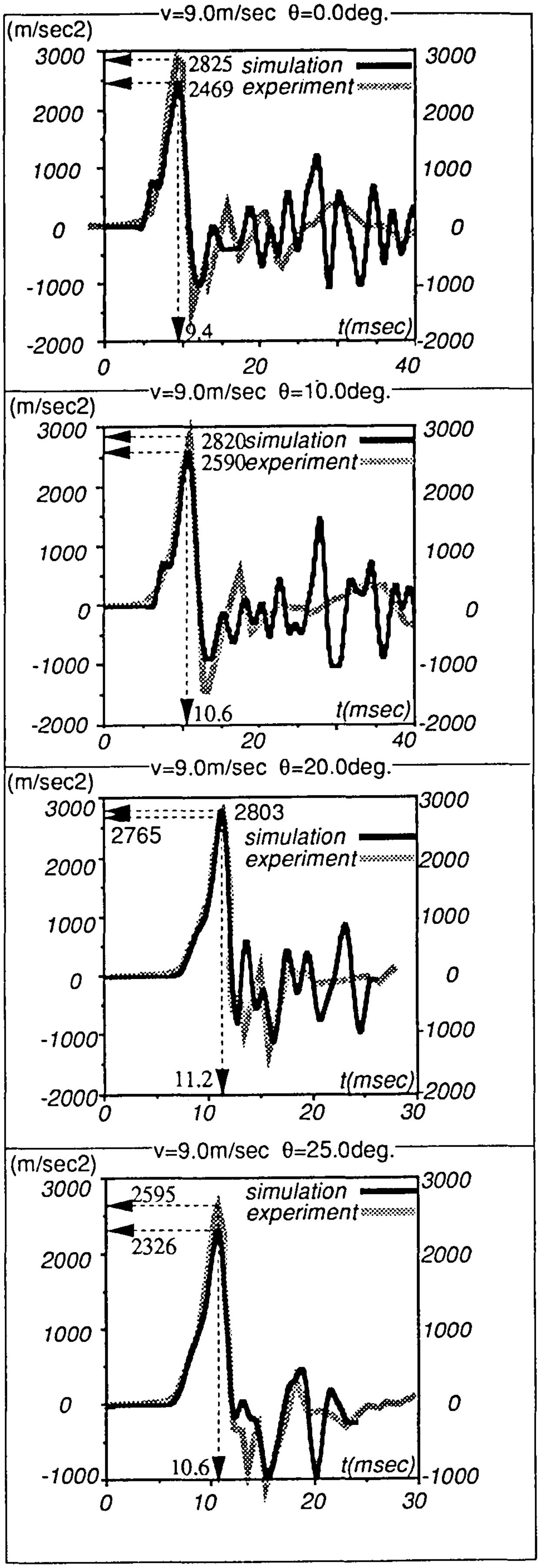


Figure 14 Upper Rib Acceleration with Impact Velocity V=9.0m/sec and Angle of Impact θ=0, 10, 20, 25 deg.

FOAM MATERIAL CALIBRATION FOR THE SIDE IMPACT SIMULATION

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Paper Number 96-S8-W-15

ABSTRACT

Foam materials such as polyurethane play a very important role as the shock and energy absorbing material in many kinds of impacts. Recent interest in the numerical analysis of side impact testing coupled with the strong influence that such a material has on the impact response have made the determination of an appropriate material model for foam mandatory. The typical mechanical behavior of this material, which should be considered in the numerical material model, can be described as highly non-linear and strain-rate dependent with high energy dissipation characteristics. Such a material also possesses hysteresis characteristics in cyclic loading. Specific numerical parameters are required in order to adequately model the behavior of this material. The main objective of this paper is to present a method of determining these parameters and provide some examples of the effect of these parameters in the chest impact simulation of the DOT-SID dummy.

INTRODUCTION

There exist many kinds of foam material. However, these foam materials are known to possess typical mechanical behavior. A typical stress-strain relationship in compression is illustrated in figure 1. An initial linear elastic relationship is typical in the low strain region at the beginning of compression loading. Microscopically this is due to the bending deformation of the edge or the extension of the face in the cellular structure. This linear elastic stage is followed by a plateau, which corresponds to the collapse of the cells. After all cells have collapsed, they come in contact with one another causing a sudden increase in stress as can be observed in the compressive stress-strain relationship. This is typical of the final stage of compression loading with the foam's

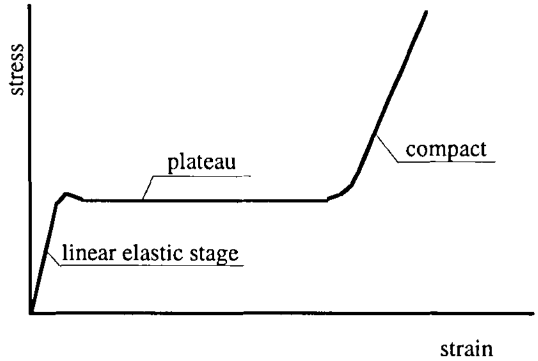


Figure 1. Typical stress-strain relationship in compression.

final modulus dependent on the base material. In tension, the foam also possess an initial linear elastic region. As with compression, this is due to extension and bending of the cells. Following this linear characteristics, some typical behavior dependent on the base material can be observed as shown in figure 2 [1].

In addition to the typical behavior of foam which has been described above, one should also consider other characteristics for the material model. They are strain rate dependency, energy dissipation and the hysteresis characteristics under cyclic loading.

Firstly, a brief description of the general formulation for the foam material in PAM_CRASH will be given. Secondly, some results of the numerical studies obtained by varying selected material parameters will be provided.

The main objective of this paper is to describe the calibration method of the material properties used to parametrize the behavior of the PAM_CRASH foam material model. This meant finding out the level of importance of those properties on the impact simulation of any model including this foam material by analyzing the sensitivity of the foam material behavior under uniaxial compression loading due to each of those parameters. Once this was done,

the side impact simulations of the DOT-SID dummy could be reliably carried out with the assoiciated side impact foam incorporated into the impactor.

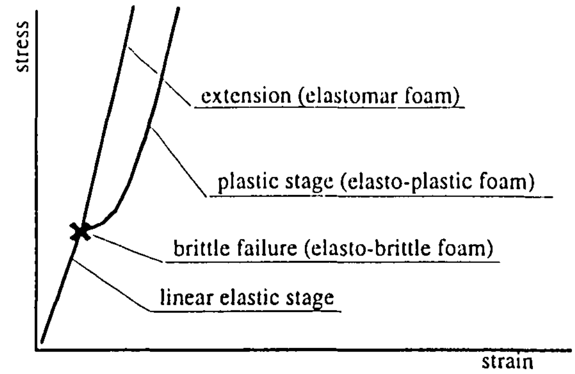


Figure 2. Typical stress-strain relationship in tension.

NUMERICAL MODEL

Basic Functions [2]

Loading -The numerical model used in this study was a non-linear elastic model of crushable foam. Some assumptions were made such as
(i) the behavior under uniaxial loading was assumed not to significantly coupled in the transverse directions,
(ii) in tension the material behaved like a linear material model with a Young modulus and a tensile cut-off stress value. Normally this limit is the tearing point of the material.

The model is based on principle stretches and stresses defined via polar decomposition. The stress-strain curve was obtained by experiments and it related nominal stresses to engineering strains, both expressed in the principal system of axes.The experimentally obtained stress-strain curve was given by pairs of stress and strain as a piecewise linear function as shown in figure 3.

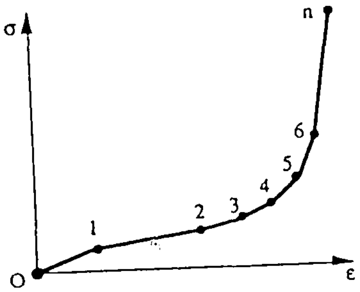


Figure 3. Given stress-strain curve of the numerical model

Unloading - The hysteresis behavior involved the definition of an unloading curve for unloading from each arbitrary point R of the given loading curve (see figure 4). The determining parameter was the hysteresis loss or energy dissipation factor α, which defined the energy loss ratio between the loading and unloading cases. In the stress-strain diagram, the unloading curve defined an area between the ε-axis that was $(1-\alpha)$ times the area between the loading curve and the ε-axis. The area between the loading and the unloading curve (shaded in figure 4) was α times the area under the loading curve, αE_L.

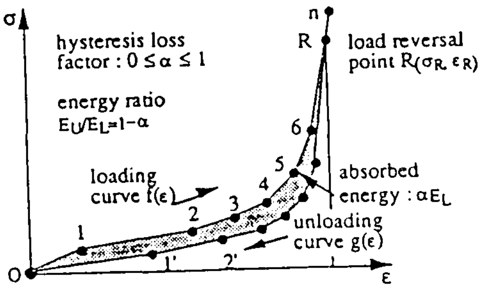


Figure 4. Hysteresis behavior

Strain Rate Behavior - In the numerical model, two types of analytical strain laws are available, the Cowper-Symonds and Jonson-Cook formulations. In this study, Cowper- Symonds law was selected. Its analytical form is shown below.

$$\sigma(\varepsilon\dot{\varepsilon}) = \sigma_0(\varepsilon)\left[1+(\dot{\varepsilon}/D)^{1/p}\right] \qquad (1.)$$

Numerical Model Example

A simple model of a foam block being compressed by two rigid walls (one stationary and one moving) was used to simulate the compression tests. Two sets of dynamic simulations were carried out to test the performance of the PAM_CRASH numerical model for an Elastic Foam with Hysteresis. The first set involved three simulations using differing rigid wall loading rates to test the material model's behavior under different strain rates (figure 5). Secondly, three simulations were carried out using different energy dissipation factors to show the material model's ability to simulate hysteresis(figure 6). The stress-strain relationship of the foam was input into the material model using data from results of a quasi-static compression test of the foam. Eight stress and

strain data points were used to define the contour of this curve.

Strain-rate variation -Strain rate had very little effect in the initial stages of loading (0-5%) as all three curves overlap one another. However, with the increase in stiffness seen during the plateau region of loading, it is evident that strain rate was a significant factor during these later stages. The loading curve at strain-rate of 0.1/s was almost the same as the quasi-static test case as strain-rate 0.1/s is in fact very close to quasi-static.

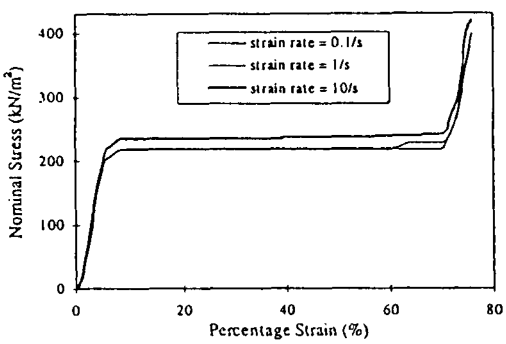


Figure 5. Strain-rate variation

Variation of energy dissipation (α) -The hysteresis of the foam material can be defined in two ways, either through a quadratic unloading curve or a linear piecewise unloading curve. As there existed distinct linear loading phases during the compression of the foam, the linear piecewise unloading option was selected Three energy dissipation factors were chosen, α = 0.3, 0.6, and 0.9. These three values were selected to represent a broad hysteresis range in which such materials can possess. The three simulation cases for energy dissipation were executed using the same loading rates so that the effect of α could be illustrated. Because the three simulations have the same strain rates, the curves describing their loading phases are identical. The only differences occur in the unloading phase of the curves. As can be seen in figure 6, the stress resistance in unloading decreases very suddenly when the energy dissipation factor was high (α=0.9). On the other hand, when the energy dissipation factor was low (α=0.3), material resistance was sustained for longer. In theory, if α is 0, the unloading path would be the same as the loading path, and if α is 1.0, resistance would be zero at the onset of unloading. As a rough guide, the area between the loading and unloading curve divided by the area under the loading curve is the energy dissipation factor.

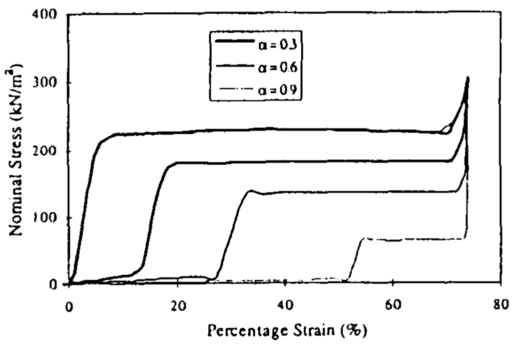


Figure 6. Variation of energy dissipation

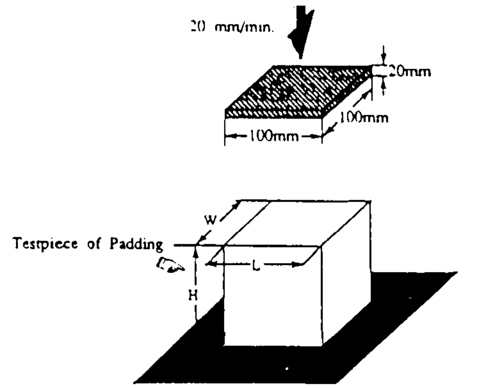
CALIBRATION OF FOAM MATERIAL FOR SIDE-IMPACT PADDING FOAM

Experimental Study [3]

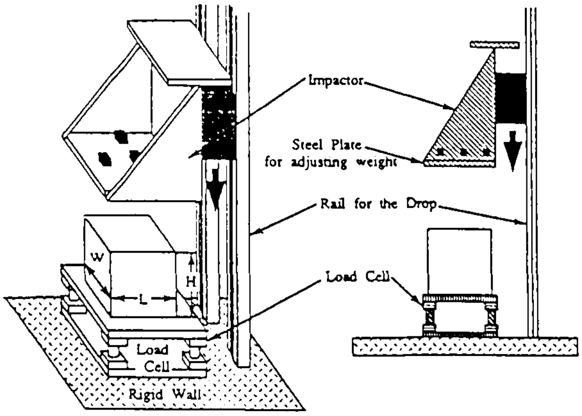
The foam material in this study was a hard urethane which was used for the side-impact padding test. As the side-impact test will be dynamic, the material model should be calibrated not only statically but also dynamically. Figure 7(a) shows the unconfined static test device and the force-displacement relationship obtained from the compression test is shown in figure 8. In the dynamic calibrations tests (see figure 7(b)), a series of impactor drop tests were conducted using varying impactor weights and different impactor drop heights. Some of the results obtained from these tests are illustrated in figure 9.

Calibration

Static Calibration -Firstly, the basic curve of the stress and strain relation was obtained from figure 8. As described in the previous section, the compression response can be specified by a linear piecewise curve constituted by up to sixteen pairs of engineering strain and nominal stress data. These points were selected so as to best represent the experimental curve. The unloading energy α can also be determined by correlating the unloading curve by varying α. The obtained numerical results for the unconfined compression test is shown in figure 10. In tension, the Young's modulus was given the same value as that of the initial Young's modulus in compression. Selection of this value was based on the microscopic point of view.



(a) unconfined uniaxial compression test device



(b) impactor drop test device

Figure 7. Calibration test devices

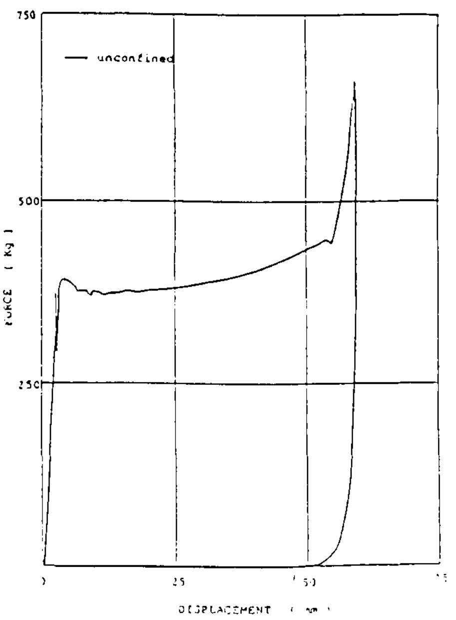


Figure 8. Static compression test result

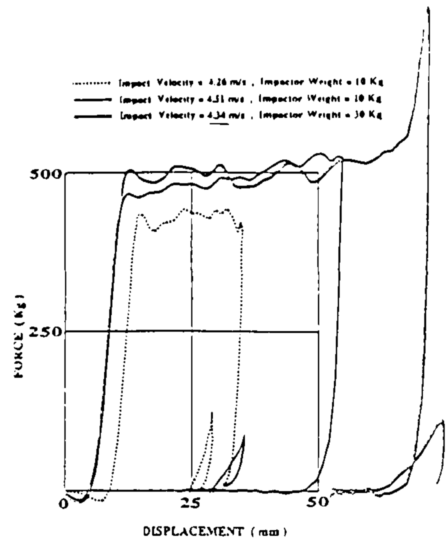


Figure 9. Dynamic test results

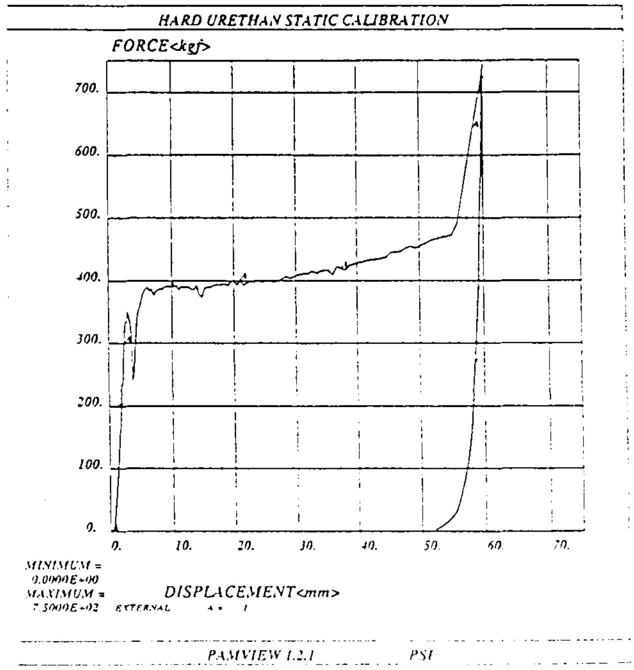


Figure 10. Static compression numerical result

Dynamic Calibration -In addition to the static calibration, the dynamic calibration was carried out in order to determine D and p in the Cooper Symonds' formula for material strain-rate dependency. These parameters can be determined directly if two stress-strain relations for different constant strain rate tests are available as there are two unknown variables. The strain-rate, however, could not be kept constant in the impact drop test conducted in this study. Therefore, a method of

curve fitting would be required. This could be done by simulating the foam impact experiment using various combinations of D and p.

A nonlinear numerical optimization technique was applied in this study in order to determine the value of the parameters appropriate to the 3 different impact configurations tested and shown in figure 9. The general purpose nonlinear optimization code PAM_OPT [4] was used. The optimization problem was defined as follows.

Minimize Objective Function =

$$\sqrt{\sum_{P_i}\left[\frac{F_i^C - F_i^E}{F_i^E}\right]^2} \qquad (2.)$$

subjected

$$F_i^E - 10\% \le F_i^C \le F_i^E + 10\% \qquad (3.)$$

for points P1,P2,P3

$$D_i^E - 10\% \le D_i^C \le D_i^E + 10\% \qquad (4.)$$

for point P3.

Here F and D are the force and the displacement respectively, the superscripts E and C signify the points obtained by the experiment and the calculation. The subscript (i) is the number of points which vary 1 to 9 (3 points in each curve and we have 3 curves dependent on the impact configuration). The position of the points are defined such that the first point was the elastic limit, the third point was the peak point and the second point was the intermediate point between the first and the third point (see figure 11).

The constraints expressed by (3) and (4) were defined to avoid iterating to the local minimum, which was very common in this type of optimization.

The obtained D and p were 193.7and 1.11 respectively and their numerical results, shown in figure 12.

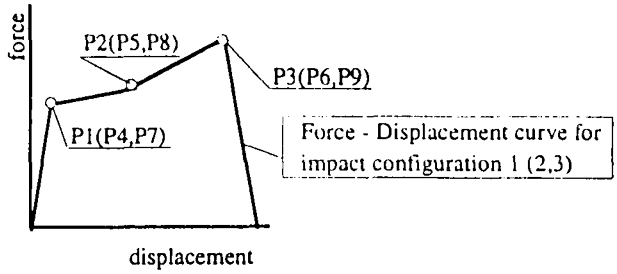


Figure 11. Positioning of the point

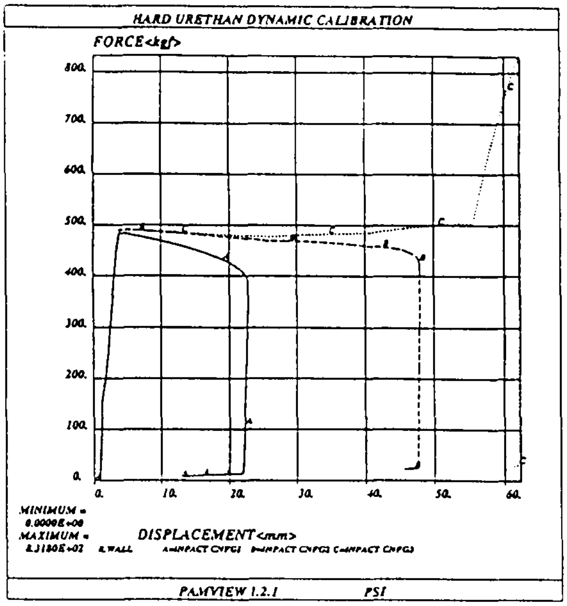


Figure 12. Dynamic numerical results

INFLUENCE OF MATERIAL PARAMETERS ON THE PADDED SURFACE IMPACTOR TEST OF DOT-SID DUMMY

In using the validated material parameters for the hard urethane foam, the padded impactor model was established and the padded surface impactor test simulation for DOT-SID dummy was carried out [3]. The typical deformation pattern is shown in figure 13. The purpose of this numerical study was to observe the influence of the material parameters of the foam when being applied to the foam of the padded impactor for the chest. The following 4 cases were selected.

CASE 1: All of validated parameters were included in the foam.
CASE 2: Strain rate dependency by Cowper-Sysmonds law was neglected.
CASE 3: Energy dissipation factor α was neglected.

CASE 4: Strain rate dependency by Cowper-Sysmonds law was neglected. Instead, the basic stress-strain relation was taken from the dynamic impactor drop test (cnfg.3) in place of the static compression test. The impactor velocity was 9m/s.

The obtained results were compared in TTI (d) and shown in table 1 by the relative ratios with respect to TTI (d)-CASE1, which showed the excellent correlation to the experimental result (not shown in the present paper).

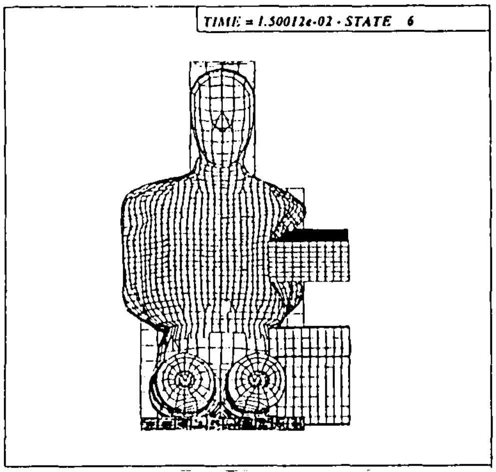


Figure 12. Typical deformation pattern of the padded surface impactor test simulation of DOT-SID dummy

Table 1. Comparison of TTI(d) in Each Case

CASE No.	TTI (d)
1	1
2	0.86
3	1.01
4	0.89

CONCLUSION

A study was undertaken using finite element methods to examine the degree of influence that certain material parameters had on a numerical foam model. To achieve this objective, an experimental study, a static calibration, and dynamic calibrations were carried out. Of particular interest in this study was the foam material's behavior due to strain-rate effects which was studied through the dynamic calibrations and simulations of foam compression. Dynamic simulation results of the foam compression illustrated the numerical foam model's ability to simulate the strain-rate and hysteresis characteristics. As was presented in the side impact simulations, these characteristics, which general foams possess, play a major role in the dummy's response to impact.

The validated numerical foam material was used to represent the padded surface of a chest impactor block. This impactor was then applied to the DOT-SID dummy in side-impact simulations, with specified velocity conditions. The conclusions obtained from this study were:

1. The strain-rate dependency of the foam was the most important material parameter as it greatly influenced the accelerations of specific dummy components. Eg. Upper ribs, lower ribs and pelvis.

2. The strain-rate effects must be considered when simulating foam materials. If the dynamic stress-strain relation from experiments are directly used as the basic stress-strain relation in a simulation without considering the strain-rate, the foam to be simulated will most definitely be unsatisfactory. ie. either too stiff or too soft compared with reality.

3. The influence of foam hysteresis on the TTI (d) is very low and may be disregarded in the side-impact simulation.

In summary, strain-rate dependency is a very important parameter which must be considered when modeling the characteristics of foam. The effect of this parameter was shown to be significant in determining the responses of the DOT-SID dummy when used as the impactor material in side-impact simulations.

REFERENCES

[1] Gibson, Ashby, "Cellular Solids - structures&properties" (Japanese edition by Otuska), Pergmon Press 1988

[2] PAM_CRASH Users's Manuals, Version 12.0,PAM SYSTEMS INTERNATIONAL, 1995

[3] TOYOTA-ESI DOT-SID Development Project Final Report, 1995

[4] PAM_OPT Users's Manuals, Version 1.1, PAM SYSTEMS INTERNATIONAL, 1995

UPPER INTERIOR IMPACT: TEST EQUIPMENT AND TESTING TECHNIQUES

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Paper Number 96-S8-W-16

ABSTRACT

This paper provides an overview of testing equipment which is used to conduct Free Motion Headform (FMH) impact testing. With the issuance of new safety regulations concerning head impact protection, automobile manufacturers and suppliers must add testing capabilities to their laboratories. Drawing upon a large amount of FMH testing experience, as well as the design and fabrication of numerous systems, this paper presents an overview of the types of systems available, as well as a discussion of the various operating aspects of the equipment. Peripheral equipment items such as a Coordinate Measurement Machine (CMM), FMH template, and FMH calibration drop tower are also reviewed. Simple techniques used in FMH tests which can help in achieving repeatable results is also presented.

INTRODUCTION

Recently, government legislation has been enacted which requires automakers to design their vehicles so that certain head impact occupant protection requirements are met. The new requirements have resulted in both automakers and suppliers adding capability to their laboratories. There are many different equipment alternatives available for conducting head impact testing.

Laboratory managers faced with decisions concerning the acquisition of test equipment must consider many factors including the overall nature of the testing (compliance, developmental), estimated number of tests per year, the degree of sophistication needed, whether some components of current equipment could be utilized, etc. The equipment used by vehicle manufacturers may have much greater through-put demands compared to equipment used by suppliers and this is an important distinction when considering various FMH facilities. In addition, the degree of adjustability and automation needed for full vehicle compliance testing is perhaps a waste of resources for conducting only component level evaluations.

Readers of this paper should become familiar with the types of systems available for FMH impact testing. The information in this paper should help individuals in the process of upgrading their laboratory to add interior head impact capabilities. In addition to the basic FMH system requirements, other test accessories are discussed which can be integrated into a FMH test facility. Each of these items are intended to simplify testing procedures, as well as improve the variability of testing results.

Other topics addressed in this paper include techniques which can be used to improve testing repeatability. A major concern among safety engineers is that "expected" testing variability distort the apparent effects of new designs. From this perspective, it is important that the causes of test-to-test variability be understood, and that the procedure which is used to conduct FMH testing has specific practices to control this variability. The techniques discussed in this paper have been derived from the execution of thousands of FMH impact tests. It is thought that implementing some of these practices into FMH testing procedures will reduce test-to-test variability, and allow more accurate evaluation of new designs. Subsequent discussion in this paper presents various information concerning FMH test facilities, procedures, and techniques.

Basic Requirements of a FMH Impact Facility

It is assumed that the reader is familiar with the basic requirements of a FMH impact test (in this paper, "FMH" and "FMVSS 201U" impact tests are considered interchangeable), however, specific procedural information and testing criteria are available through publicly available literature. Here, only a general description of a FMH test is discussed and the purpose here is to set the stage for subsequent discussion.

The general parameters of a typical FMH are as follows:

- 10 pound modified Hybrid III dummy head in free flight
- 15 mph impact velocity
- impact configuration perpendicular to the surface
- test data includes center of gravity X, Y, Z acceleration
- acceleration-based injury index criteria
- impact areas include pillars, roof, headers, and side rails
- vehicle supported so that its suspension is inactive

Any FMH test laboratory must meet these basic parameters. There are many equipment alternatives available which can be incorporated into a system to meet these requirements. The distinguishing features of available equipment options is mainly in the degree of automation. As the amount of automation in a system increases, the ease of use also increases, as does the cost.

Major Components of a Typical FMH Test Facility

Presented in Figure 1 is a three-quarter view drawing illustrating the various features of a typical FMH facility. Specific items have been referenced on this drawing and these references are used throughout this section of the paper. A general discussion of each aspect of the facility is presented in this section.

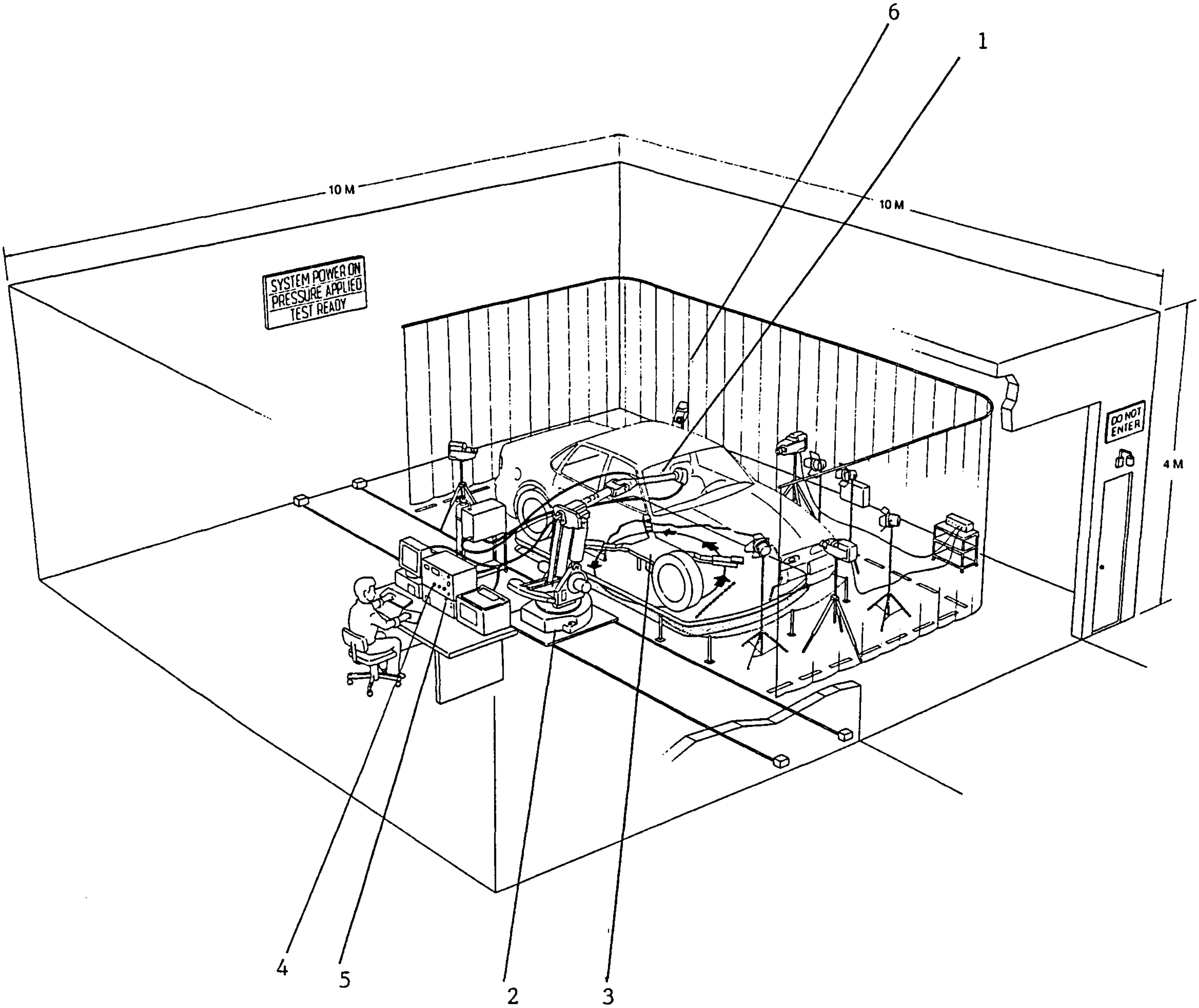

Figure 1. Overview of a FMH facility.

1. FMH Actuator - The actuator is used to accelerate the FMH up to the required impact velocity. The unit must be fairly small in size (12" or less) in order to be positioned and operated inside a vehicle. If the system is too large, specific impact points (such as the roof or A-pillar) will be very difficult to test. The propulsion device must be designed so that it brings the FMH up to the desired velocity, and then release the FMH into free flight. There are a few alternatives available, most of which use a charge of compressed gas as the energy supply to propel the headform. Presented in Figure 2 is a photograph showing a typical FMH actuator.

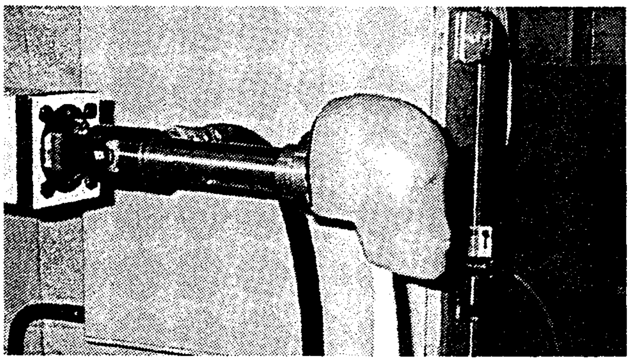

Figure 2. Typical FMH actuator.

The actuator is made up of several parts including the piston, propulsion gas supply and headform attachment device. The gas is supplied through an accumulator in which the target pressure charge is stored prior to firing. As the fire valve opens, the gas moves the piston forward with the headform still attached. The length of the piston is fixed so that upon reaching the end of the shaft the FMH is allowed to detach itself from the propulsion system. The headform attachment device consists of a circular plate with magnets around the periphery to hold the FMH on the actuator.

2. Positioning System - One of the most important aspects of any FMH impact laboratory is the system used to position the propulsion device. Typically, the propulsion device is rigidly attached to the positioning system. The aiming of the FMH at the target point is critical with regard to the repeatability of testing results. There are many available options concerning the positioning system. In general, most positioning systems can be grouped into three (3) classifications. They are as follows:

A **fully automated** system is one which can be completely controlled by a single individual utilizing a control unit in which no manual adjustments are necessary to aim the actuator for each test. An example of this type of system is an industrial robot operated with a hand pendant or computer interface.

A **semi-automated** system is one in which there is some automation in the movement/positioning of the headform actuator, yet there are still manual adjustments required. An example of this type of system is when the operator can move the arm (with the actuator attached) into the vehicle from a control stand, with final positioning done inside the vehicle using manual adjustments. One type of semi-automated system utilizes air bearings to maneuver the arm/actuator structure around the vehicle. This system uses air bearings to raise the unit off of the floor so that it can easily be placed in the proper position. Once it is in position, the air pressure is removed and the actuator is in the proper location.

A **manual system** is one in which all of the positioning of the arm is done by individuals working on a test frame, where no arm movement is done through a control station. A typical system consists of a rigid arm attached to a sliding A-frame. The A-frame is attached to a base test frame. The actuator is attached to the end of the arm with an adjustable interface plate used for different impact configurations.

Presented in Figures 3 through 6 are examples of the various types of positioning systems. The systems shown here range from a fully automated system utilizing a heavy duty robot fully adjustable using a hand pendant to a fully manual system with all mechanical adjustments. The semi-automated system (Figures 4 and 5), requires only minor adjustments of the propulsion device to set up for an impact test.

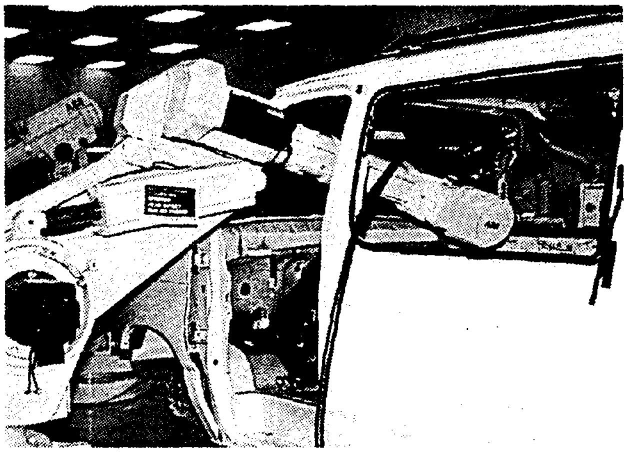

Figure 3. Fully automated positioning system. (Courtesy of Ford Motor Company)

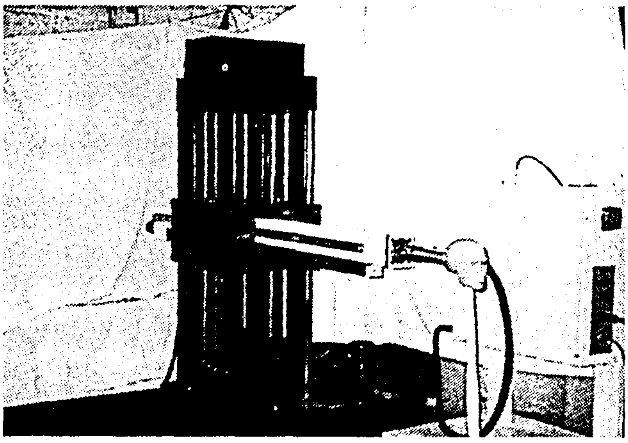

Figure 4. Semi-automated positioning system.

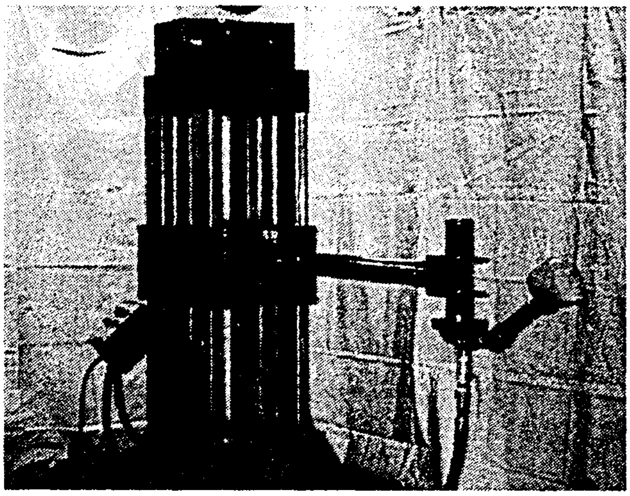

Figure 5. Semi-automated system utilizing air bearings for positioning.

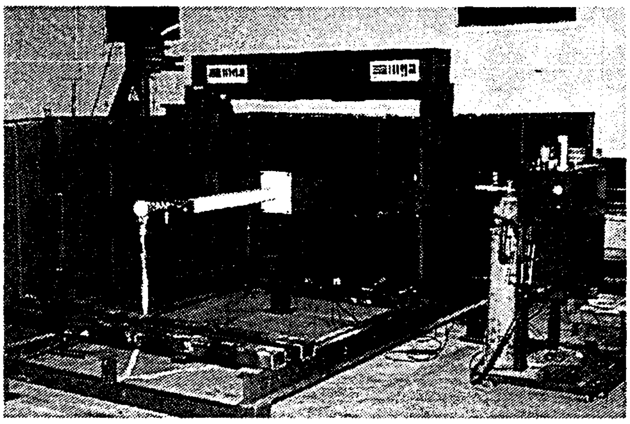

Figure 6. Manual positioning system.

<u>**3. Vehicle Support System**</u> - The government procedure requires that the test vehicle be supported so that its suspension is inactive. This is done by raising the vehicle off of the ground through supports on the frame or body rails. There are various options available for doing this, including jack stands, electric vehicle lifts, or hydraulic lifts.

<u>**4. Control Box**</u> - The control box is essentially the central component in any FMH test facility. It provides the system user interface and allows the user to carefully monitor the systems' status. The control box for any type of FMH system should include various safety interlocks. The front face of the control box displays all of the pertinent information needed in order to conduct a FMH test properly. These include pressure readings, safety pin status, horn on/off, and fire and abort buttons.

<u>**5. Data Acquisition System (DAS)**</u> - The DAS needed for FMH testing must meet the requirements specified by the Society of Automotive Engineers (SAE) Recommended Practice J211. This practice includes requirements for data sampling rates and filtering characteristics. Engineers conducting this type of testing typically prefer higher sampling rates because the duration of the event is typically less than 5 msec. Higher sampling rates allow a more thorough analysis of the testing results.

<u>**6. Enclosed Area**</u> - The safety of personnel working around the FMH impact system is very important. Curtains and walls are used to keep unnecessary personnel away from the equipment. For many laboratories, the system used to enclose the impact area is interlocked with the control system. If the system is under pressure, and someone enters the area, all pressure will be automatically dumped. Additionally, door interlocks can also be used to prohibit access into the testing area if the system is pressurized.

Complementary FMH Equipment

In addition to the major components of any FMH test laboratory, there are other items which can be incorporated into a typical test facility. The term "complementary" is used here because most of the items described in this section are not mandatory for a FMH facility, yet they can be very useful in improving the accuracy and repeatability of testing results.

<u>**FMH Drop Test Calibration Stand**</u> - Presented in Figure 7 is a photograph showing a typical FMH calibration drop tower. Calibration of the FMH (as well as the accelerometers used inside the FMH) must be completed to have any degree of confidence in the test results which are produced. The

method used to calibrate the FMH involves dropping the FMH from a specified height onto a machined surface and recording the center of gravity x, y, and z accelerations. Acceptance is based upon the acceleration response of the FMH.

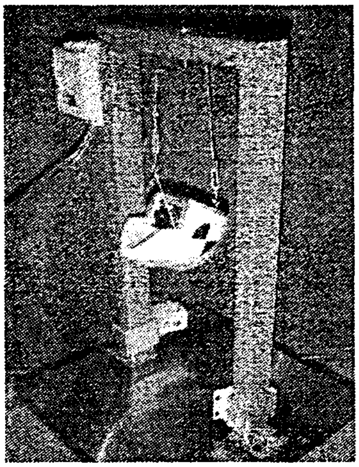

Figure 7. FMH calibration drop tower.

FMH Template - Presented in Figure 8 is a photograph illustrating the use of a template for lining up the actuator with the target point. Positioning of the actuator is a critical issue when considering the accuracy and repeatability of testing results. The FMH template is designed so that it attaches to the actuator in the same manner as the FMH. The template takes into account the desired pre-impact free flight distance and piston length and has the same contour as the FMH, except in two dimensions. Without using a template, it would be very difficult to align the actuator so that the initial contact occurs within the FMH head impact zone.

Coordinate Measurement Machine (CMM) - The procedure used to determine the applicable impact locations requires a great deal of in-vehicle plane definition and point measurement. This process can be made much easier through the use of electronic Coordinate Measurement Machines or CMM's. There are many types of CMM's available for making dimensional measurements. A CMM used for interior vehicle measurements must have characteristics such as ease of use in confined areas, high levels of accuracy, and the capability to measure points in space in three (3) dimensions. Presented in Figure 9 is a photograph of a CMM which works well for FMH testing. This machine, manufactured by FARO Technologies, is a multi-degree of freedom system which operates by placing a probe on a point in space, and, through a variety of sensors on the arm, the three dimensional coordinates of the point are electronically recorded using a computer.

Methods in which a CMM can be used in FMH testing are as follows:

- Transferring of impact point locations from a vehicle drawing package (in vehicle coordinates) onto the actual vehicle structure.
- The targeting procedure requires the precise location of many specific points inside the vehicle interior. These points include dummy reference points, as well as vehicle reference points. This process is much easier using a CMM in that coordinates of specific points can be electronically recorded and manipulated using a computer.
- A CMM can be used to accurately document the precise impact angle and location of the actuator within the vehicle.

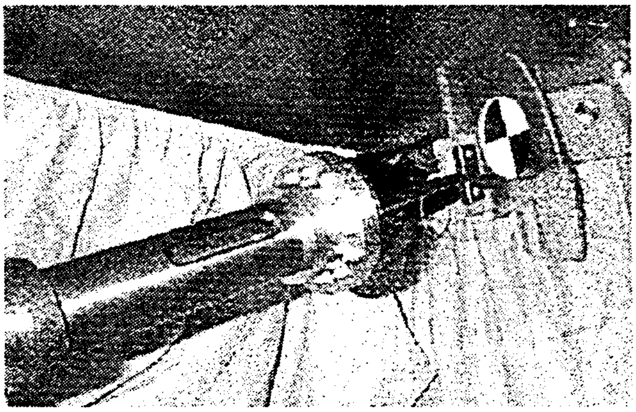

Figure 8. FMH template attached to the actuator.

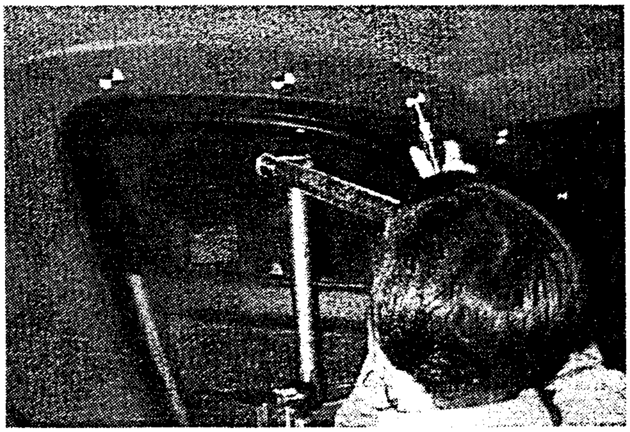

Figure 9. Use of a CMM for targeting a vehicle.

Testing Techniques

In general, FMH impact testing has a significant amount of variability. This variability is due to a variety of issues such as headform positioning, headform "soak" time, target determination, impact velocity, etc. The levels of variability which can be expected has been documented through various technical literature. Based upon experience gained through conducting many tests, a few techniques for improving test-to-test variability can be implemented into normal testing procedures. A few of these techniques are described here:

Inspection of the FMH - The FMH, which is a modified dummy head, should be carefully inspected prior to each test. The purpose of this inspection is to verify that the FMH has not been damaged or is in need of basic maintenance. Items which should be addressed include the following:

- Are there any tears or rips in the rubber skin?
- Is the rubber skin fitted properly on the head and not "slipping" off of the headform?
- Are all the bolts on the backing plate tightened?

Actuator Angle/Location Measurement - As discussed earlier, a template can assist in aligning the actuator properly. Once the actuator has been carefully positioned, the precise location and related angles should be carefully recorded. All of these measurements are made relative to the vehicle. The main reason that these measurements are so critical is that the exact duplication of the actuator position for tests conducted on the same type of vehicle is critical if the results are going to be compared. As a minimum, the following measurements should be made for each impact test:

- **Plan View Angle (PVA)** - This angle is measured in the counterclockwise direction taken from an "overhead" perspective of the vehicle with 0° pointing to the rear of the vehicle (see Figure 10).
- **Side View Angle (SVA)** -This angle is measured relative to a horizontal plane in the vehicle. It is the angle which exists between this plane and the direction of motion of the impactor (see Figure 11).
- **Actuator/Vehicle Reference Point** - The three (3) dimensional coordinates of two points on the actuator should be recorded. If a vehicle reference point (which can be the three dimensional coordinates of the target) is known, the precise position of the actuator can be duplicated on subsequent tests.

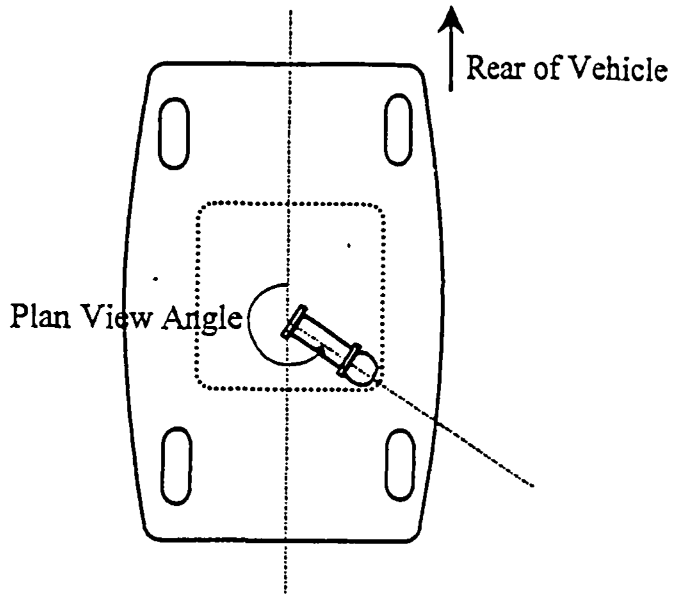

Figure 10. Plan view angle.

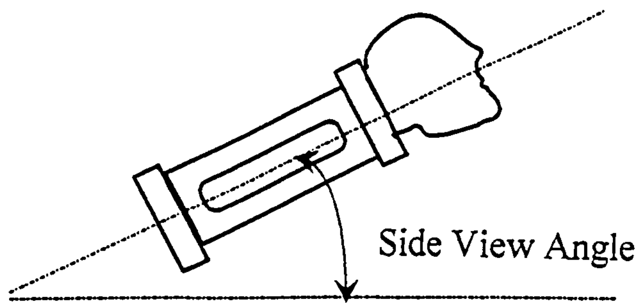

Figure 11. Side view angle.

"Chalking" the Target Point - Prior to every FMH impact test, the target point on the vehicle should be painted with transferrable chalk. Upon the FMH impact, the chalk will be imprinted on the FMH. A photograph of the FMH with the chalk imprint should be taken following each test. In addition, measurements of where the imprint occurs within the FMH head impact zone should be recorded. This information can be quite helpful in interpreting test results. The location of the impact point relative to the CG influences how much rotation the FMH encounters, and thus can effect the acceleration response.

Velocity Range - One issue from the standpoint of repeatability and comparison of testing results is the impact velocity of the headform. The velocity range specified for compliance related testing is 14.4 ± 0.5 mph. When conducting developmental testing and comparing tests results on different design alternatives, the impact velocity for each test should be as close as possible. For example, if one test is at the lower limit of the velocity range specified above, and the other test is at the higher end, this can cause difficulties in comparing results. One other issue concerning velocity is that a second accelerometer mounted in the FMH x-axis direction should be used to confirm both the acceleration and velocity.

Review of Testing Data - For every FMH impact test conducted, the data produced should be carefully reviewed. Issues which should be addressed include the following:

- Do all of the data channels start and finish near zero g's?
- Does the x-axis acceleration integrate out to the "expected" impact velocity?
- Does the x-axis acceleration double integrate out to the correct displacement prior to impact?

If each of these items are verified on a test-by-test basis, there will be a higher degree of confidence in the results.

CONCLUSIONS

The discussion in this paper attempts to provide laboratory personnel with information which may be helpful in addressing head impact testing issues. Due to new legislation, many automotive related companies are being required to add capabilities to their laboratories. The decision on what equipment to add, or what current equipment may possibly be used, is easier to make if future requirements such as through-put, type of test (component, full vehicle), etc. are known. If the future requirements are known, or at least estimated, combined with some background knowledge on the types of systems available, then an appropriate strategy can be developed for facility changes.

Once a facility has been brought on-line, it is important that effort be directed toward conducting high quality tests. The primary objectives should be to improve testing procedures and techniques so that repeatable test methods are used. The levels of test variability can be controlled mostly through strict adherence to testing procedures, careful pre-test measurements, and constant review of testing results. If each of these issues are addressed, the quality of the test should be high enough to allow new design alternatives to be effectively evaluated.

ACKNOWLEDGMENTS

The authors of this paper wish to express appreciation to the associates of MGA Research Corporation who are involved in both the design and fabrication of FMH test systems, as well as the execution of FMH tests. In addition, the authors appreciate the openness of other engineers in the industry in sharing their ideas relative to head impact protection issues.

REFERENCES

Code of Federal Regulations, Title 49 (Transportation), Chapter V (NHTSA, DOT), Part 571, 572, and 589-Federal Motor Vehicle Safety Standards; 201U, Head Impact Protection. Docket 92-28, Notice 4, August 18, 1995.

NHTSA, Laboratory Test Procedure for Federal Motor Vehicle Safety Standard No. 201U, Upper Interior Head Impact Protection (TP-201U-00, 1995).

NHTSA, Notice of Proposed Rulemaking to Amend Federal Motor Vehicle Safety Standard No. 201 - Head Impact Protection. Docket No. 92-98; Notice 2, U.S. Department of Transportation, Washington, D.C.

Instrumentation for Impact Test, Recommended Practice SAE J211 OCT88, Volume 4, SAE Handbook, pp. 34. 185-190 (1990).

Technical Session 9

Data Collection and Analysis
Chairperson: Peter Vulcan, Australia

LINKAGE OF STATE DATA AND THE CODES PROJECT

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ABSTRACT

NHTSA's Crash Outcome Data Evaluation System (CODES) project linked crash, EMS, ED, inpatient hospital and rehabilitation, and insurance data for a twelve month period in seven states to generate medical and financial outcome information for everyone involved in motor vehicle crashes. The linkage was performed using a probabilistic linking algorithm. Occupant-specific population-based data for 879,679 passenger vehicle drivers and 10,353 motorcyclists were standardized for analyses that showed that safety belts and motorcycle helmets were effective in reducing mortality, morbidity, severity, and cost. The average hospital inpatient charge for unbelted drivers was five times the charge for those who were belted. Helmets were 67 percent effective in preventing brain injuries. Brain injured motorcycle riders had inpatient charges twice as high as those for the non-brain injured. Full results of this study are described in a Report to Congress (NHTSA, 1996) and its companion Technical Report (Johnson and Walker, 1996).

INTRODUCTION

This paper presents state-specific and combined results documenting the effectiveness of safety belts and helmets in reducing mortality, morbidity, severity and health-care charges. In addition, it discusses how probabilistic linkage techniques increase both the quality and usefulness of existing state data.

The availability *at the state level* of medical outcome information for motor vehicle crash victims is limited. Some states support statewide databases such as EMS run reports, hospital emergency department records, or rehabilitative and long-term care facility treatment summaries. Not all states collect or build statewide files from all these sources of information. However, where they are available, these databases and the hospital discharge database are a valuable information source for highway safety research, particularly when an individual patient record can be associated with data on a police crash report.

Therefore, NHTSA used police-reported crashes as the study population. The police reports identified crashes, circumstances about the crashes, the vehicles, and the people involved. Patient information from the available data sources, usually EMS, ED, hospital discharge, and long-term and rehabilitative care data, identified injury outcomes and charges for those who were injured. The different databases were *linked* to obtain population-based occupant-specific outcome data for injured crash victims. Linking the databases enabled the information about the injury-causing event (the motor vehicle crash) to be directly related to specific medical and financial consequences for each person involved in the crash. This detailed information was used to evaluate the failures *and successes* resulting from the use or non-use of safety devices. Figure 1 shows schematically the linking of databases in a state where all such databases are available.

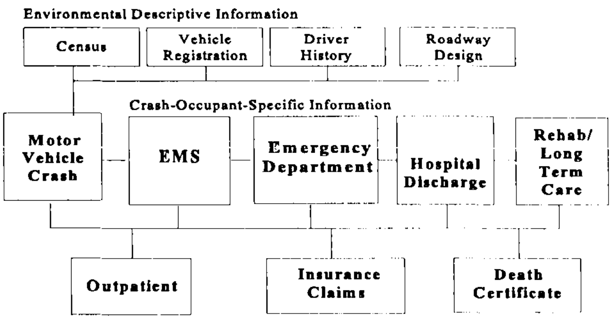

Figure 1. Crash and Injury Data Sources.

Grants

In the May 5, 1992, *Federal Register*, NHTSA published a grant solicitation requesting applications from states to create a Crash Outcome Data Evaluation System

(CODES). The announcement specified that applicants needed crash, EMS, ED, hospital discharge, and rehabilitative/long-term-care data that were statewide and computerized. In addition, they had to be willing to collaborate with the owners of these databases, link the data, perform analyses as specified by NHTSA, and send NHTSA a copy of the linked data and results of the analyses. Any state agency, nonprofit organization, or educational institution that *could set up a coalition of data owners and users to perform the linkage* was eligible to apply. Any representative 12 month period after January 1, 1990, was allowed. Thus, the number of possible applicants was maximized and each state could use their most recent data. Twenty states responded to the solicitation. Selection of the grantee states was independent of safety belt and helmet use rates or laws.

On September 30, 1992, NHTSA awarded grants to conduct the study to entities in seven states: the Departments of Health in **Missouri**, **New York**, and **Pennsylvania**; the Department of Public Safety in **Maine**; the Department of Transportation in **Wisconsin**; and state university systems in **Hawaii** and **Utah**. Besides having the needed data, the seven states had other characteristics useful for this study. All of the states except Maine had enacted mandatory safety belt use laws. At one time or another, all the states had also adopted helmet use laws, but during the study period, universal adult helmet laws only existed in three: Missouri, New York, and Pennsylvania. Each state had a statewide database for police crash reports and a statewide hospital inpatient discharge file.

All states except Wisconsin had a statewide EMS database. For all drivers and injured passengers, Wisconsin had dates of birth and zip codes on its crash file. This facilitated linkage (in the absence of EMS data) to the hospital discharge and insurance claims files.

Only Missouri and Utah had access to statewide emergency department (ED) data. New York obtained ED data for New York City. The other states attempted to obtain ED information for specific population groups from insurance claims databases. Hawaii and New York were no-fault insurance states. New York had access to statewide vehicle insurance claims information, and Hawaii had access to statewide health insurance claims information.

To promote collaboration, each grantee formed an advisory committee of the owners and users of the databases they intended to link. In most of the states, this was the first time these diverse groups collaborated on highway safety issues. These advisory committees addressed the problems of data accessibility, confidentiality, uniformity, and quality. They worked to define potential uses for the data and to set up and review research projects whose results were included as part of the grantees' final reports to NHTSA. In short, these committees worked to coordinate the components that would promote the use of linked data for supporting injury control in the highway safety environment for the current study and in the future.

States differed in the amount and type of data collected on police crash reports and coded onto their crash databases. Some of these differences affected the CODES analyses. For instance, Missouri and Wisconsin do not collect or code information about vehicle passengers who were not injured in the crash. Thus, the safety belt benefit analyses presented in this report were restricted to drivers. However, the results of the belt analyses for drivers were not significantly different from the corresponding results for all occupants, in the five states that had such data.

Data Linkage

Until recently, linking data from two different data sets has been time-consuming and expensive because of the need for exact matches. The CODES grantees linked their available databases using probabilistic linkage (Jaro, 1995). This computer algorithm uses a combination of indirect identifiers (age, date of birth, date of event, sex, etc.) and, when available, direct identifiers (name, unique number, etc.). After completing the linkage, each state had a database in which crash-involved occupants were linked to the available medical outcome databases (EMS, emergency department, hospital discharge, and/or rehabilitation/long-term care). Those occupants reported by the police as uninjured were less likely to be linked to a medical outcome record, while those reported as having incapacitating injuries were more likely to be linked. Those in the middle (i.e., occupants who were reported with possible or non-incapacitating injuries) had varying linkage rates. They were less likely than those with serious injuries to be transported or treated at an inpatient facility, but very likely to receive outpatient treatment. Thus, the final linkage rates varied according to the availability of claims or outpatient data.

The success of the linking process was influenced by two factors. First, although the probabilistic linkage algorithm increased the likelihood of accurate matches, some databases lacked sufficient information to discriminate among the events and persons involved. Because of privacy considerations, some data systems that collect a person's name do not code it on their electronic database, and it is therefore, not available for linking. Having a victim's name or a common identifying

number on each record enhanced the accuracy and helped to increase the number of matches obtained from the various files. Second, it was not possible to identify all persons in medical outcome databases (EMS, hospital discharge, etc.) whose injuries resulted from motor vehicle crashes. This problem would be mitigated if these data systems uniformly collected and coded external cause of injury information (E-codes) on the patient records.

Outcome Measures

To estimate the benefits of safety belts and motorcycle helmets with respect to different categories of injury severity, outcome measures for crash-involved occupants were established. A precursor to the actual outcome measures was a combined scale of "injury severity" and "treatment given" for each person in the linked files. This preliminary scale was based on information generated from the linked data (Table 1.).

Table 1.
Severity/Treatment Definitions Used in the CODES Analysis of Effectiveness of Safety Belts and Motorcycle Helmets

Severity/ Treatment	Definition
Not Injured	Reported by the police either as possible injury or not injured and did not link to a medical outcome record
Slightly Injured	Reported by the police: as injured (except possible injury) but did not link to a medical outcome record *or* as possible injury and linked to an insurance claim record
Trans-ported	Linked to an EMS and/or Emergency Department record but was not admitted as an inpatient for treatment
Inpatient	Linked to medical outcome record indicating inpatient treatment (acute, rehabilitative and/or long-term care)
Died	Police-reported as killed or linked to a medical outcome record indicating death within 30 days after the crash as a result of the crash

Each crash-involved motor vehicle occupant or motorcycle rider was coded into one of the five mutually exclusive categories.

The actual outcome measures derived from this scale were:

(1) -- Died (vs. survived);

(2) -- Died or inpatient (vs. lesser or no injury);

(3) -- Died, inpatient, or transported (vs. lesser or no injury);

(4) -- Any injury: Died, inpatient, transported, or slightly injured (vs. no injury).

These dichotomous measures permitted analysis by logistic regression that in turn allowed the inclusion of other factors that otherwise might have confounded the safety belt results.

The linking of the various databases in the grantee states produced a large number of crashes that contributed 879,670 passenger vehicle drivers and 10,353 motorcyclists for this study. Table 2 shows the distribution of crash-involved passenger vehicle drivers and motorcycle riders by the severity/treatment levels listed in Table 1. The distribution is different for motorcycle riders because they are more likely than passenger vehicle drivers to be injured in police-reported crashes.

Table 2.
Number of Drivers and Motorcycle Riders Contributing to the CODES Analysis of Effectiveness of Safety Belts and Motorcycle Helmets, by Severity/Treatment Levels

Severity/ Treatment Levels	Passenger Vehicle Drivers	Motorcycle Riders
Not Injured	703,319	2,892
Slightly Injured	81,353	3,128
Transported	78,054	2,378
Inpatient	14,599	1,604
Died	2,345	351
Totals	879,670	10,353

To evaluate whether safety belts and motorcycle helmets are beneficial in reducing mortality, morbidity and injury severity, NHTSA wanted to use a measure employed in many previous studies: effectiveness. Effectiveness can be defined as the percentage reduction in injuries or deaths for people wearing safety belts or

helmets compared to people not wearing safety belts or wearing helmets. For example, if the effectiveness of safety belts in reducing injuries is 45 percent, then 45 percent of the unbelted, injured drivers would not have been injured had they been wearing their belts.

Effectiveness was the preferred statistic because it can be easily understood by a wide audience. However, it could not be computed directly because other contributing risk factors needed to be added to the analyses to ensure any safety equipment effects were not confounded by them. These factors included 'type of crash' (rollover, single-vehicle fixed object, single-vehicle non-fixed-object, multiple-vehicle head-on, and multiple-vehicle other), 'area' (rural or urban), 'age of driver,' 'gender,' 'posted speed limit,' 'roadway conditions' (dry or other), 'late night' (a surrogate for alcohol use), 'seating position,' and 'vehicle size' (passenger car vs. light truck or van). For the helmet analyses, the factors 'type of crash,' 'seating position,' and 'vehicle size' were not used.

To include these other variables, PROC LOGISTIC (SAS Institute Inc, 1989) was used to compute odds ratios. A simple additive model without interactions was used. Each state ran four models (one for each outcome variable) for safety belt analysis and four models for motorcycle helmet analysis. Further details regarding the analyses are given in the CODES Technical Report (Johnson and Walker, 1996).

RESULTS

Figure 2 shows the overall distribution of injuries by belt use for drivers in the CODES project, summed over all the states. The numbers are not raw numbers, but include the cumulative effects of all the contributing factors and have been adjusted to reflect the weighted-average odds ratios shown in Figures 3 through 6.

The triangles show how much larger the percentage of uninjured belted drivers (84.8 percent) is compared to the percentage of uninjured unbelted drivers (68.6 percent), and how much smaller the percentages are in the belted triangle at all injury levels. For drivers transported by EMS (but not hospitalized or died), the percentages are approximately twice as large for unbelted drivers as for belted drivers. For hospitalized drivers, the percentages are approximately four times as large, and for those who died, the percentages are ten times as large.

However, these data are very likely inflated by drivers who claimed to have been belted but were not, probably because they wished to avoid a lecture or fine from the investigating officer. This has been verified by

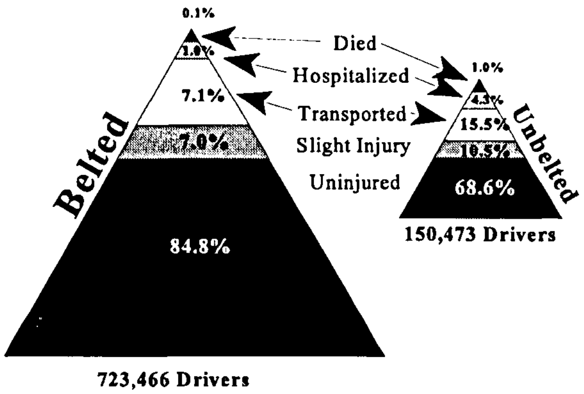

Figure 2. Injury severity by belt use in the CODES project. Areas inside the triangles represent the number of cases (adjusted for covariates) in each category.

comparing the "percentage belted" from police reports to the "percentage belted" from studies using roadside observers. In most minor crashes, drivers are out of the vehicle before the reporting officer arrives. Therefore, close to all of the uninjured, unbelted drivers have both the opportunity and motive to tell the officer they were belted. This is also true for the injured, although the opportunity for misrepresentation is lessened as the injury level increases.

The effect of this over-reporting is that the bottom level of the belted triangle is spuriously increased and the bottom level of the unbelted triangle is decreased. Consequently, the relative percentages of the two triangles are more disparate than they should be. Methods of adjusting for this over-reporting will be discussed later.

Odds Ratios for Belt Use

Figures 3 through 6 present the benefits of safety belts, by state, as odds ratios, one figure for each outcome measure. The odds ratios are the exponents of the "belt use" coefficients from the logistic regression, and the ends of the error bars are the exponents of (coefficient ± 1.96 * standard error of the coefficient). On the right side of each figure is the exponent of a weighted average of all the states (Fleiss, 1981). In all four cases, tests of association showed significant differences among the states, and tests of homogeneity showed significant differences among the standard errors. The latter is not surprising given the large sample size differences among the states. Nevertheless, the weighted averages are presented as a best estimate, although the standard errors for the weighted averages are spuriously small. Most important, even though the state specific odds ratios varied by state, **all states showed the same pattern of**

safety effects for all outcome measures, at significance levels of $\alpha < 0.001$ in all cases.

Figure 3 shows the belt odds ratios for died. The best odds ratio was 0.078 (Hawaii). This means the driver's odds for died, given a police-reported crash occurred and the safety belt was worn, were approximately 1/13 the odds of those drivers who did not

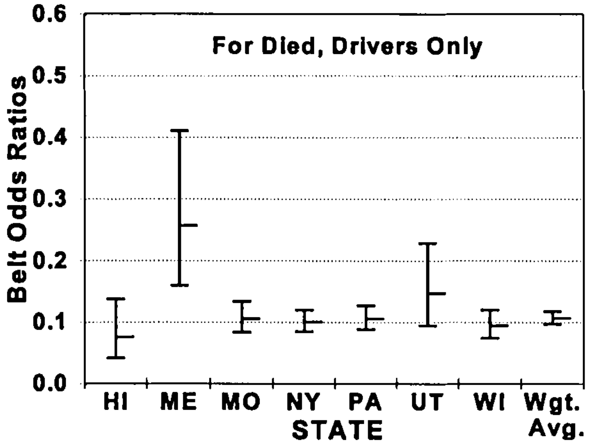

Figure 3. Belt odds ratios for deaths by CODES state, with a weighted average in the right I-beam. See text for details.

wear their safety belts. The least favorable odds ratio in the same situation was 0.257 (Maine), which means the odds for died for belted drivers were approximately 1/4 of the odds for unbelted drivers.

Figure 4 shows the belt odds ratios for hospitalized

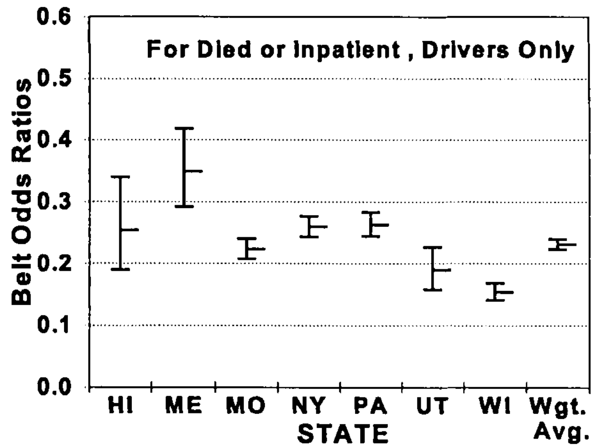

Figure 4. Belt odds ratios for hospitalized or died, by CODES state, with a weighted average in the right I-beam. See text for details.

or died. The best odds ratio was 0.154 (Wisconsin). This means the unbelted driver's odds were 6.5 times the odds of those drivers who did wear their safety belts. The least favorable odds ratio in the same category was 0.350 (Maine), which means the odds of hospitalized or died for belted drivers were about 1/3 of the odds for unbelted drivers.

Figure 5 shows the belt odds ratios for transported, hospitalized and/or died. The best odds ratio was 0.240 (Wisconsin). This means the unbelted driver's odds were 4.2 times the odds of those drivers who did wear their safety belts. The least favorable odds ratio in the same category was 0.500 (New York), which means the odds of transported, hospitalized and/or died for belted drivers were half of the odds for unbelted drivers.

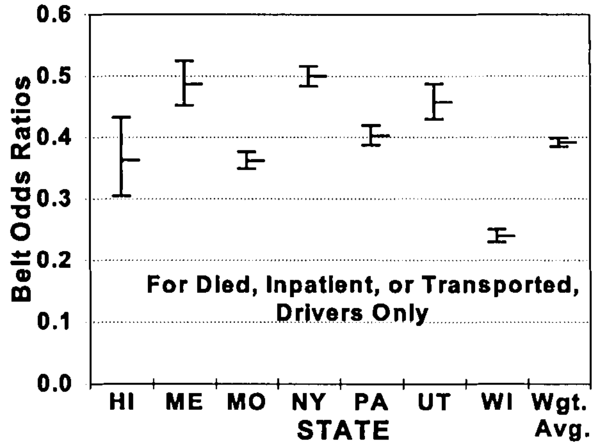

Figure 5. Belt odds ratios for transported, hospitalized, and/or died, by CODES state, with a weighted average in the right I-beam. See text for details.

Figure 6 shows the belt odds ratios for any injury. The best odds ratio was 0.242 (Wisconsin). This means the unbelted driver's odds were 4.1 times the odds of those drivers who did wear their safety belts. The least favorable odds ratio in the same category was 0.539 (Maine), which means the odds of any injury for belted drivers were about 1/2 of the odds for unbelted drivers.

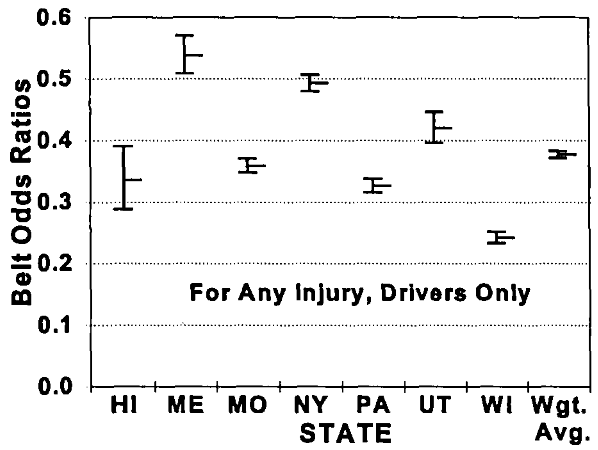

Figure 6. Belt odds ratios for any injury by CODES state, with a weighted average in the right I-beam. See text for details.

Effectiveness of Safety Belts

The results of the study revealed that safety belts are highly effective in reducing morbidity (the occurrence of any injury) and mortality. They also show that safety belts cause a downward shift in the severity of injuries.

However, these effectiveness estimates may be inflated because of over-reporting of belt use on police crash reports. Table 3 presents two sets of estimates for safety belt effectiveness. The first estimate is based on safety belt use as reported on the police crash reports. The second is adjusted to reflect safety belt use as reported in traffic studies by impartial roadside observers.

Table 3.
Safety Belt Effectiveness by Outcome for Crash-involved Drivers in the CODES States

Outcome	Effectiveness Estimates	
	Belt Use as Reported by Police	Belt Use Adjusted for Over-reporting
Died	89%	60%
Died or Inpatient	75%	45%
Died, Inpatient, or Transported	54%	30%
Any Injury	52%	20%

The adjustment factor is the difference between the reported and observed use rates in each state. For example, if a state's crash-reported use rate is 70 percent, and the state's observed use rate is 50 percent, then the adjustment factor would be 20 percent.

Only one-way adjustments were used, moving drivers from belted to unbelted. There is no reason for a belted driver to report being unbelted. Adjustments were also graded. The full adjustment was given in the uninjured category, no adjustment was given in the fatal category, and intermediate adjustments were given in the intermediate outcome categories. Each state was adjusted separately, then overall rates were computed. The estimates from these adjustments for over-reporting are consistent with results from earlier NHTSA analyses.

Inpatient Charges and Safety Belt Use

The CODES results showed that the average inpatient charge for unbelted passenger vehicle drivers admitted to an inpatient facility due to a crash injury was more than 55 percent greater than the average charge for those who were belted, $13,937 and $9,004, respectively (Table 4.). Private insurance accounted for 69 percent of the inpatient charges compared with 16 percent for public and 15 percent for other sources. In all cases, the average inpatient charge was greater for drivers who were unbelted.

Table 4.
Average and Total Inpatient Charges by Source of Payment and Safety Belt Use for Crash-involved Drivers in the CODES States

Source of Payment	Average Charge		Total Charges
	Safety Belt Use		
	Used	Not Used	
Public[1]	$13,322	$18,922	$26,498,675
Private[2]	$8,581	$14,058	$113,156,421
Other[3]	$8,180	$10,534	$24,788,922
All Sources	$9,004	$13,937	$164,444,018

[1]Includes Medicaid, Medicare, etc.
[2]Includes Worker's Compensation
[3]Usually Self Payment

Effectiveness of Motorcycle Helmets

The study results also showed that motorcycle helmet effectiveness ranged from 9 percent in preventing any kind of injury to 35 percent in preventing a fatality

(Table 5.). These results confirm previous NHTSA estimates. Utah's data were not included because their police crash form had no indicator for 'Helmet Not Worn.'

Helmets cannot protect the rider from most types of injuries, but helmets are very effective at preventing brain injuries. Further analysis of the CODES data, possible only because of the linked medical outcome, showed motorcycle helmets are 67 percent effective in preventing brain injuries (Table 5.). Thus, if all motorcyclists had been wearing helmets, 67 percent of those unhelmeted motorcyclists who received inpatient care for a brain injury would not have sustained the brain injury. In other words, unhelmeted motorcyclists were more than three times as likely to suffer a brain injury as were helmeted motorcyclists.

Table 5.
Effectiveness of Motorcycle Helmets by Outcome for Crash-involved Motorcycle Riders in CODES States (except Utah)

Outcome Measure	Effectiveness
Died	35%
Died or Inpatient	26%
Died, Inpatient, or Transported	26%
Any Injury	9%
Brain Injury	67%

Inpatient Charges and Motorcycle Helmet Use

The average inpatient charge for motorcycle crash victims receiving inpatient care was $14,377 for those who used helmets, and $15,578 for those who did not, an 8 percent increase in charges for those electing not to wear a helmet. Private insurance sources accounted for 63 percent of inpatient charges compared with 23 percent for public and 14 percent for other sources. For the private and public sources, average inpatient charges for motorcycle crash victims were 15 percent and 5 percent higher, respectively, for the unhelmeted (Table 6.).

Examination of the average inpatient charges revealed that the average charge for inpatient care for a motorcyclist who sustained a brain injury is more than twice the average charge for motorcyclists receiving inpatient care for other injuries. On average, approximately $15,000 in inpatient charges would be saved during the first 12 months for every injured motorcycle rider not sustaining a brain injury. Therefore, if all injured motorcycle riders wore helmets, fewer victims would incur the high cost of inpatient care associated with brain injury.

Table 6.
Average and Total Inpatient Charges by Source of Payment and Motorcycle Helmet Use for Crash-involved Motorcycle Riders in the CODES States (except Utah)

Source of Payment	Average Charge		Total Charges
	Helmet Use		
	Used	Not Used	
Public[1]	$23,793	$24,925	$5,364,759
Private Insurance[2]	$13,617	$15,687	$14,764,706
Other[3]	$10,565	$8,913	$3,403,183
All Sources	$14,377	$15,578	$23,532,648

[1]Includes Medicaid, Medicare, etc.
[2]Includes Worker's Compensation
[3]Usually Self Payment

DISCUSSION

CODES demonstrated that linked, comparable data could be generated to evaluate the benefits of belts and helmets using medical and financial outcomes. Linkage enabled injury severity to be standardized among the CODES states. Besides the belt and helmet study, these data were used to generate state-specific analyses and will continue to be used in the future. The CODES states learned new linkage skills that can be applied to the linkage of other types of records and also can be shared with other states interested in linkage. Also important is the fact that linkage identified previously unknown problems with missing and inaccurate data. Correcting these problems for the study improved the quality of the data in the permanent files, making the state data (linked or unlinked) even more valuable for future uses.

REFERENCES

Fleiss, J. L. (1981), *Statistical Methods for Rates and Proportions (Second Edition).* New York: John Wiley & Sons, pages 160-168.

Jaro, M. A. (1995), "Probabilistic Linkage of Large Public Health Data Files," *Medicine: 14*(5/6/7), 491-498.

National Highway Traffic Safety Administration (1996). *Report to Congress on Benefits of Safety Belts and Motorcycle Helmets, Based on Data from the Crash Outcome Data Evaluation System (CODES)*. DOT HS 808 347. Washington, D.C.: Department of Transportation, February 1996.

Johnson, S. W. and Walker, J. (1996). *NHTSA Technical Report: The Crash Outcome Evaluation System (CODES)*. DOT HS 808 338. Washington, D.C.: Department of Transportation, National Highway Traffic Safety Administration, January, 1996.

SAS Institute Inc., *SAS/STAT® User's Guide, Version 6, Fourth Edition, Volume 2,* Cary, NC: SAS Institute Inc., 1989, 846 pp.

A LINKED ROAD INJURY DATABASE: A POWERFUL TOOL FOR ROAD SAFETY MANAGEMENT, EVALUATION AND RERSEARCH

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ABSTRACT

The Western Australian Road Injury Database, maintained by the Road Accident Prevention Research Unit, consists of linked records of all police reported crashes, hospital admissions, ambulance trips and deaths from road traffic crashes in Western Australia from 1988 until 1992 inclusive. The merging of police reports with vehicle licence details allows the injury experience of vehicle types to be determined. In addition to providing an extremely valuable research tool, proposed enhancement of data collection and linkage methods will provide a powerful executive decision support system available to road safety agencies in this state.

BACKGROUND

The Western Australian Road Injury Database consists of linked records of all police reported crashes, hospital admissions, ambulance trips and deaths from road traffic crashes in the state from 1988 to 1992 inclusive (Ferrante et al, 1993). Records for 1993 and 1994 will be added soon.

These records were rigorously linked within each data source to detect recurrent crashes and hospital episodes. Linkage between each data source expanded the information available for each casualty in each crash. These linkages were conducted using specialised software employing probabilistic techniques on name-identified data from each source. The quality and accuracy of the linkage process and the resultant linked data has been thoroughly investigated and reported elsewhere (Rosman et al 1994, 1996).

These linked records have not only increased the amount of information available for each casualty, but have enabled injury status to be more accurately defined through reference to the cause of death on the death certificate and the detailed diagnoses on the hospital discharge record. The merging of police reports with vehicle licence details prior to linking with the hospital discharge records enabled us to measure the determinants of severe injury using crash and vehicle parameters. The details available on the vehicle licence record include the make and model of the vehicle, its year of manufacture and its weight.

It is anticipated that the linkage of police, transport and health information on road crash casualties will continue. A review of data collection procedures in Western Australia is in progress with an expected improvement in the timeliness and quality of all information. New data sources and reporting mechanisms are being investigated. As this process takes effect the database will grow from a research tool to one which can monitor the effect of safety interventions and immediately report on their outcome. Interest in this concept has been shown by police, road and transport authorities with widespread support for the adoption of an enhanced linked data system for coordination and management of all aspects of road safety.

Other jurisdictions have become interested in the use of linked transport and health data to monitor road safety interventions. Demonstrated reductions in injuries and deaths and the consequent savings in cost to the community from safety interventions have helped to argue for their adoption. The US Crash Outcome Data Evaluation System (CODES) project, funded by the National Highway Traffic Safety Administration (NHTSA) in seven states, linked data from police crash reports, emergency medical services, hospital emergency departments, hospital discharge files, claims and other sources without using name-identified records. The linked information was used to evaluate the benefits of seat belts and motorcycle helmets (NHTSA, 1996).

The contribution to the severity of outcome of certain crash, environment, vehicle and casualty factors can be addressed using such linked databases. Attention can be focussed on one aspect (eg, the crashworthiness of vehicles) while controlling for other factors using sophisticated multi-variate analyses.

The crashworthiness of vehicles, or their potential for causing injuries, can be assessed in a laboratory where new vehicles are crashed into barriers under controlled conditions. Vehicle factors in road crashes can also be studied by examining the crashed vehicles soon after the crash and reconstructing the crash circumstances from interviews with police, witnesses and casualties. This process can be difficult, time consuming and expensive.

Large datasets containing information on all reported crashes in a geographical area have the advantage of allowing more powerful analyses. The Monash University Accident Research Centre (MUARC) used injury data

from the Traffic Accident Commission (TAC) in Victoria, merged with police reports of crashes, and police reported tow-away crashes in New South Wales to calculate the crashworthiness of several makes and models of vehicles. Injury risk was calculated from the NSW data and injury severity was calculated from the Victorian TAC casualty records (Cameron et al, 1994).

In the late 1960s the Australian Design Rules (ADRs) were introduced to set manufacturing and accessory standards for new vehicles. Rules which would influence the severity of an injury in a crash came into force mainly between 1969 and 1974. Seat belts had to be fitted in passenger cars for front seats in 1969 and for rear seats in 1971. For these vehicles, seat anchorage standards were introduced in 1971 and 1972 and head restraint rules were introduced in 1972, 1974 and 1975. Standards for steering columns date from 1971 and strength standards for side doors date from 1977.

In this paper, the results of preliminary analyses of the vehicle factors influencing injury severity of drivers of passenger cars has been used to demonstrate the power of simultaneous access to crash and injury details. The year of manufacture of vehicles has been used to identify the effect of vehicle manufacturing standards introduced since 1969.

METHODS

Data sources

The WA Road Injury Database consists of linked police crash reports, hospital discharge records, ambulance trips and death registrations for road crash casualties between 1988 and 1992. During this period, there were approximately 70,000 casualties of road crashes reported to the police of which about 10,000 were matched to a corresponding hospital discharge record of a casualty admitted as a result of a road crash (ICD9 CM codes E810.0 to E826.9). About 1,400 death registrations linked to either a police crash report or a hospital discharge record.

The linkage process was performed using the Generalised Iterative Record Linkage System (GIRLS) on name- identified records from all sources. Other information used to identify individual casualties included date of crash or admission to hospital; name and gender of the casualty; road user type; and cause of death. Probabilistic linkage allowed matching to occur based on the probability of a link (weight) calculated from agreement or disagreement of complex sets of rules. Several passes through the data were needed to extract all possible links, with manual checks at each pass to ensure separation of definite and possible links.

In order to calculate the crashworthiness of vehicles, records of drivers were selected from the Road Injury Database. Factors available for analysis were the age and gender of the driver, the crash type and the speed limit at the crash site. Vehicle factors other than the year of manufacturer were the weight of the vehicle, the point of impact, whether the vehicle was the colliding or target vehicle and whether the vehicle was towed away. All these factors were available in the Police section of the database.

Injury status was available for those drivers admitted to hospital from their matched hospital discharge record. Abbreviated Injury Severity (AIS) scores were assigned using the ICDMAP software from Johns Hopkins University. Overall severity scores as well as an AIS for each body region were calculated from the 18 diagnosis fields available and added to each hospital discharge record. The Maximum Abbreviated Injury Score (MAIS) was used in the following analyses.

Definitions

Injury severity The Abbreviated Injury Scale (AIS) is a severity measure usually assigned to acute injuries. It was developed by the Association for the Advancement of Automotive Medicine (AAAM) to determine the risk of death. However, software developed by the Johns Hopkins University can be used to convert injuries recorded on the hospital discharge record (coded according to the International Classification of Diseases (ICD 9CM)) to AIS (McKenzie et al, 1985). Evaluation of several measures of injury severity based on the ICD9 CM codes has shown that a score of AIS three or greater is highly correlated with other measures and produces similar results. This is a convenient measure which can readily be used in regression analysis (Rosman et al, 1996). A severe injury was defined to be one which required admission to hospital and the injury diagnoses yielded an AIS score of three or greater.

Crashworthiness Crash worthiness of a vehicle is defined here as the risk of severe injury to the driver in any crash. The risk of severe injury is calculated by multiplying the probability of injury to the driver in a reported road crash by the probability of severe injury in a crash in which the driver was injured. This two step process was necessary because the casualty records were held separately from the property damage records in the linked database. Both sets of records covered the same five year period (1988-1992).

Logistic Regression

When calculating the risks of injury to the driver due to vehicle factors it is necessary to control for the type of crash as well as environmental and driver factors which could also contribute to the severity of injuries to the driver.

For binary outcome measures such as 'any injury' compared to 'no injury' and 'severe injury' compared to 'minor injury', the appropriate regression technique is logistic regression (Hosmer and Lemeshow, 1989). This method models the simultaneous independent effect on the outcome of several competing factors. Models of injury risk and injury severity examined the effect of the year of manufacture, driver age (<25; 25-59; >=60) and gender, crash type (single vehicle; multi-vehicle) and speed limit (<75kmh; >= 75kmh).

RESULTS

A total of 235,044 drivers of passenger vehicles were selected for analysis of whom 29,021 had been injured. Of those injured, 4,602 had been admitted to hospital, 983 who survived with severe injuries and 605 deaths. Thus there were 1,588 drivers in the 'severe' injury (MAIS>=3) group.

The risk of injury and the risk of severe injury for each year of vehicle manufacture are displayed in Table 1. The values apply to male drivers under 25 years in a multi-vehicle crash in a low speed zone (under 75 kmh). This set of criteria represents the lowest risk situation. The highest risk situation is for female drivers over 60 years, in a single vehicle crash, in a high speed zone. The age groups and speed zones are those used by Cameron et al, 1994 in their study of the crashworthiness of specific vehicle makes and models. The risks calculated here are appreciably lower than those of Cameron et al for two reasons. The numerator of all drivers with 'severe' injury, or injuries of severity AIS three or greater or death, is more strictly defined and the denominator of all police reported crashes involving a standard passenger vehicle is more broadly defined than the tow away crashes used by Cameron et al.

Table 1.
Injury risk by year of vehicle manufacture

Year of vehicle manufacture	Risk of injury if in a crash	Risk of severe injury if injured	Risk of severe injury if in a crash
1969	.0135	.0100	0.0001350
1970	.0085	.0137	0.0001160
1971	.0059	.0143	0.0000844
1972	.0061	.0093	0.0000567
1973	.0052	.0094	0.0000489
1974	.0031	.0065	0.0000202
1975	.0029	.0061	0.0000177
1976	.0022	.0053	0.0000117
1977	.0023	.0063	0.0000145
1978	.0020	.0052	0.0000104
1979	.0019	.0057	0.0000108
1980	.0016	.0048	0.0000076
1981	.0017	.0049	0.0000083
1982	.0017	.0053	0.0000090
1983	.0017	.0056	0.0000095
1984	.0014	.0050	0.0000070
1985	.0013	.0042	0.0000055
1986	.0017	.0056	0.0000095
1987	.0020	.0052	0.0000104
1988	.0016	.0046	0.0000074
1989	.0015	.0045	0.0000067
1990	.0015	.0045	0.0000067

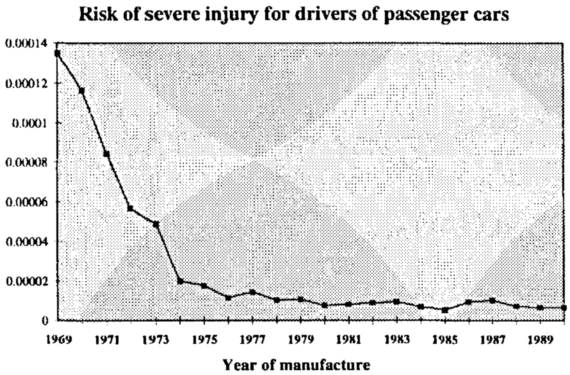

Figure 1.
Risk of severe injury by year of vehicle manufacture (1969-1990)

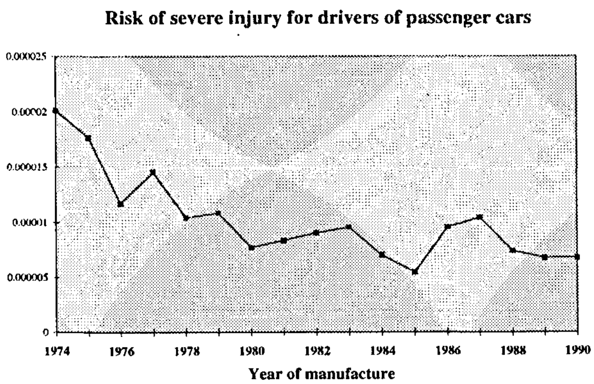

Figure 2.
Risk of severe injury by year of vehicle manufacture (1975-1990)

From Figures 1 and 2 it can be seen that the risk of severe injury for drivers involved in a road crash was greatest in 1969 (140 in 1,000,000). This fell to about 17 in 1,000,000 by 1975 and further to about 7 in 1,000,000 by 1980. Figure 1 illustrates the sharp decline in severe injury risk occurring between 1970 and 1975 by when most of the design rules affecting severe injury were in place. However, it is evident from Figure 2 that a further significant, if less rapid, decline in risk occurred between 1975 and 1980. It should be possible to measure the effect of the introduction of air bags in passenger vehicles in future analyses using 1993, 1994 and 1995 linked police and hospital data.

Preliminary investigation of alternative criteria in the risk calculations indicate regrouping of drivers' age (<=45; 45-64; >=65) would be preferable since injury risk increased at age 45 and again at age 65. Three speed limit zones (<=70; 71-90; >90) have also been proposed to reflect the speed limits in place on most roads and highways in Western Australia. More crash categories and inclusion of additional factors such as the weight of the vehicle, its role in the crash and the point of impact are under investigation. These results will be used with economic and long term outcome estimates in studies of harm reduction.

CONCLUSION

Linked road crash and injury data provides a valuable resource for research into the determinants of injury. By focussing in this paper on vehicle factors, we have measured the effect of the adoption of vehicle design standards on injury outcome for the Western Australian population over five years. These results demonstrate the possibilities for the thorough evaluation of road safety interventions taking all relevant factors into account. In consultation with data collection agencies, the Road Accident Prevention Research Unit is exploring ways of using record linkage, geographical information and data warehousing techniques to improve the timeliness, scope, accuracy and completeness of the data sources. In addition to providing an extremely valuable research tool, this work will also provide an executive decision support system designed to assist road safety agencies in this state.

REFERENCES

Cameron, M.; Finch,C.; Le,T. *Vehicle crashworthiness ratings: Victoria and NSW crashes during 1987-1992. Summary Report* Monash University Accident Research Centre. Report No.55 February 1994.

Ferrante,A.M.; Rosman,D.L.; Knuiman,M.W. The construction of a road injury database. *Accident Analysis and Prevention* 25(6):659-666;1993.

Hosmer,D.W.; Lemeshow,S. Applied logistic regression. New York: Wiley;1989.

McKenzie,E.J.; Steinwachs,D.M.; Shankar,B. Classifying trauma severity based on hospital discharge diagnoses. Med Care 27(4);1989.

Rosman, D.L.; Knuiman,M.W. A comparison of hospital and police information on road crash casualties. *Accident Analysis and Prevention*. 26(2):215-222;1994.

Rosman,D.L.; Knuiman,M.W.; Ryan,G.A. An evaluation of road crash injury severity measures. *Accident Analysis and Prevention.* In press; 1996.

Rosman,D.L. The feasibility of linking hospital and police information on road crash casualties without names. *Accident Analysis and Prevention.* In press; 1996.

U.S. Department of Transportation, National Highway Traffic Safety Administration. *Benefits of Safety Belts and Motorcycle Helmets.* Report to Congress, February 1996.

ANALYSIS OF THE CRASH EXPERIENCE OF VEHICLES EQUIPPED WITH ANTILOCK BRAKING SYSTEMS (ABS)

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ABSTRACT

This paper describes the findings from initial analyses of the crash experiences of passenger cars (PCs) and light trucks and vans (LTVs) equipped with antilock braking systems (ABS). Separate analyses were conducted for PCs and LTVs. Detailed findings are presented for PCs and LTVs for each type of ABS system, using four individual crash types, and on favorable or unfavorable road surfaces.

INTRODUCTION

Section 2507 of the Highway Safety Act of 1991 (the Act) directed the National Highway Traffic Safety Administration (NHTSA) to initiate rulemaking to consider the need for any additional brake performance standards, including ABS, for all passenger vehicles, i.e., PCs and LTVs weighing less than 10,000 pounds. Meanwhile, automobile manufacturers have offered ABS to consumers either as a standard feature or as an option on millions of PCs and LTVs since 1985.

The objective of ABS is to automatically modulate braking pressure to prevent the vehicle's wheels from locking during braking. Two types of ABS systems are presently available: All wheel (AWAL) and Rear wheel (RWAL). RWAL is much more prevalent in the on-road LTV fleet, while most of the on-road PC fleet is equipped with AWAL.

The focus of this study was to determine the impact of ABS on specific types of crashes considered to be "ABS relevant", by examining the change in the proportion of crashes in which ABS had the potential to prevent the crash, assuming that the presence or absence of ABS does not affect the occurrence of nonrelevant crashes.

DATA

Data from NHTSA's Fatal Accident Reporting System (FARS) were used to analyze the crash experience of ABS-equipped and non-ABS-equipped vehicles in both the PC and LTV analyses. FARS, begun in 1975, contains a census of the most severe traffic crashes, i.e., those resulting in a fatality, occurring in the United States each year. FARS data for calendar years 1989-1993 were used in the analyses.

For the PC analysis, state crash files from Florida, Missouri, and Pennsylvania for the period 1989 - 1993 were used, along with data from Maryland for the period 1989 - 1992 in addition to the FARS data. In the LTV analysis, data from Florida, Maryland, Michigan, and Missouri for the period 1989 - 1991 were used along with the FARS data. These states were chosen for study in the analyses because each, for the period shown, recorded the vehicle identification number (VIN) for vehicles involved in crashes of all severities. The VIN was needed in order to identify specific makes and models of vehicles equipped with ABS and to identify comparable non-ABS equipped vehicles.

For both the PC and LTV analyses, four types of crashes were identified as "ABS-relevant", i.e., crashes for which it was assumed that ABS would be beneficial in avoiding the crash and/or ameliorating the outcome of the crash. The four "ABS-relevant" crash types identified were: (1) rollovers, (2) side impacts with parked vehicles or fixed objects, (3) frontal impacts with parked vehicles or fixed objects, and (4) frontal impacts with another motor vehicle in transport. Crash types (1) and (2) typically involve driver loss of control. For these crash types, ABS is expected to increase the directional stability of the vehicle, allowing the driver to maintain greater control and remain on the roadway. Crash types (3) and (4) typically involve driver loss of control or the presumption that the driver did not apply the brakes or was not able to stop in time. Both analyses examined the experiences for ABS and non-ABS equipped vehicles in the four ABS-relevant crash types, compared to a control group of crashes that were assumed to be unaffected by the presence of ABS. The control group consisted of crashes in which vehicles had rear damage only, e.g., crashes involving vehicles backing into another vehicle or fixed object, non-rollover non-collisions, and other multivehicle crashes that did not involve a frontal impact. In addition, the ABS-relevant crashes and control crashes were further

classified based upon whether or not the crash occurred under "favorable" or "unfavorable" road conditions. Road surfaces that were paved, free of debris, and dry were considered "favorable." Road surfaces that were wet, snowy, icy, unpaved, or composed of gravel were considered "unfavorable."

ANALYSIS

The basic approach was to study the change in the proportion of ABS-relevant crashes for ABS equipped vehicles compared to non-ABS equipped vehicles. Since the presence or absence of ABS could not be expected to be the only important factor in the crash, the analysis technique used must control for factors related to the driver, environment, or other crash characteristics.

Logistic regression, as described in Hosmer and Lemeshow, was chosen as the analytical method. This technique has been successfully used in other NHTSA studies. To accurately estimate the impact of ABS, variables were included in the logistic regression to control for those factors, other than ABS, which could influence the proportion of ABS-relevant crashes. For example, if ABS equipped pickup trucks are more likely to be driven by younger males than by other segments of the driving population, then driver and vehicle characteristics could confound estimating the impact of ABS. To address this issue, variables representing the age and sex of the driver, whether or not the crash occurred on a curved road segment, whether the crash occurred in a rural setting or an urban setting, and the age of the vehicle were included in the logistic regression models. Using the state and FARS data, for favorable or unfavorable surfaces, for each type of ABS (AWAL or RWAL), for the four ABS-relevant crash types, a logistic regression model was estimated:

LOGIT (P) = AGE YOUNG MALE CURVED ABS RURAL* VEH-AGE (1**.)

Where the data modeled include the particular ABS crash type response being analyzed and control crashes, P is the probability of an ABS-relevant response, AGE is the age of the driver, YOUNG is an indicator variable with the value 1 if the driver is under 25 years of age and 0 otherwise, MALE is an indicator variable representing the driver's sex, CURVED is a variable indicating whether or not the crash occurred on a curved or straight road segment, RURAL is a variable indicating whether or not the crash occurred in a rural or urban area, and VEH-AGE represents the age of the crash-involved vehicle.

Each of these models was re-estimated with only those variables whose coefficients were found to be statistically significant, however, the ABS variable was always retained. The final model results yielded estimates of the ABS coefficients (and their standard errors) for each database (FARS and the various state files), crash type, ABS system type, road surface type (favorable or unfavorable), for PCs and for LTVs. Since each coefficient represents the change in the log odds ratio of an ABS-relevant crash to an ABS-nonrelevant crash in the presence of an ABS-equipped vehicle, a negative coefficient indicates a reduction in crashes associated with the presence of ABS.

While crash reporting thresholds may differ somewhat from state to state, it appears reasonable to assume the effects of ABS should not differ dramatically. The results from the final models appeared to support this assumption, therefore the ABS coefficients for each state were statistically combined to form single estimates of the common log odds ratio for similar levels of ABS system type, crash type and road surface type, using the statistical methods described in Fleiss. These coefficients were translated into the percentage change in the expected number of relevant crashes using:

$$\text{Expected percentage change} = 100*[\exp(\text{ABS coefficient}) - 1] \qquad (2.)$$

Replacing the (ABS coefficient) in the above equation with (ABS coefficient $\pm$ 1.96*(standard error of the ABS coefficient)) yields estimates of the 95% confidence limits for the expected percentage change in relevant crashes. Tables 1., 2., and 3. present a summary of the statistically significant ($p = 0.05$ level) effects of ABS for PCs, AWAL LTVs, and RWAL LTVs, respectively. In each Table, the crash types Roll = rollover crashes, Side = Side impact crashes with parked vehicles or fixed objects, Front = Frontal impact crashes with another motor vehicle in transport, and Ror = Frontal impact crashes with parked vehicles or fixed objects; crash severity All = All severities and Fatal = fatal crashes only; road type Both = favorable and unfavorable, Fav = favorable only,

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*RURAL was not recorded in the Missouri data. A variable indicating whether or not the crash occurred on a road with a 45 MPH or greater speed limit was substituted.

**For RWAL equipped LTVs, SPORT (indicating if the vehicle was a sport utility) and PICKUP (indicating if the vehicle was a pickup) were also included in the model.

and Unfav = Unfavorable only. For each table, 95% CL represents the 95% confidence limit values for the percentage change shown.

Table 1.
Summary of Statistically Significant Effects of ABS for Passenger Cars

Crash Severity	Crash Type	Road Type	% Change	95%CL
All	Roll	Both	+24	+ 6 to + 45
All	Ror	Both	+15	+ 9 to + 22
All	Side	Both	+36	+25 to + 48
All	Front	Unfav	- 35	- 39 to - 32
All	Front	Fav	- 9	- 11 to - 7
Fatal	Roll	Both	+60	+21 to +111
Fatal	Side	Both	+91	+44 to +154
Fatal	Front	Unfav	- 35	- 52 to - 11

Table 2.
Summary of Statistically Significant Effects of ABS for AWAL-equipped Light Trucks and Vans

Crash Severity	Crash Type	Road Type	% Change	95% CL
All	Roll	Both	-36	-54 to -10
All	Ror	Both	-24	-40 to - 5
All	Front	Unfav	-21	-33 to - 6
All	Front	Fav	+14	+ 3 to +27

Table 3.
Summary of Statistically Significant Effects of ABS for RWAL-equipped Light Trucks and Vans

Crash Severity	Crash Type	Road Type	% Change	95% CL
All	Roll	Unfav	-31	-36 to -24
All	Roll	Fav	-46	-51 to -40
All	Side	Unfav	-29	-36 to -22
All	Side	Fav	-15	-23 to - 6
All	Front	Both	+11	+9 to+14
Fatal	Front	Both	+32	+21 to+43

CONCLUSIONS

Several findings for passenger cars are noteworthy; while a significant reduction in non-fatal frontal impacts with another motor vehicle in transport crashes was found to be associated with the presence of ABS, significant increases in non-fatal frontal and side impacts with parked vehicles or fixed objects were also found to be associated with the presence of ABS. For fatal crashes, significant increases in rollover and side impacts with parked vehicles or fixed objects were also found.

For light trucks and vans, the two types of ABS, i.e., AWAL and RWAL were analyzed separately. No significant reductions in fatal crashes were found for either AWAL or RWAL-equipped vehicles. While the relatively small sample size of AWAL-equipped vehicles made it more difficult to detect significant reductions in fatal crashes, a significant reduction in non-fatal rollover crashes was associated with the presence of ABS for these vehicles. For RWAL LTVs, significant reductions in non-fatal rollover crashes and side impacts with fixed objects or parked vehicles were found. However, for RWAL LTVs, significant increases in non-fatal and fatal frontal crashes with another vehicle in transport were also found.

Both analyses are based upon data that comprise the initial years of crash experiences for the first groups of vehicles equipped with ABS. While the findings indicate reductions for specific crash types, increases were also noted. Thus, NHTSA estimates that there has been little or no net crash reduction associated with ABS, to date. Further analysis is warranted, especially for passenger cars. NHTSA, therefore, has implemented a plan of analysis and vehicle testing to obtain a clearer understanding of the performance of ABS, particularly in crashes that typically result in rollovers and collisions with

fixed objects. Meanwhile, NHTSA urges drivers to gain an in-depth understanding of the operation of their ABS-equipped vehicles.

REFERENCES

Fleiss, Joseph, "Statistical Methods for Rates and Proportions". John Wiley and Sons, 1981.

Hertz, Ellen; Hilton, Judith; and Johnson, Delmas Maxwell, "An Analysis of the Crash Experience of Light Trucks and Vans Equipped with Antilock Braking Systems". U.S. Department of Transportation, NHTSA, DOT HS 808 278, May 1995.

Hertz, Ellen; Hilton, Judith; and Johnson, Delmas Maxwell, "An Analysis of the Crash Experience of Passenger Cars Equipped with Antilock Braking Systems". U.S. Department of Transportation, NHTSA, DOT HS 808 279, May 1995.

Hosmer, D.; Lemeshow, S., "Applied Logistic Regression". John Wiley and Sons, 1989.

Kahane, Charles J, "Preliminary Evaluation of the Effectiveness of Rear-Wheel Antilock Brake Systems for Light Trucks". U.S. Department of Transportation, NHTSA, December 1993.

PEDESTRIAN CRASH DATA STUDY - AN INTERIM EVALUATION

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ABSTRACT

In July 1994, a Pedestrian Crash Data Study (PCDS) was initiated within the United States to collect detailed crash reconstruction data for pedestrian crashes. This paper will report on the scope and design of the PCDS. It will also examine the results of early months of data collection and report on the new techniques used for data collection, including the use of video recording for vehicle and scene documentation and the development of a pedestrian contour gauge for the documentation of the pedestrian's contacts with the vehicle. Additional analyses of the pedestrian crash circumstances, including pre-crash, at crash, and injury consequences will, also, be discussed.

BACKGROUND

In 1992, a need was identified for the National Highway Traffic Safety Administration (NHTSA) within the United States Department of Transportation to collect pedestrian crash data through the Crashworthiness Data System (CDS) a component of the National Accident Sampling System (NASS). Detailed pedestrian crash data that had been collected prior to 1987 were becoming obsolete, and new and current data were needed to ensure that pedestrian crash analyses capabilities are consistent with real world crash events.

Pedestrian data collected prior to 1987 as part of the NASS Continuous Sampling System (CSS) had become over nine years old, and the Pedestrian Injury Causation Study (PICS) data collected in the 1970's had become over seventeen years old. NHTSA analysts now needed current data to determine whether late model year vehicles, with their shorter and more sloping hoods, are producing the same type of injuries that occurred during and before the mid-1980's. Additionally, analysts needed to obtain cases having detailed and reliable documentation, suitable for laboratory and computer reconstructions, to establish an injury model for use with instrumented impact devices for simulating pedestrian impacts.

SIZE AND NATURE OF THE PROBLEM

In 1994, pedestrian-vehicle impacts resulted in 5,472 pedestrian fatalities and 90,000 pedestrians injured (see reference number 5). These figures are a slight decrease from 1993 when 5,638 pedestrians were killed and 93,000 were injured. Preliminary figures for 1995 indicate that 5620 were killed and 91,000 were injured. Passenger car, van, and light truck involvements account for nearly 83 percent of the pedestrian fatalities and for nearly 96 percent of the pedestrians injured. One pedestrian is killed by a motor vehicle every 96 minutes and injured every 6 minutes in the United States.

Data on pedestrian injuries from the 1982-1986 NASS data files, the last pedestrian data files available for analyses, show that approximately 40 percent of the pedestrian injuries resulted from contact with the vehicle, 32 percent resulted from contact with the ground and 26 percent of the injuries were from unknown contact sources. Data collected in the PCDS will be used to determine if newly designed vehicles are creating the same or different types of injury patterns since the mid-1980's. These data are needed to determine the types of injuries sustained and the contact mechanisms involved in pedestrian impacts with late model year vehicles.

PRIOR PEDESTRIAN CRASH DATA COLLECTION EFFORTS

In 1977, PICS was initiated to collect data on the crash mechanisms of pedestrian crashes through on-scene investigations of selected crashes. The study investigated 1,997 crashes in 5 major metropolitan areas in the United

States over a 30-month period. The PICS data identified the injury causal agents during the collisions, determined injury severity to help evaluate costs and countermeasures associated with pedestrian crashes, and resulted in suggestions on ways to change vehicle body surfaces to eliminate and/or reduce certain types of injuries.

From 1979 to 1986, NASS CSS collected detailed injury and crash data on over 4,000 pedestrian crashes. The pedestrian data included a representative sample of fatal, injury and non-injury pedestrian crashes for all types of vehicles, including passenger cars, vans, light trucks, and heavy trucks.

Beginning in 1988, the focus of the NASS changed to vehicle crashworthiness and the Crashworthiness Data System (CDS) was implemented. The case selection criteria for the NASS CDS focused on the selection of severely injured occupants of towed vehicles, which excluded most pedestrian crashes from the data system. However, basic pedestrian data continued to be collected through the General Estimates System (GES) component of the NASS. The GES is based on the police accident report information which does not provide the detailed crash investigation data that were collected in the PICS and the earlier CSS. Likewise, pedestrian data gathered in the Fatal Accident Reporting System (FARS) are also based on the police accident report and other official records which do not furnish the type of data needed for detailed analysis of pedestrian crashes.

SCOPE OF PEDESTRIAN CRASH DATA STUDY

The PCDS became operational in 1994 with the first data collection site in Seattle, Washington. Five additional sites became operational during 1995. These sites are: Chicago, Illinois; Buffalo, New York; Fort Lauderdale, Florida; Dallas, Texas; and, San Antonio, Texas. The six sites were selected based on the availability of applicable pedestrian crashes from the 24 CDS locations.

A pedestrian is considered as any person who is on a trafficway or on a sidewalk or path contiguous with a trafficway, or on private property and who is in contact with the ground. Persons in or on a nonmotorist conveyance are not pedestrians and are excluded from this study.

For a crash to qualify for the Pedestrian Crash Data Study:

- The vehicle must be moving in a forward direction at the time of the impact.
- The vehicle must be a late-model-year passenger car, light truck or van. Late-model-year is defined as being manufactured in the last 5 years. It also includes non-late-model-year vehicles where the exterior design is the same as late-model-year-vehicles (e.g. Ford Taurus 1988 to 1994).
- The pedestrian may not be lying down or sitting.
- The striking portion of the vehicle's structure must be original equipment manufacturer (OEM) without previous damage and/or parts removed in the impact area.
- The pedestrian impacts are the vehicle's only impacts.
- The first point of contact between the vehicle and the pedestrian must be forward of the top of the A-pillar.

The Pedestrian Crash Data Study will collect data on 900 crashes over a three to four year period for clinical analysis. In 1994, 16 cases were initiated during the start-up phase and 91 cases were collected in 1995. The yield for 1996 and 1997 is expected to be 300 cases per year. The projection for 1998 is about 200 cases. Approximately 74 cases are included in the data analyses for this paper.

OPERATIONAL PROCEDURES

The data are collected through on-scene crash investigations (or within 24 hours) of pedestrian crashes involving late model year passenger cars, vans, and light trucks. If a vehicle or pedestrian can not be located and interviewed, or the vehicle damage measurements can not be obtained within 24 hours of the crash, the case is dropped from the study.

Police cooperation has been established at each site to conduct on-scene crash investigations or follow-ups within 24 hours. Notification of the crash is facilitated through a variety of media including the telephone and monitoring of police and emergency medical services radio frequencies.

If an investigation is conducted on-scene, the

researcher notifies the police of their presence immediately upon arrival at the scene and proper investigation protocols are followed so as to ensure there is no interference or disruption to any police investigation. Once a determination is made that the case meets the selection criteria, the crash investigation commences.

DATA COLLECTION FORMS

Data are collected and automated on 144 different variables in the Pedestrian Crash Data Study. Environmental, human, and vehicle data are collected for all phases of the crash. As shown in table 1, there are 24 variables in the pre-crash phase, 38 variables in the at-crash phase and 82 or more variables in the post crash phase. Additionally, there are 6 variables that are derived on the analysis files as they are created, such as the Maximum AIS (MAIS), Day of Week, and Injury Severity Score (ISS). A complete listing of automated variables is included in the appendix.

Table 1.
The Distribution of PCDS Forms by their Relationship to the Crash Events

Number of PCDS Variables by Event Type			
	Pre-Crash	At-Crash	Post-Crash
Environmental	11	11	0
Human	11	16	47*
Vehicle	2	11	35

* add 13 variables per injury

There are five primary data collection forms: Accident Form; Pedestrian Assessment Form; Pedestrian Injury Form; General Vehicle Form; and, Vehicle Exterior Form.

The Accident Form collects data on the general characteristics of the event such as the time of day, the vehicle class, and the general area of damage for the vehicle involved.

The Pedestrian Assessment Form documents data on the characteristics of the pedestrian (age, sex, height, weight), their avoidance actions, orientation at impact, alcohol and drug presence, and the consequences of their injuries such as their treatment, hospital stay, and injury severity. Height measurements include ground to knee, hip, shoulder and overall height.

The Pedestrian Injury Form contains thirteen variables for **each** injury that is documented from official or unofficial records. Each injury is coded according to AIS90 injury descriptors with modifications for NASS CDS. In addition to the injury description, additional data collected for each injury include: the contact source of the injury; the striking profile; the type of damage; and the damage depth. Injuries are documented sequentially on the form by order of occurrence.

The General Vehicle Form contains vehicle make and model data, official record data for the driver, such as alcohol and drug information, pre-crash data as to vehicle movement, environmental data, and reconstruction data for determining impact speed.

The Vehicle Exterior Form contains pedestrian contact data for both front and side pedestrian contacts, front and side pedestrian vertical and wrap measurements, detailed hood measurements, material identifications, and vehicle dimensions. Non-automated data include: the scene diagram; the crash case summary form; and, interview forms for the pedestrian and driver.

NEW TECHNIQUES IN DATA COLLECTION

Two new techniques were implemented for this study. The use of video cameras was implemented to quickly document the on-scene crash data. A contour gauge to measure pedestrian contacts was developed to expedite vehicle inspections and provide a measurement grid for quality assurance.

When the study was initiated, the Hi8 video camera was compared to 35mm single lens reflex cameras. The study showed that the video camera was capable of quickly capturing physical evidence during an on-scene investigation. In addition, the field researcher provided an audio description of the video image. Evidence generated in a pedestrian crash is often very minor and barely visible. The Hi8 video camera is ideal for documenting this type of evidence because it is capable of viewing detailed physical evidence on the pavement left from the pedestrian at the point of impact, or even a tiny thread of fabric left

on the vehicle. The slide photography, traditionally done in NASS CDS, is not as efficient in capturing on-scene evidence as the video camera. The video camera is capable of filming thirty frames per second which enables data quality reviewers to freeze frames of captured evidence and to make accurate assessments of the data collected.

With Hi8 video selected as the medium, a structured guideline for video taping each case has also been developed. The accident scenes are video taped to show actual paths of the vehicle and the pedestrian along with audio descriptions which associate the evidence with a scaled reference in the environment. The vehicle is also documented in a video format where each contact made by the pedestrian is viewed with various angles, closeups, and finally referenced with the contour gauge.

The contour gauge was created to provide a frame of reference on the vehicle for verifying the accuracy of the measurements and to provide an efficient and uniform method to document the pedestrian contact evidence. In addition, it provides an opportunity to reapply the exact locations of contacts on similar vehicles for simulation of impacts. The contour gauge consists of two scaled ribbons which create an isometric coordinate system which wraps to the shape of each vehicle. The first scaled ribbon begins on the ground, below the center of the front bumper, and wraps over the vehicle along the longitudinal center which creates the "X" axis. This "X" axis wrap scale also assists in referencing the wrap orientation of the pedestrian with the ground. The "Y" axis is then placed laterally across the hood, or windshield with some vans, and referenced with the front axle of the subject vehicle. Scaled contact markers are then placed on the vehicle to identify the evidence and measured within the coordinate system created by the contour gauge. More than one marker may be used to identify the evidence when long streaks or large swiping areas and dents occur.

The new technology permits capturing a quality and controlled visual documentation of each pedestrian crash case in a video format, along with duplicating accurate scaled measurements of physical evidence with the development of the contour gauge. A reliable source of data documentation has been developed for use in computer reconstructions or actual simulations and examinations of pedestrian interactions with vehicles.

DATA ANALYSIS

Data from seventy-four pedestrian crashes representing the first eighteen months of the study were analyzed for this study. All cases were single vehicle and single pedestrian with an equal number of drivers and pedestrians.

Pedestrian Characteristics

Thirty-four (46%) of the pedestrians in the study were male. None of the 40 (54%) females who were involved were reported to be pregnant. Eleven (15%) of the pedestrians were under the age of 13, while 7 (10%) were between the ages of 13 and 19. An additional 45 of the pedestrians were between the ages of 19 and 65, and 10 (14%) were over the age of 65. There was one pedestrian whose age was unknown. Figure 1 shows the distribution of the pedestrians by their age.

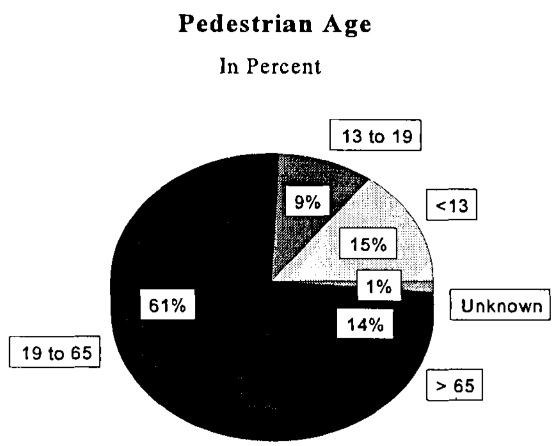

Figure 1. Percentage of involved pedestrians by age.

Fifteen (20%) pedestrians were 152 centimeters (5 feet) or shorter. An additional 30 (41%) were between 153 and 168 cm (between 5' and 5' 6"). Twenty-seven (36%) were between 169 and 183 cm (between 5'6" and 6 feet). Two pedestrians (3%) were over 183 cm (six feet) tall.

Vehicle Characteristics

Figure 2 shows the distribution of the vehicle types by their involvement in the PCDS. Of the involved vehicles, 50 (68%) were passenger cars and

24 (32%) were other light vehicles, collectively referred to as light trucks, vans, and utility vehicles. This is nearly identical to the composition of vehicle registrations in the United States. However, within the "other" group, the mix of vehicles found in this study differs from registration data. The four utility vehicles in the study make up five percent of the data, closely matching the six percent of registered vehicles. Overall, vans make up eight percent of registered vehicles, but 13 vehicles (18 percent) in the study were vans. Moreover, the split for registered vehicles is equal for minivans and full-size vans, each making up about four percent of the fleet. In the present study, 15 percent of the vehicles were minivans, and 3 percent (2 vehicles) were full size vans. The remaining 7 vehicles (9 percent) were pickup trucks, which are 19 percent of registered vehicles. The present study differs from the registered vehicle fleet mainly by an over representation of minivans, and an under representation of pickup trucks.

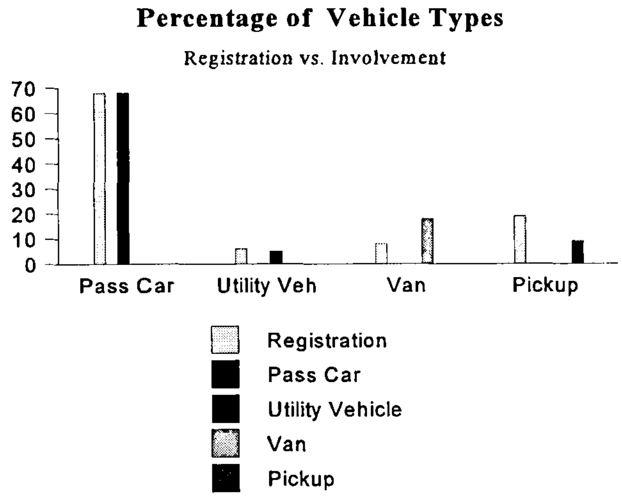

Figure 2. Percentage of vehicle types by registration and involvement.

Figure 3 shows the distribution of the pedestrians injuries by vehicle type. There were 411 injuries to the pedestrians. Two hundred eighty-five (69%) of the injuries were from passenger cars. Thirty-one (8%) of the injuries were from utility vehicles, 41 or 10% from pickups, and 54 or 13% from vans. These percentages are all close to the distribution of vehicles in the study.

Pre-Crash

Prior to the crash, 51 (69%) of the pedestrians were walking, 20 (27%) were running or jogging and 3 (4%) were not moving.

The pedestrian pre-crash actions included: 63 (85%) were impacted when crossing a roadway or driveway; 4 (5%) were moving with or against the flow of traffic; 4 (5%) pedestrians were stopped; and the remaining 3 (5%) had various other pre-crash actions.

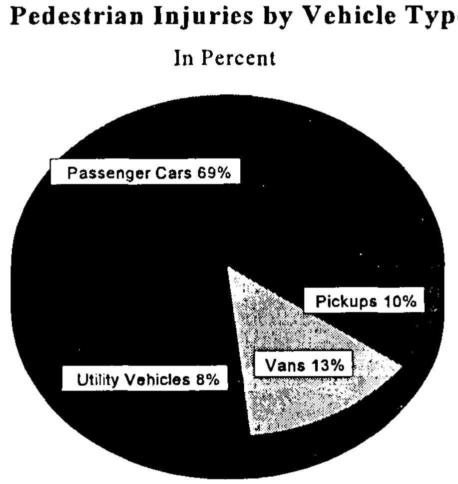

Figure 3. Percentage of pedestrian injuries distributed by vehicle type.

The vehicle driver's pre-crash attention to the driving task was reported as paying full attention for 58 (78%) crashes and distraction by other occupants or outside events accounted for 16 (22%) of the crash events. Almost half (49%) of the drivers intended to continue straight through an intersection or the crash was not intersection related. The driver's critical pre-crash event in over half (55%) of the cases was a pedestrian in the roadway. This suggests that the pedestrian did not have the right of way. This assumption was made based on the driver's intent to travel straight, usually at a higher speed.

When a vehicle was involved in a turning maneuver, a pedestrian was more likely to be struck in a left turn (28%) rather than a right turn (14%) action. The driver's critical pre-crash event was the presence of a pedestrian in the roadway in 41 (56%) crashes. When interviewing the drivers, in the action of turning at an intersection, many appeared to have had their primary attention focused on other motor vehicles with the pedestrian as a second priority.

Also, the timing involved in each turn usually encountered a waiting period for traffic to clear giving the chance of a pedestrian to enter the scene. Most drivers reported to have started their left turn through a gap of opposing traffic without checking for pedestrians to their left. The drivers did not consider that the pedestrian was in the cross walk and had the right of way. When the driver's intention was to perform a right turn, they reported that their primary attention was for checking traffic from their left and not looking for pedestrian traffic on their right.

Forty-six of the drivers (78%) had the opportunity to attempt an avoidance maneuver. The driver's most likely avoidance maneuver was braking only in 34 (46%) of the crashes. However, in 12 of 74 (16%) of the cases, the driver braked and also made a steering maneuver. Drivers made no avoidance maneuver in 27 (37%) of the crashes.

At Crash

Fifty-seven (77%) crashes were at or related to an intersection or driveway. The weather was reported as being clear for 46 (62%) crashes, rain for 27 (37%)) and snowing 1 (1%) of the crashes. However, since most of the cases were from the data collection site in Seattle, Washington the weather will be reflective of Seattle with 141 days with rain (39%).

The variables describing the pedestrian's orientation at impact enables the examination of the pedestrian's body, as it interacts with the vehicle at impact. At various impact speeds the orientation of the pedestrian has contributed to the level of injury. The pedestrian is wrapped or carried by the vehicle in 29 (39%) of the cases. The pedestrian is knocked to the ground in 21 (28%) crashes, thrown in 9 (12%), shunted or pushed aside in 8 (11%), passed over in 2 (3%) and all other impact types account for the 5 (7%) remaining cases as noted in Figure 4.

The pedestrian's arm orientations at impact varied: 35 of 74 (47%) pedestrians impacted were holding something in their hands or arms, 36 (49%) were not holding something. The carrying of an object may contribute to or prevent an injury depending on the crash dynamics. One pedestrian extending her arm while holding an umbrella received a fractured forearm when the leading hood edge of a sport utility vehicle struck her arm. If her arm had not been in this position it would not have been struck.

A positive example of carrying an object was noted in a case with a child wearing a backpack. At impact she wrapped over the front hood of a vehicle with her back against the striking surface. Because her backpack absorbed most of the impact force, she received no significant injuries.

Pedestrian To Vehicle Interaction

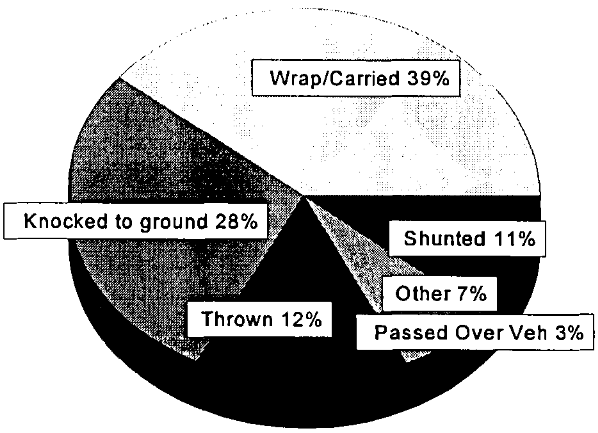

Figure 4. Percentage of crashes distributed by pedestrian to vehicle interaction.

Sixty-five (88%) of the pedestrians struck were oriented with their side to the striking vehicle. In examining the leg orientation, 45 (61%) of the pedestrians had one leg forward and apart from the other leg at impact. The combination of leg positioning and being struck on their side caused the pedestrian's hips and upper body to rotate as they were impacting the vehicle. The physical evidence on the vehicle has shown the upper extremities swiping and at the same time denting the hood. The combination of this action with a pedestrian running results in enhanced pedestrian momentum. The running pedestrian's momentum usually increased the severity of the injury. One such case resulted in the nylon jacket at the pedestrian's elbow being melted to the hood. In addition, the elbow also formed a curved narrow dent.

Figure 5 shows the distribution of impact speeds in the PCDS grouped in 15 KMPH (9 MPH) ranges . The impact speed is coded as a measure of severity in almost all of the cases (99%). The reconstructionist provided a range of accuracy based on the type of impact, availability of physical evidence and accuracy of the documentation. Thirty-three (45%) were reported as accurate to 2 KMPH, 34

(47%) were accurate to 8 KMPH, 1 (1%) was accurate to 16 KMPH. In 5 cases (7%) the reconstructionist did not make an assessment of their accuracy. The actual impact speed is reported on the PCDS file.

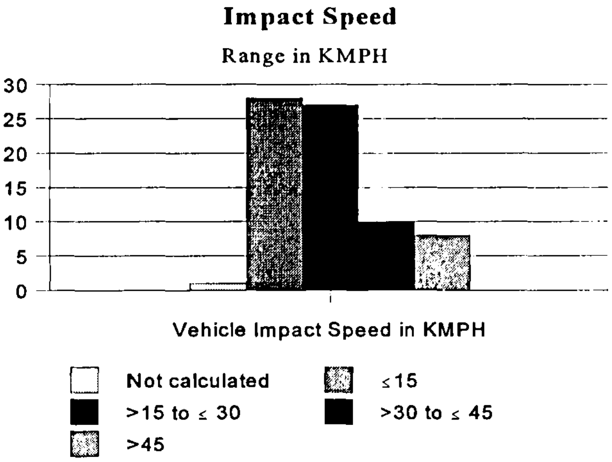

Figure 5. Number of crashes broken down by impact speeds.

The exterior of the vehicle that strikes the pedestrian is throughly documented, including 37 automated variables and detailed sketches of pedestrian contacts. The documentation is based on the plane of initial contact. The front plane contains data on 64 (86%) cases. While the side plane accounts for the remaining 10 (14%) of the cases.

The wrap distance from the ground to where a head contacted are shown in Figure 7. The ground to head contact is collected for both planes. Previous studies have shown the head contact to be a significant source of injury. However, in the 64 front plane contacts, 37 (50%) had no head contact.

Outcome vs. Injury

Of the seventy-four pedestrians involved in crashes, 72 pedestrians or 97% received some type of injury and 67 pedestrians or 90% received treatment at a medical facility. Although 5 people were injured, they did not receive any type of treatment for their injuries. Over half of those involved, 39 or 53% were treated at a trauma center and 24 or 32% were transported to a hospital for treatment. The average hospital stay for the 21 pedestrians who were hospitalized was five days.

Injury data were collected from both official and unofficial data sources (autopsy reports, hospital discharge summaries and emergency room reports, interview data, etc.) and coded to NASS injury coding protocols which are based upon AIS90. The AIS90 developed by the Association for the

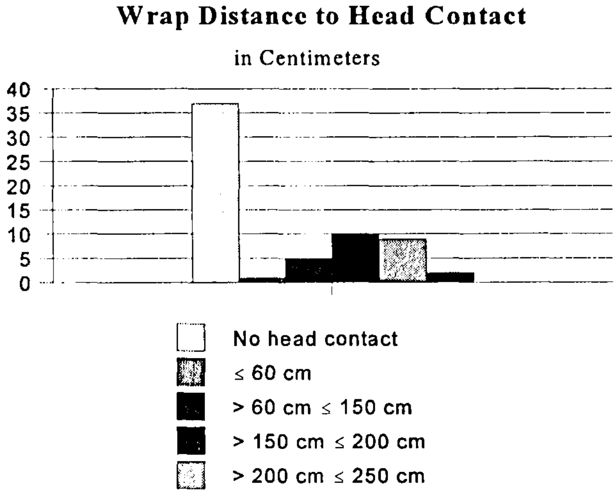

Figure 6. Number of crashes broken down by wrap distance to head contact.

Advancement of Automotive Medicine is a systematic way to describe injuries by using a specific coded format. One major modification that NASS made to AIS90 was the inclusion of a single digit to account for the location or aspect of the injury on body (e.g. left leg, right arm, forehead, etc.).

The overall distribution for Maximum AIS (MAIS), which is the highest single AIS code for a patient with multiple injury levels, is shown in figure 7 . The highest AIS severity sustained by any pedestrian in any crash was no higher than an AIS 5. Sixty-five or 88% of the pedestrians received more than one injury.

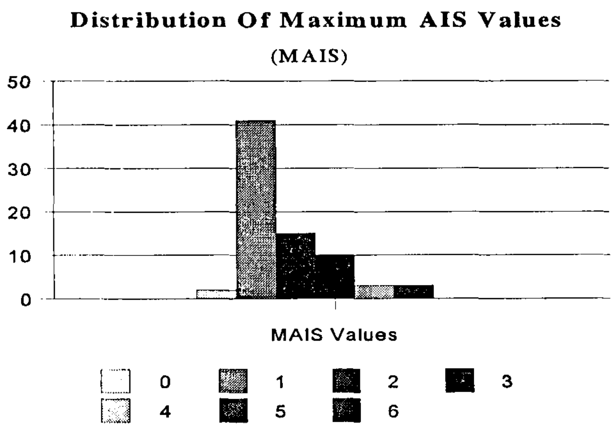

Figure 7. Number of crashes broken down by maximum AIS.

A total of 411 injuries were sustained by the 72 pedestrians that were injured. Lower extremity injuries accounted for 158 or 38% of the injuries followed by the upper extremities having 79 or 19% of the total injuries. The face was the next most frequent body region injured having 69 or 17% of the injuries, the head receiving 53 or 13 % of the injuries and the spine receiving 31 or 8% of the total injuries. The total injury distributions for all body regions are shown in Figure 8.

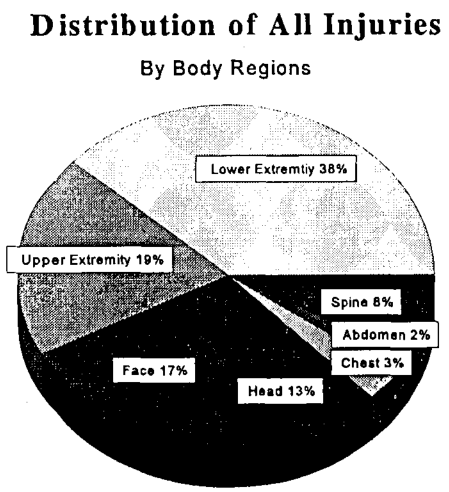

Figure 8. Percentage of all injuries distributed by body region.

It is noted that overall injury distributions among body regions change when soft tissue or integumentary injuries are excluded from the total injury distributions. Distributions for the 129 non-integumentary injuries among body regions is shown in Figure 9. Lower extremity injuries remain the most frequent body region injured with 34%, however, the head then represents 22% of injuries, followed by the spine with 16% and the upper extremities with 13% of the injuries.

The 411 injuries that occurred actually represented 95 different types of injuries. Soft tissue injuries (AIS 1) accounted for 282 or 69% of the injuries and accounted for 28 of the different injury types by body region. Deleting these injuries due to their minor severity and outcome, the following is a listing of the five most frequent injuries that occurred along with the injury's count:

Injury	Count
Lower Extremity Fractures	44
Upper Extremity Fractures	17
Head Injury - LOC	15
Cerebrum Injuries	12
Facial Fractures	9

LOC= Loss or level of Unconsciousness

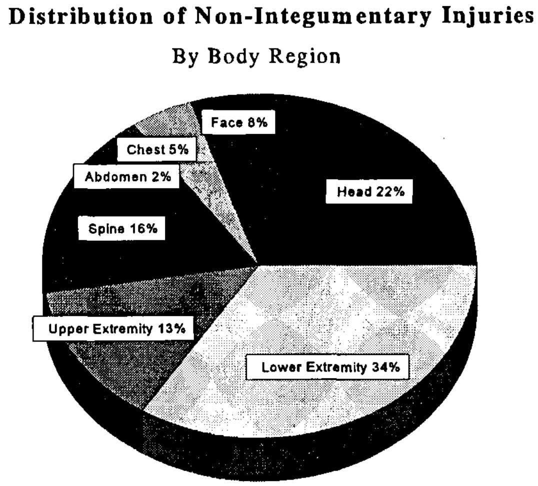

Figure 9. Percentage of all non-integumentary injuries by body region.

In regard to head injuries, it is noted that only one skull fracture occurred, whereas there were 12 injuries to the cerebrum and none to the cerebellum. Fifteen diffuse or Loss of Consciousness (LOC)

injuries also occurred. Only four rib fractures occurred to the injured pedestrians. It is noted that no injuries occurred to the throat.

The data also show that almost half (32 of 74) of the cases have collected a head wrap contact measurement to the vehicle denoting that the face or head contacted the hood or windshield. Sometimes these head contacts could result in no injuries, but this also clearly shows that, half of the time, the head or face did make contact with the vehicle. This also correlates with 29 of 74 (39%) pedestrian interactions are occurring as being wrapped and wrapped slid to windshield types. In some cases, which involved the center of gravity height of the pedestrian closely matching the wrap transition point, more significant injuries or even a pelvic fracture resulted. With the number of vans, trucks and sport utility vehicles (24 of 74, 32%) involved in the study so far, the wrap transition is generally higher than the average person, resulting in more of a blunt force and slow wrap effect. In other cases where the wrap transition is farther below the pedestrian's center of gravity, the effect is a faster wrap sometimes resulting in more trauma to the head or upper extremities. In one such case a pedestrian wrapped and slid to the windshield striking the A-pillar which resulted in a serious head injury. It should be noted that there are cases where the pedestrians are being struck by the vehicle at significant speeds and have wrapped, with the impact being distributed to the body, and remarkably resulted in no significant vehicle related injuries.

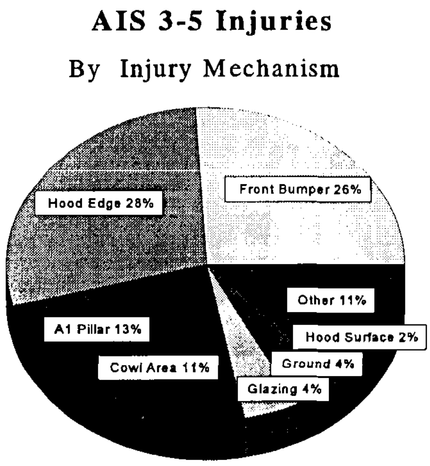

Figure 10. The percentage of AIS 3 to AIS 5 injuries distributed by the injury mechanism.

Injuries are documented on the injury forms according to the sequence in which the body region contacted the vehicle or other injury component (e.g. ground). The first seven injury occurrences represent 144 of 158 or 91% of the injuries to the lower extremity, 64 of 79 injuries or 81% to the upper extremity and 25 of 31 injuries or 81% to the spine. However, this same number of contacts represent only 36 of 53 injuries (68%) sustained to the head and 33 of 69 injuries or 48% of the injuries sustained by the face. These data documents that head and facial injuries follow extremity injuries during the crash sequence.

Table 2.
The Distribution of the Contact Sources by AIS Levels

Contact Source by AIS Level			
Contact	AIS 1-2	AIS 3-5	Total
Front Bumper	57	12	69
Hood Edge	21	13	34
Wiper Blade	7	0	7
A1 Pillar	8	6	14
Hood Surface	31	1	32
Cowl Area	2	5	7
Front Fender Side	15	0	15
Windshield Glazing	37	2	39
Ground	121	2	123
Other	66	5	71
Total	365	46	411

Ninety-nine percent of the injury mechanism sources were coded as being known for the pedestrians. Twenty-eight different contacts were coded as causing injuries. The nine most frequent contacts, which represent 80% of the injuries, are broken out in Table 2 and the remaining contacts, 20%, are grouped into the Other category.

The ground was the most frequent injury contact with 123 contacts. However, 99% of the injuries from this contact were at minor AIS levels. Serious injuries (AIS 3-5) were more likely to be caused by contact with the front bumper, hood edge, cowl area or A1 pillar. These distributions are shown in Figure 10

Injury severity outcome was also tabulated against impact speeds. In Table 3, it is clear that impact speed does affect the severity of the outcome. Approximately 42 of the 46 (94%) AIS 3-5 injuries occur at impact speed greater than 15 KMPH and the number of AIS 1 or AIS 2 injuries is likely to remain significant at any speed due to the nature of those injuries being cuts, abrasions, lacerations, etc. to integumentary tissues.

Table 3.
The distribution of Impact Speeds by AIS levels.

Impact Speed vs. AIS Levels						
KMPH	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	TOTAL
0-15	74	5	2	0	1	82
16-30	120	18	8	1	0	147
31-45	60	10	10	2	1	84
46-66	48	19	14	5	1	87
Unknown	5	5	1	0	0	11
Total	307	57	35	8	3	411

CONCLUSIONS

From this early evaluation of the data variables in this study and conducting the research in the field, some general conclusions about pedestrian crashes can be made as noted in this interim evaluation of the data. However, it is clear that each case is unique and includes many variables, and therefore should be examined individually.

As PCDS data collection continues during the next several years and the number of cases increases, more data will be available for review.

DATA AVAILABILITY

To obtain copies of the Pedestrian Crash Data Study file or individual pedestrian cases contact:

Marjorie Saccoccio, DTS-44
DOT/Volpe National Transportation Systems Center
Kendall Square
Cambridge, MA 02142
USA

REFERENCES

1 Abbreviated Injury Scale - 1990 Revision, Association for the Advancement of Automotive Medicine, Des Plains, IL, 1990.

2 Documentation for the Data File of the Pedestrian Injury Causation Study, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1982.

3 Pedestrian Crash Data Study, 1996 Data Collection, Coding and Editing Manual, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1996.

4 National Accident Sampling System. Crashworthiness Data System, AIS-90 Injury Coding Manual, U. S. Department of Transportation, National Highway Traffic Safety Administration, 1993.

5 Traffic Safety Facts 1994, A Compilation of Motor Vehicle Crash Data from the Fatal Accident Reporting System and the General Estimates System, U. S. Department of Transportation, NHTSA, 1995.

APPENDIX 1
PEDESTRIAN CRASH DATA STUDY VARIABLE LIST

PEDESTRIAN ACCIDENT FORM

AC01 Primary Sampling Unit
AC02 Case Number - Stratum
AC03 Number of General Vehicle Forms Submitted
AC04 Date of Accident
AC05 Time of Accident
AC06 SS15 Administrative Use
AC07 SS16 Pedestrian Crash Data Study
AC08 SS17 Impact Fires
AC09 SS18
AC10 SS19
AC11 Number of Recorded Events in this Accident
AC12 Accident Event Sequence No.
AC13 Vehicle Number
AC14 Class of Vehicle
AC15 General Area of Damage
AC16 Vehicle Number or Object Contacted
AC17 Class of Vehicle
AC18 General Area of Damage

DERIVED VARIABLES

Day of Week
Year
Stratification
Month

PEDESTRIAN ASSESSMENT FORM

PED01 Primary Sampling Unit
PED02 Case Number - Stratum
PED03 Pedestrian Number
PED04 Pedestrian's Age
PED05 Pedestrian's Sex
PED06 Pedestrian's Overall Height
PED07 Pedestrian's Height - Ground to knee
PED08 Pedestrian's Height - Ground to Hip
PED09 Pedestrian's Height - Ground to Shoulder
PED10 Pedestrian's Weight
PED11 Pedestrian Attitude
PED12 Pedestrian Motion
PED13 Pedestrian's Action Relative to Vehicle
PED14 Pedestrian's Body (Chest)Orientation Prior Impact
PED15 Pedestrian's First Avoidance Actions
PED16 Pedestrian's Head Orientation at Initial Impact
PED17 Pedestrian Body (Chest)Orientation Initial Impact
PED18 Pedestrian's Arm Orientation at Initial Impact
PED19 Pedestrian's leg Orientation at Initial Impact
PED20 Vehicle/Pedestrian's Interaction
PED21 Police Reported Alcohol Presence
PED22 Alcohol Test Result for Pedestrian
PED23 Police Reported Other Drug Presence for Pedestrian
PED24 Other Drug Specimen Test Result for Pedestrian
PED25 Injury Severity (Police Rating)
PED26 Treatment - Mortality
PED27 Type of Medical Facility
PED28 Hospital Stay
PED29 Working Days Lost
PED30 Glasgow Coma Scale (GCS) Score
PED31 Was the Pedestrian Given Blood?
PED32 Arterial Blood Gases (ABG)-HCO3
PED33 Time to Death
PED34 1st Medically Reported Cause of Death
PED35 2nd Medically Reported Cause of Death
PED36 3rd Medically Reported Cause of Death
PED37 Number of Recorded Injuries for This Pedestrian

DERIVED VARIABLES

Maximum AIS
Injury Severity Score

PEDESTRIAN INJURY FORM

PI01 Primary Sampling Unit Number
PI02 Case Number - Stratification
PI03 Pedestrian Number
PI04 BLANK
PI05 Source of Injury Data
PI06 Body Region
PI07 Type of Anatomic Structure
PI08 Specific Anatomic Structure
PI09 Level of Injury
PI10 AIS Severity
PI11 Aspect
PI12 Injury Source
PI13 Injury Source Confidence Level
PI14 Direct/Indirect Injury

PI15 Striking Profile
PI16 Type of Damage
PI17 Damage Depth

PEDESTRIAN GENERAL VEHICLE

VEH01 Primary Sampling Unit Number
VEH02 Case Number - Stratum
VEH03 Vehicle Number
VEH04 Vehicle Model Year
VEH05 Vehicle Make
VEH06 Vehicle Model
VEH07 Body Type
VEH08 Vehicle Identification Number
VEH09 Police Reported Travel Speed
VEH10 Speed Limit
VEH11 Police Reported Alcohol Presence for Driver
VEH12 Alcohol Test Result for Driver
VEH13 Police Reported Other Drug Presence for Driver
VEH14 Other Drug Specimen Test Result for Driver
VEH15 Vehicle Curb Weight
VEH16 Vehicle Cargo Weight
VEH17 Vehicle Special Use(This Trip)
VEH18 Impact Speed
VEH19 Accuracy Range of Impact Speed Estimate
VEH20 Data Source of Impact Speed
VEH21 Driver's Attention to Driving
VEH22 Pre-Event Vehicle Movement
VEH23 Critical Precrash Event
VEH24 Attempted Avoidance Maneuver
VEH25 Precrash Stability After Avoidance Maneuver
VEH26 Precrash Direction Consequences of Avoidance Maneuver
VEH27 Relation to Junction
VEH28 Trafficway Flow
VEH29 Number of Travel Lanes
VEH30 Roadway Alignment
VEH31 Roadway Profile
VEH32 Roadway Surface Type
VEH33 Roadway Surface Condition
VEH34 Traffic Control Device
VEH35 Traffic Control Device Functioning
VEH36 Light Conditions
VEH37 Atmospheric Conditions

PEDESTRIAN EXTERIOR VEHICLE FORM

PEV01 Primary Sampling Unit
PEV02 Case Number - Stratum
PEV03 Vehicle Number
PEV04 Original Wheelbase
PEV05 Original Average Track Width
PEV06 Hood Material
PEV07 Hood Original
PEV08 Hood Length
PEV09 Hood Width Forward Opening
PEV10 Hood Width Midway
PEV11 Hood Width Rear Opening
PEV12 Hood/Fender Vertical/Lateral Crush From Pedestrian
PEV13 Windshield Contact Damage From Pedestrian Contact
PEV14 Front Bumper Cover Material
PEV15 Front Bumper Reinforcement Material
PEV16 Front Bumper - Bottom Height
PEV17 Front Bumper - Top Height
PEV18 Forward Hood Opening
PEV19 Front Bumper Lead
PEV20 Ground to Forward Hood Opening
PEV21 Ground to Front/Top Transition Point
PEV22 Ground to Rear Hood Opening
PEV23 Ground to Base of Windshield
PEV24 Ground to Top of Windshield
PEV25 Ground to Head Contact
PEV26 Ground Clearance
PEV27 Side Bumper-Bottom Height
PEV28 Side Bumper-Top Height
PEV29 Centerline of Wheel
PEV30 Top of Tire
PEV31 Top of Wheel Well Opening
PEV32 Bottom of A-Pillar at Windshield
PEV33 Top of A-Pillar at Windshield
PEV34 Top of Side View Mirror
PEV35 Centerline to A-Pillar at Bottom of Windshield
PEV36 Centerline to A-Pillar at Top of Windshield
PEV37 Centerline to Maximum Side View Mirror Protrusion
PEV38 Ground to Side/Top Transition
PEV39 Ground to Hood Edge
PEV40 Ground to Centerline of Hood
PEV41 Ground to Head Contact

DATA COLLECTION AND ANALYSIS OF VEHICLE FACTORS IN RELATION TO PEDESTRIAN BRAIN INJURY

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Paper Number 96-S9-O-07

ABSTRACT

This paper relates the severity of brain injuries in fatal pedestrian collisions to relevant characteristics of the head impact locations on the striking cars. Based on cases in which there was no significant impact to the head from contact with the road, the correlation of the nature and severity of the impact to the head with the characteristics of the injury to the brain yields information which is relevant to the assessment of the brain injury potential of head impact locations on passenger cars.

INTRODUCTION

The NHMRC Road Accident Research Unit has investigated 176 fatal pedestrian collisions in the Adelaide area since 1983 as part of a continuing study of mechanisms of injury to the brain in road crashes. Characteristics of those cases which are relevant to the study of the role of the striking car in the production of head injuries to the pedestrian are presented here.

METHOD OF INVESTIGATION

The investigation of each case commenced with attendance at an autopsy of a fatally injured pedestrian. All injuries and marks on the body were photographed and the lengths of body segments were measured. The location of any impact to the head was recorded; often this was done after the scalp had been reflected at autopsy, revealing one or more subgaleal haematomas. The brain was removed and, after processing, was examined by a neuropathologist. In a small number of cases, not included in the 176, the injuries to the head were so severe that the case was not of interest for the brain injury study and so no further investigation was attempted.

A detailed inspection was made of the striking car and also the crash scene in an attempt to determine the object associated with the impact to the head. This inspection was by performed with knowledge of the nature of the scalp lesion resulting from the impact.

Physical evidence such as the location of any skid marks and scuff marks on the road surface was recorded at the scene of the collision. Officers from the Police Accident Investigation Section attended all fatal accidents and, in the case of a pedestrian accident, marked the estimated point of impact and the rest positions of the vehicle and the pedestrian. In relevant cases, the investigators from the Road Accident Research Unit conducted test skids to measure the coefficient of friction for use in estimating the speed lost in skid marks due to braking.

The striking vehicle was then examined at either the Police compound or elsewhere. This was done as soon as possible after the accident, usually within 24 hours, to try to record any wipe marks in road grime before the vehicle was washed, as well as scuff marks and scratches in the paint work and dents in the body panels. If it was thought likely to be helpful, the driver of the vehicle and any witnesses were interviewed. The information obtained was then used in an attempt to reconstruct the kinematics of the collision between the pedestrian and the vehicle.

Case Selection

For the purposes of this paper cases were selected according to the following criteria: the striking vehicle was a passenger car or passenger car derivative; there was sufficient information to estimate the speed of the vehicle on impact; there was evidence of contact between the pedestrian's head and the car; and there was no evidence of a significant impact between the pedestrian's head and the road surface or similar non-vehicular object. There were 44 cases which satisfied all of these criteria.

Brain Injury Severity

Brain injury severity was assessed as "severe" if injury to the brain or other intracerebral injury was listed as the cause or one of the causes of death as determined at autopsy by the forensic pathologist. The other two categories of brain injury severity were "minor" or "moderate" according to the nature and extent of the brain lesions identified by neuropathological examination. In the selected sample there were no cases in which the brain injury severity was rated "minor".

Impact Location on the Head

All of the cases selected had an identifiable point of impact on the head. In cases in which there was more than one impact to the head the location was taken to be the more significant impact.

RESULTS

Characteristics of the Cases by Outcome

Some characteristics of the cases are summarised in Table 1 in terms of age and sex of the pedestrian and his or her orientation to the car on impact, together with the part of the car struck by the head. These variables are presented in terms of the severity of the injury to the brain.

Table 1
Characteristics of Pedestrian by Brain Injury Severity

Characteristic	Brain Injury Severity		Total
	Moderate	Severe	
Sex			
Male	53.8	64.5	61.4
Female	46.2	35.5	38.6
Age (years)			
0-15	7.7	25.8	20.5
16-30	23.1	9.7	13.6
31-45	7.7	25.8	20.5
46-60	15.4	6.5	9.1
61-75	15.4	19.4	18.2
76+	30.8	12.9	18.2
Orientation			
Left side	46.2	45.2	45.5
Right side	30.8	45.2	40.9
Back	15.4	3.2	6.8
Front	7.7	3.1	4.5
Unknown	-	3.2	2.3
Object Struck			
Bonnet	46.2	9.7	16.0
Leading edge	7.7	3.2	2.0
Fender	-	3.2	8.0
Plenum	15.4	19.4	14.0
Wiper pivot	-	3.2	2.0
Windscreen	30.8	22.6	20.0
Windscreen and dash	-	3.2	
Windscreen frame	-	12.9	6.0
A-pillar	-	19.4	14.0
Roof	-	3.2	4.0
Total			
Row per cent	29.5	70.5	100
Column number	13	31	44

The pedestrians whose characteristics are shown in Table 1 were more likely to have been struck on the left side than the right, with there being very few cases in which the pedestrian was facing the car, or with his or her back towards it. Almost three quarters of the head impacts were located behind the rear edge of the bonnet of the car.

The estimated impact speeds ranged from 9 to 92 km/h. The relationship of the estimated impact speed of the car to the severity of the brain injury is shown in Figure 1. The numbers of cases are small, particularly in the moderate brain injury severity category, but the two curves are similar except in the 60 to 80 km/h range. It should be remembered that in each of these cases there was at least one fatal injury. Hence it may be that above an impact speed of 60 km/h, a fatal injury to a body region other than the head is likely to occur at a slightly lower impact speed than for a fatal head injury.

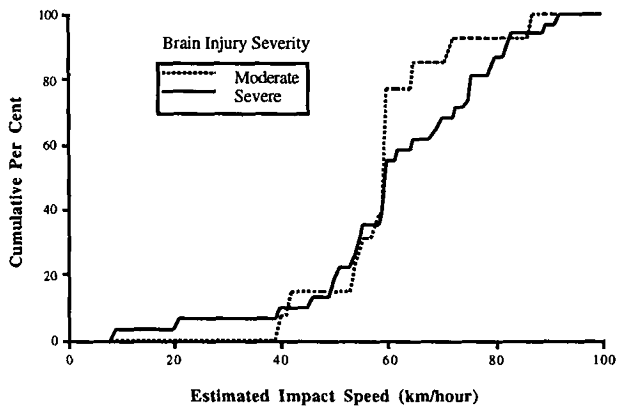

Figure 1. Cumulative speed distribution of vehicles by brain injury severity.

Most of the impact speeds shown in Figure 1 are higher than those at which vehicle design changes are commonly thought likely to be effective in reducing the severity of the injuries sustained by the pedestrian. The high impact speeds are largely a consequence of both the high urban area speed limit in Australia and enforcement practices. Up to the early 1960s that limit was 30 mph, or 48 km/h; it is now 60 km/h and an enforcement tolerance of up to an additional 10 km/h is not uncommon. In one third of the 38 cases in this sample that occurred in 60 km/h speed zones the speed of the car on impact was greater than 60 km/h.

In 33 per cent of the cases the driver did not attempt emergency braking. In 39 per cent the brakes were applied before striking the pedestrian and in the remaining 28 per cent emergency braking was initiated immediately after the impact.

The year of manufacture of the striking vehicle ranged from 1964 to 1990, with half of the cars having been manufactured after 1976.

Location of Impacts on the Head

The location of the impact on the head of the pedestrian is shown in Figures 2 and 3, for cases of moderate and severe brain injury, respectively.

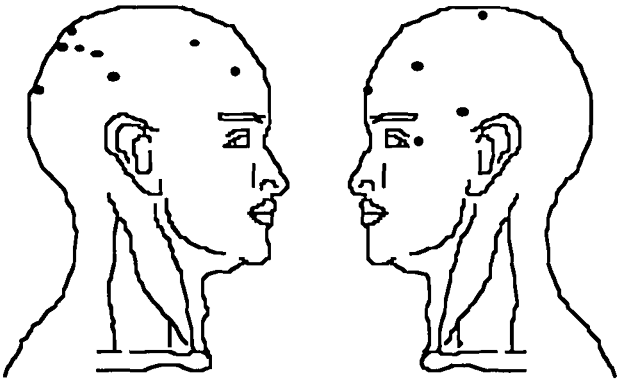

Figure 2. Location of pedestrian head impacts in cases of moderate brain injury.

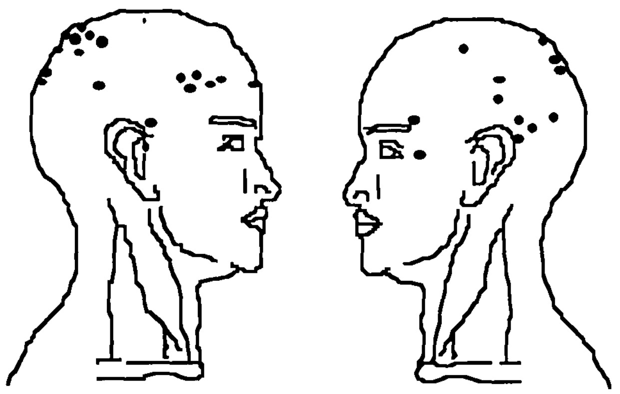

Figure 3. Location of pedestrian head impacts in cases of severe brain injury.

The locations of impacts to the head in cases of severe brain injury tended to be more toward the rear of the head than for cases of less severe brain injury. For pedestrians who were hit on the side of their body, 42 per cent of those who sustained a severe head injury struck the back of their head on the car compared to 20 per cent of those with a moderate brain injury. In this respect these pedestrian cases differ from the distribution of impacts on the head of car occupants who sustained severe brain injury; few of their impacts were to the rear of the head. (McLean et al., 1996)

It might be expected that the association between severe brain injury and impacts on the back of the head may result from the impact speed of the car. However, considering only pedestrians over 10 years of age who were hit on the side, 65 per cent of those struck at a speed of 60 km/h or less were struck on the back of the head compared to only 14 per cent of those who were hit by a car travelling at a speed greater than 60 km/h. It may be that at the higher impact speeds there is not sufficient time for the body of the pedestrian to be rotated through 90 degrees to expose the back of the head to the car.

Location of Head Impacts on the Vehicle

Figure 4 shows the distribution of pedestrian head impacts on the surface of the car for cases of moderate and severe brain injuries. The five head impact locations closest to the front of the car (four severe brain injury, one moderate) were all the result of a collision with a child pedestrian.

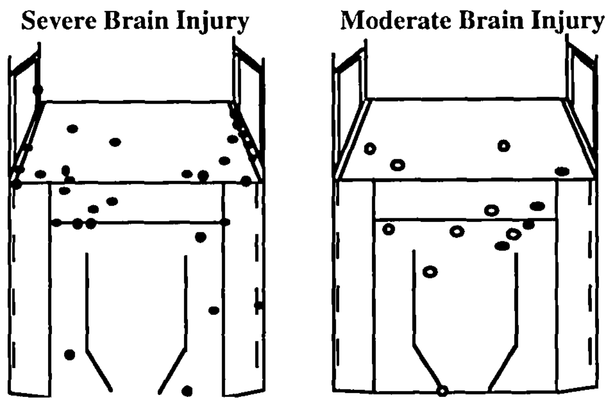

Figure 4. Pedestrian head impact locations on the car by brain injury severity.

Although no allowance is made in the data presented in Figure 4 for differences in factors such as impact speed, car frontal shape and age or sex of the pedestrian, it is nevertheless interesting to note that the head impact locations on the vehicle for the severe brain injury cases were much more likely to be on "hard" objects than were those for the moderate brain injury cases. The "hard" objects involved were the A-pillars and the base of the windscreen, and the join between the rear edge of the bonnet and the plenum chamber. There was also one severe brain injury case in which the head hit the windscreen wiper pivot.

When the estimated impact speed is taken into account, by grouping the cases into "high" speed and "low" speed impacts with the break point being 60/61 km/h, there is some indication that the head impact locations are further back from the front of the car in both the severe and moderate brain injury groups. (Figures 5 and 6) The wrap around distance to the likely head impact location does, of course, also depend on the height of the pedestrian and the dimensions of the front of the car, neither of which have been allowed for in the data presented here.

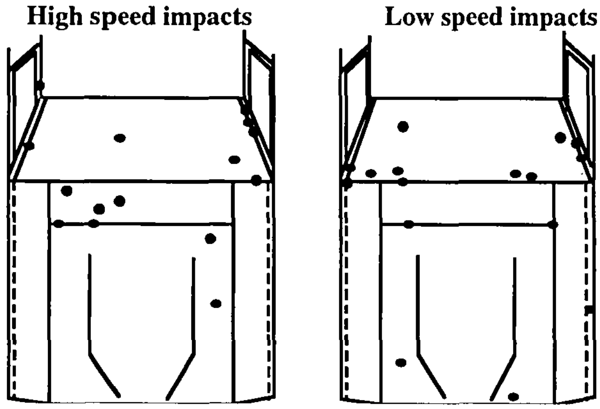

Figure 5. Pedestrian head impact locations on the car by estimated impact speed for severe brain injury cases. (Note; [a] "High" speed is greater than 60 km/h)

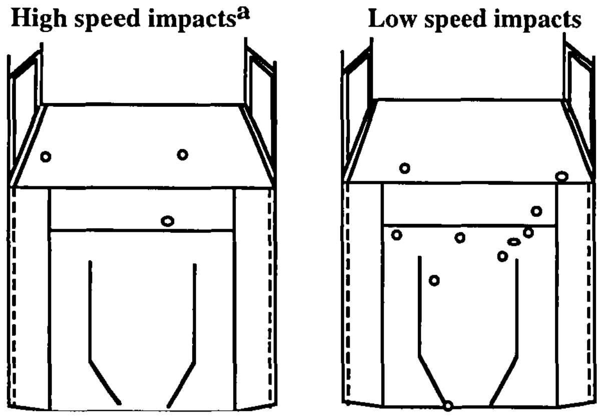

Figure 6. Pedestrian head impact locations on the car by estimated impact speed for moderate brain injury cases. (Note; [a] "High" speed is greater than 60 km/h)

DISCUSSION

This examination of vehicle factors in brain injuries resulting from fatal collisions between a pedestrian and a car draws attention to several matters.

The various approaches that have been proposed to assess the injury potential of the front of a passenger car in a collision with a pedestrian have been concentrated on low speed collisions (up to 40 km/h). Only 4 of the 44 cases in this sample of fatal collisions between a pedestrian and a car occurred at an impact speed within that range. While that is largely a reflection of the unusually high urban area speed limit in Australia (McLean et al, 1994), nevertheless it does appear to be desirable to continue to look for ways to reduce the injury potential of those parts of the car that are associated with fatal brain injuries to pedestrians.

In particular, the proposals for impact test procedures have been limited either to that part of the front of the car extending back to the base of the windscreen (EEVC, 1994) or, even more restrictive, to the central part of the bonnet of the car (Hoyt et al., 1990). In this sample, excluding the cases in which the pedestrian was under 12 years of age, 19 of 27 severe brain injury cases and 4 of 12 moderate cases, involved head contacts with the car outside the area addressed by the EEVC test procedure. None of the severe cases and only two of the moderate brain injury severity cases were in the area that was proposed for impact testing by NHTSA. (Hoyt et al., 1990)

CONCLUSIONS

Clearly, it is preferable to concentrate on the development of test procedures that are realistic in terms of current vehicle design. For example, it may be thought that modification of the A-pillar, to an extent that would make a meaningful difference to the risk of brain injury to a pedestrian, is impractical. Perhaps the solution is not to modify the A-pillar but rather to specify a performance requirement for pedestrian head protection. This would leave the designer free to develop, for example, an air bag restraint system for the head and upper torso of the pedestrian struck by the car, as has been proposed by some manufacturers.

ACKNOWLEDGEMENTS

Drs. P.C. Blumbergs and Grace Scott conducted the neuropathology examinations of the brains in this study.

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REFERENCES

EEVC. "Proposals for methods to evaluate pedestrian protection for passenger cars". EEVC Working Group 10 report. 1994.

Hoyt TA, MacLaughlin TF, Kessler JW. "Experimental pedestrian accident reconstructions: head impacts".. Washington DC: National Highway Traffic Safety Administration, 1988. Report No. DOT HS 807 288.

McLean AJ, Anderson RWG, Farmer MJB, Lee BH, Brooks CG. "Vehicle travel speeds and the incidence of fatal pedestrian collisions". Volume 1. Canberra: Federal Office of Road Safety, Australian Department of Transport; 1994. Report No.: CR 146.

McLean, AJ; Kloeden, CN; Farmer, MJB. "The role of the upper interior in car occupant brain injury". Paper No. 96-S8-O-03; Proc. 15th ESV Conference 1996 (in press).

A STUDY OF SOFT TISSUE NECK INJURIES IN THE UK

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ABSTRACT

This study examines in detail some of the factors associated with soft tissue neck injuries in the UK. The data were drawn from a retrospective study of vehicle crash injuries in which the overall soft tissue neck injury rate was 16%. This study shows how although it is commonly assumed that soft tissue neck injuries are a rear impact phenomenon, over 50% of the injuries actually occur in frontal crashes and over 25% in side impact crashes. In both front and rear impacts, these injuries are associated with seat-belt use. The incidence of soft tissue neck injury has been shown to double over the ten-year period of the study with the effect more prominent in females. Females (21%) overall are more at risk sustaining soft tissue neck injury compared to males (13%). In all cases, such injuries are more likely to be self-reported than clinically diagnosed. Head restraints have not been found to mitigate neck injuries in either front or rear impacts at a statistically significant level. A slight but non-significant trend towards reduced neck injury rates is observed in cases of seat back yielding in a rear impact.

INTRODUCTION

Whilst Spitzer et al (1995) define 'whiplash' as 'an acceleration-deceleration mechanism of energy transfer to the neck', a universally agreed definition of soft tissue neck injury is less easy to come by. The term in this study relates to a range of symptoms that arise following a motor vehicle crash as a result of neck hyper-extension, neck hyper-flexion or a combination of both of these mechanisms. Such symptoms may include complaint of neck pain, stiffness and/or tenderness together with more vague clinical manifestations which are thought to be associated with damage to the soft tissue constituents of the head/neck/shoulder complex. As Pearce (1989) notes, few topics provoke so much controversy based on so little fact as this type of injury. It is an injury shrouded in mystery and 'creates clinical insecurity in those who attempt to explain its mechanism, prognosis and treatment'. Medical impairment associated with soft tissue neck injury is apparently an increasing universal problem which has some association with the global progression towards mandatory restraint use (Cameron, 1981; Thomas, 1990). Whilst the biomechanics of neck injuries have been previously described in-depth elsewhere, (Walz and Muser, 1995; Bogduk, 1986; Melvin, 1979) it has become clear in recent times that there is a need for a greater understanding of the vehicle, collision and occupant parameters that are prevalent in neck injuries (and particularly soft tissue neck injuries) before preventative measures can be adopted.

Neck Injury and Seat Belt Usage

Rutherford et al (1985) indicated a relative increase of 18% in neck 'sprains' co-incident with the UK seat-belt use increasing from 26% to 93% after the introduction of the UK seat belt law and this data was supported in a study by Galasko et al (1993) who found a corresponding increase in incidence of soft tissue neck injuries. They studied occupants in car crashes between the years 1982 and 1991 and found that in 1982, 12 months before the introduction of the compulsory seat belt legislation, the incidence of soft tissue neck injury was 8%. Immediately following the introduction of the law, the incidence of soft tissue neck injury rose to 21% and thereafter it rose steadily each year. By 1991, the incidence had risen to approximately 46%.

Maag et al (1990) found that neck sprains were relatively more numerous among belted occupants compared to unbelted occupants by a factor of 1.68 while Larder et al (1985) found that 93% of drivers and 96% of front passengers who sustained a neck injury wore their seat-belts in a population of predominantly unrestrained occupants.

Neck Injury and Head Restraint

Nygren et al (1985) examined the performance of different types of head restraints in rear-end collisions and suggested that they do have a certain influence on the incidence of neck injury in this type of collision but they observed that further studies were necessary since the knowledge of function is generally low. Olsson et al (1990) observed that 'most modern cars are equipped with head restraints designed to prevent whiplash injuries but neck injuries are still common in rear

impacts indicating that restraints are not functioning satisfactorily'. They concluded that 'a distance of more than 10cm between the head and the head restraint correlates with an increase risk of neck injury'. This work was supported by Svensson et al (1993) who found that the head-to-head-restraint gap was the largest influence on head-neck motion in a rear impact and Parkin et al (1993), in an observational study of driver head-restraint position found that 50% of the driving population had the restraint positioned greater than 15cm from the back of the head horizontally. Only 5% of drivers had the restraint correctly positioned vertically while 50% of the population positioned 10cm or more below the centre of the head. Similarly Viano and Gargan (1995) found in their observational study that only 10% of drivers had head-restraints in the most favourable position to prevent neck extension in a rear-end crash. In the same study, they conducted a series of simulated rear-end collisions and found that the lowest response of neck extension occurred with a small gap between head and head-restraint and also a high head-restraint.

Neck Injury and Seat Yield

Some authors have postulated that a controlled yield of the seat-back during an impact has a beneficial effect in terms of neck injury outcome since such a design reduces the recoil of the body during the latter stage of the impact thereby diminishing the risk of hyperflexion injury to the cervical spine. Kihlberg (1969) reviewed rear impact data from the US Automotive Crash Injury Research (ACIR) study and found that the frequency of flexion/torsion neck injuries was substantially less than for those cases in which the seat remained intact while Parkin et al (1995) found that with the presence of yield, the occupant was less likely to suffer an AIS 1 neck injury whilst a seat which exhibited no residual damage was more likely to result in AIS 1 neck injury. Overall, AIS 1 neck injuries were approximately twice as frequent in an undamaged seat than in a yielding seat. Von Koch (1995) observed a considerable difference in relative rebound velocity between seats of different stiffness coefficients.

Impact Classification

Larder et al (1985) found that in frontal impacts, 17% of occupants sustained a neck injury whilst for rear impacts, the rate was 31% and Lovsund et al (1988) found that more than 10% of car occupants involved in a rear-end collision sustained a neck injury. Galasko et al (1993) found that for drivers, 52% were injured in a rear impact, 27% in a front impact and 16% in a side impact. Comparable rates were found for front seat passengers.

Methodology

The data used in this study are from a study of vehicle crash performance and occupant injury (the Co-operative Crash Injury Study) which commenced in the UK in 1983 and ended in May 1992. In all, the CCIS database holds information on some 6,973 vehicles involved in crashes containing 11,866 occupant who sustained between them 42,876 injuries.

Each vehicle in the study was inspected within a few days of the collision. The general sampling criteria of the CCIS study are:

i) that the vehicle involved was towed away from the scene of the accident to a garage or recovery yard.
ii) that the vehicle was less than six years old at the time of the collision
iii) that there was an injury in the vehicle according to the UK Police system of injury classification.

About 80% of serious and fatal accidents in each study area were investigated along with 10-15% of slight accidents according to the UK Police system of injury classification. The resulting sample represents all levels of injury outcome while being biased towards more serious injuries. Consequently, there may be a degree of under-reporting of the phenomenon of soft tissue neck injury due to the masking effect of serious injury.

Medical data concerning each occupant was obtained from hospitals and each occupant was also requested to complete a questionnaire which provided additional data several days after the crash. Injuries were coded according to the Abbreviated Injury Scale, 1985 revision (American Association for Automotive Medicine; 1985).

A more comprehensive overview of the Co-operative Crash Injury Study can be attained in Mackay et al (1985).

RESULTS

Soft tissue neck injury in this study is defined according to the Abbreviated Injury Scale 1985 revision. The strict definition is 'Strain, Acute (no fracture or dislocation)'. The AIS code number is 70101.1.

1. Database Characteristics

The CCIS data-base phases I-III involves information on the following:

11,866 Occupants

6,937 Vehicles

42,876 Injuries

1(a); Impact Classification - The impact classifications where these are known for all occupants including those with and without soft tissue neck injury are as shown in Table 1:

As can be seen from Table 1, the soft tissue neck injury rate according to this definition is **16%** (i.e. 1887 occupants out of 11,866) but for rear impacts, the rate is **38%**; more than twice the rate than for any other impact class. However although the risk is much higher in rear impacts, it should be noted that over 50% of soft tissue neck injuries do occur in frontal impacts.

Of occupants who sustained a soft tissue neck injury, 51% were male and 49% were female while the overall gender breakdown in the CCIS database is 61% male and 37% female (2% of occupants not known). Of the occupants in the database, there were 6,403 front seat occupants who were seated in the driver or front seat passenger positions in vehicles which sustained only one impact.

1(b); Collision Severities for Soft Tissue Neck Injury - Figures 1 & 2 show the speed distributions for soft tissue neck injury/no soft tissue neck injury in both frontal and rear impacts. MAIS 1 injuries only are included. As can be seen from both figures, at the MAIS 1 level of injury severity, soft tissue neck injuries occur at relatively lower mean and median collision severities compared with all other injuries.

1(c); Maximum Abbreviated Injury Score (MAIS) - Injury risks were evaluated for both soft tissue neck injured occupants and for all occupants. These are shown in Table 2. As can be seen from this table, for 76% of occupants, MAIS 1 is the highest severity of overall injury level assessed by threat to life.

Table 1.
Impact Classifications for Occupants with and Without Soft Tissue Neck Injury

Impact Classification	Soft Tissue Neck Injury		No Soft Tissue Neck Injury		Total
	N	%	N	%	
Rear	237	38	393	62	630
Front	1,045	15	5,869	85	6,914
Left-side	188	12	1,351	88	1,539
Right-side	280	15	1,608	85	1,888
Top	97	15	545	85	642
Unclassified	40	16	213	84	253
Totals	1,887	16	9,979	84	11,866

Table 2.
Maximum Abbreviated Injury Scores for Occupants With and Without Soft Tissue Neck Injury - CCIS Study

MAIS	Occupants with Soft Tissue Neck Injury		All Occupants	
	N	%	N	%
1	1,437	76	4,923	51
2	361	19	2,193	23
3	64	3.5	815	8
4	6	0.4	291	3
5	2	0.1	331	3
6	0	0	262	3
9 (not known)	17	1	911	9
Totals	1,887	100	9,726*	100

*** (2,140 Occupants sustained no injuries).**

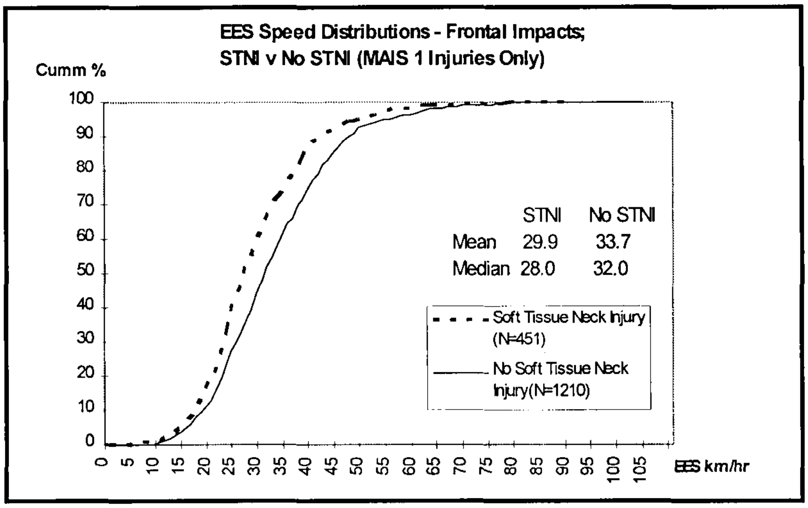

Figure 1.

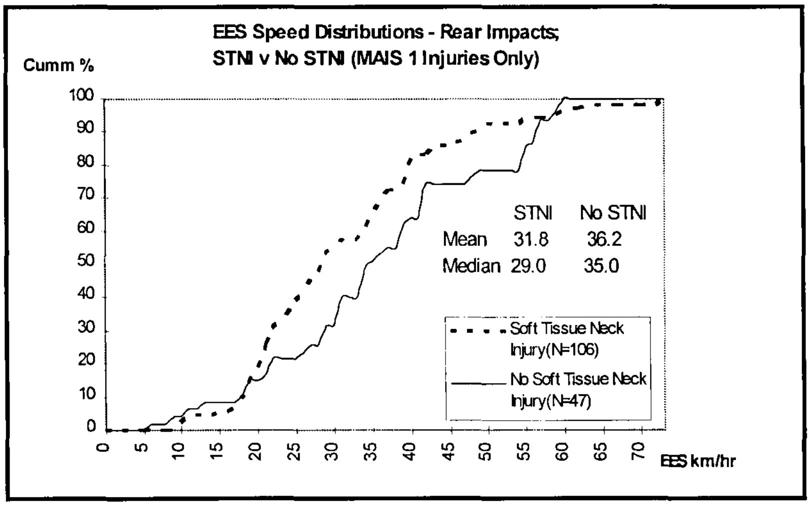

Figure 2.

Table 3.
Restraint Use by Soft Tissue Neck Injury (All Impact Types)

	Soft Tissue Neck Injury		No Soft Tissue Neck Injury		Total
Restraint Use	N	%	N	%	
Used	1,530	20	6,264	80	7,794
Not Used	208	8	2,268	92	2,476
Not Known	149	9	1,447	91	1,596
Total	1,887	16	9,979	84	11,866

Table 4.
Gender of Occupants - Soft Tissue Neck Injury v All Occupants (all Impact Directions)

	Soft Tissue Neck Injury		No Soft Tissue Neck Injury		Total
Gender	N	%	N	%	
Male	955	13	6,273	87	7,228
Female	928	21	3,453	79	4,381
Not Known	4	2	253	98	257
Totals	1,887		9,979		

Table 5.
Data Sources for Soft Tissue Neck Injuries

	All Injuries	MAIS 1	MAIS 2	MAIS 3
Data Source	%	%	%	%
All data sources	5	9	3	1.5
Hospital Records Only	3	8	3	1
Questionnaire Only	7	12	3	1
Hospital Records & Questionnaire	6	9	4	2
Police Data	8	11	3	3

1(d); Restraint Use - The issue of restraint use for soft tissue neck injuries was then analysed across the whole database. This is shown in Table 3.

The figures are for all occupants in all vehicles and the high numbers of unrestrained occupants reflect the predominantly unrestrained population of rear seat occupants. The effect of seat-belt wearing on neck injury is explored later in the results section but it is interesting to note that 20% of restrained occupants sustained a soft tissue neck injury compared to 8% of unrestrained occupants.

1(e); Gender - The issue of gender was also addressed. Again occupants who sustained soft tissue neck injury were compared to all occupants in the database. The results are shown in Table 4. As can be seen from this table, females are at greater risk of sustaining soft tissue neck injury than males. The reasons for this are by no means clear. Physiological and anatomical differences may in part explain these differences.

1(f); Injury Data-sources In this section, the incidence of soft tissue neck injuries according to differing sources of medical data was examined. The results are shown in Table 5. Each percentage figure represents the number of soft tissue neck injuries expressed as a percentage of the total number of injuries that occurred in that classification. When casualties sustained only minor injuries of maximum AIS 1, the rates of soft tissue neck injury were higher than when more severe injuries were sustained. This could be explained by the presence of more severe injuries masking the presence of a soft tissue neck injury.

Of note is the fact that the rate of neck injury (7%) was higher if the occupant self-reported compared to the rate for clinical diagnosis at the hospital (3%). This is also true when only MAIS 1 injuries are investigated (12% compared to 8%). This could imply that the injury may not present itself until some time after the accident has occurred in which case the questionnaire is the most accurate means of reporting the injury. The issue of fraudulent claims should not however be overlooked.

2; Soft Tissue Neck Injury as a Function of Time

The first analysis in this category examines soft tissue neck injury as a function of time. Figure 1 shows the changing rate of the incidence of soft tissue neck injury.

As can be seen from the graph, neck injury rates increased almost linearly over the study-period. The rates for years 1983 and 1992 have not been included as data were collected for only part of each of these years.

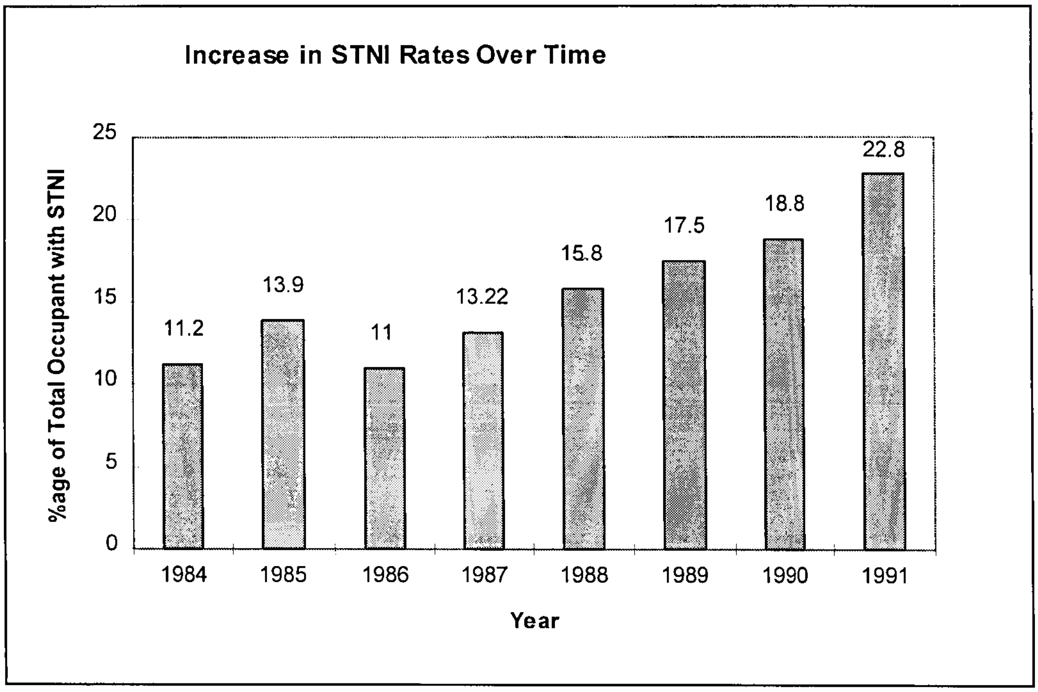

Figure 3.

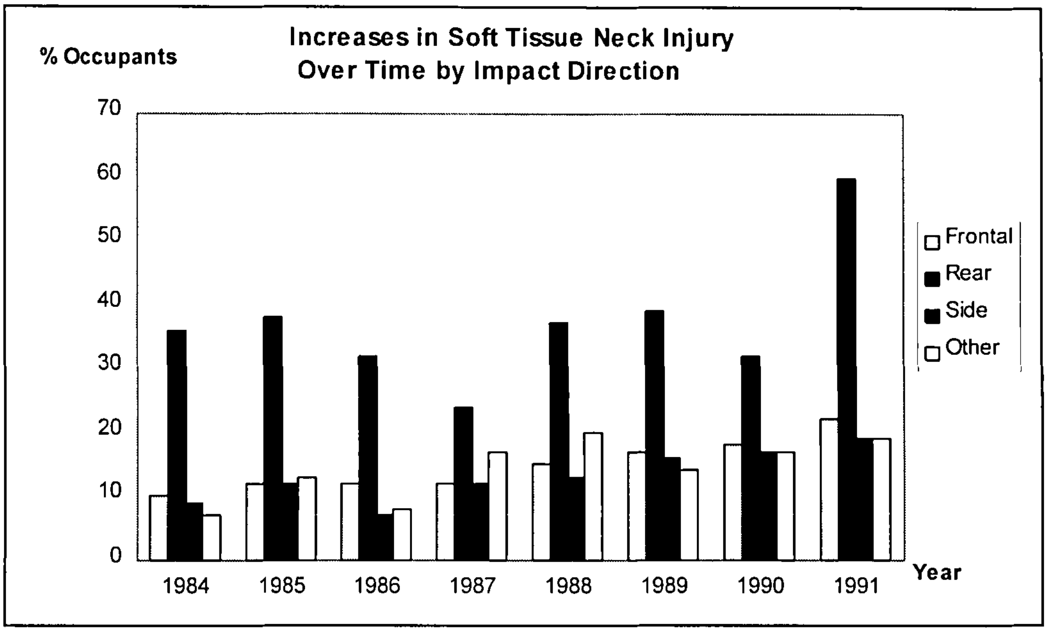

Figure 4.

This relationship has also been examined for differing impact classifications. Of interest is the fact that soft tissue neck injuries have increased for all impact classifications since the beginning of the study although the picture is somewhat confusing in the case of rear impacts. However, a clear relationship exists particularly for frontal impacts. It is also worth observing that the data were collected over a period of time just before the general introduction of improved restraint technology (seat-belt pretensioners, seat-belt grabbers etc.) in the UK. This relationship is shown in Figure 4.

Gender differences in the increase of rate of STNI over time have also been observed. Figure 5 shows this relationship. All occupants in all impact types are included in this analysis. In can be clearly seen that the STNI rates for females have increased at a greater rate than that for males. The rate for females was 14% in 1984 and had risen to 31% by 1991 while the rate for males was 10% in 1984 and had risen to 18% by 1991

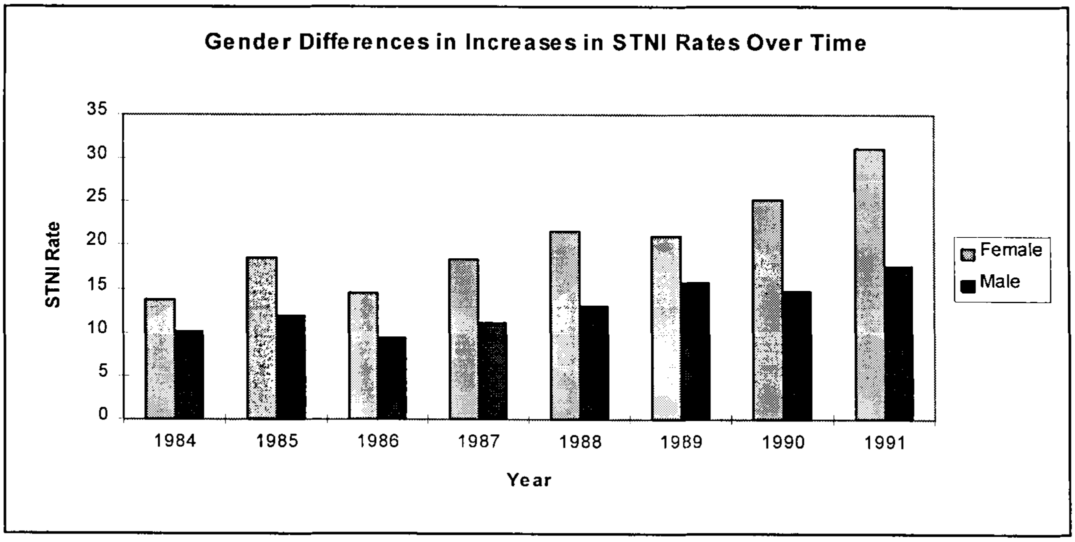

Figure 5.

3. Frontal Crash Occupant, Vehicle and Collision Characteristics;

This section explores differing occupant and collision characteristics associated with soft tissue neck injury in frontal impacts. All analyses were performed using front seat occupants only. Vehicles were selected for analysis on the basis that they sustained only one impact so that the occupant kinematics were as straightforward as possible.

3(a): Seat Belt Effectiveness - The effect of belt use on soft tissue neck injury in frontal impacts was studied for front seat occupants only. Rear seat occupants were excluded from this analysis since belt usage rates over the period of the study was very low primarily because the mandatory rear seat belt wearing laws were not introduced until very late in the study period (July 1991). In each case, the occupants experienced one impact only. The results are shown in Table 6.

Males were significantly more likely to sustain a neck injury if they were restrained than if they were unrestrained ($\chi 2$ = 26.2, df = 1, p<0.000). The same relationship was observed for women ($\chi 2$ = 35.34, df = 1, p<0.000) so overall, neck injuries are significantly more likely in restrained occupants in frontal crashes compared to unrestrained occupants.

3(b): Occupant and Seating Characteristics - In this section, seat back heights and head restraint heights in relation to occupant heights, weights and ages were assessed. The results are shown in Table 7.

Table 6.
Seat Belt Use in Frontal Impacts; STNI-Vs-No STNI

Males							
	Used		Not Used		Not Known		Total
Injury Condition	N	%	N	%	N	%	
Soft Tissue Neck Injury	344	85	38	9	22	6	404
No Soft Tissue Neck Injury	1,692	70	460	19	274	11	2,426
Females							
	Used		Not Used		Not Known		Total
Injury Condition	N	%	N	%	N	%	
Soft Tissue Neck Injury	340	87	38	10	15	4	393
No Soft Tissue Neck Injury	968	69	310	22	130	9	1,408

Table 7.
Occupant Height, Weight and Age In Relation to Seat Characteristics-Frontal Impacts

Males		
	STNI	No STNI
	Mean	Mean
Seat Back Height and Head Restraint Height (cm)	78.2	77.5
Age (years)	33.0	32.9
Weight (kg)	73.5	76.5
Height (Meters)	1.77	1.76
Females		
	STNI	No STNI
	Mean	Mean
Seat Back Height and Head Restraint Height (cm)	77.1	76.9
Age (years)	35.0	36.3
Weight (kg)	60.7	59.8
Height (meters)	1.64	1.63

As can be seen from the above table, for frontal impacts, there are no discernible differences in occupant characteristics or seat adjustment in terms of neck injury outcome for both males and females. Males in this study are generally taller than females yet there is little difference in terms of seat back height/head restraint height combination.

<u>3(c); Head Restraint Type and Effectiveness</u> - Table 8 shows the effectiveness of head restraints in frontal impacts. As can seen from this table, slight but non-statistically significant trends emerge which suggest that head-restraints are slightly detrimental in terms of neck injury outcome in frontal crashes. The data also suggest a slight trend towards adjustable head restraints being slightly less detrimental in this type of impact but again this is not statistically significant.

<u>3(d); Vehicle Type</u> - The incidence of soft tissue neck injury in different vehicle types was explored to establish if there was any potential relationship between seat-belt geometry (using the number of vehicle side-doors as a proxy) and soft tissue neck injury. Table 9 shows the results for frontal impacts.

No statistical relationship was observed between number of side doors and incidence of soft tissue neck injury ($\chi 2 = 0.4515$, df = 1, p = n.s.) although there is a very slight non-significant trend suggesting that soft tissue neck injuries are more prevalent in 4 side-door vehicles ($p>0.50$).

Table 8.
Head Restraint Type and Effectiveness

Frontal Impacts						
	No Neck Injury		Neck Injury		χ^2	p
Head Restraint	N	%	N	%		
None	442	83	90	17	2.28	0.20
Fixed	328	79	86	21		
None	442	83	90	17	1.081	0.30
Adjustable	2068	81	481	19		
None	442	83	90	17	1.449	0.20
Fixed & Adjust.	2396	81	567	19		

Table 9.
Relationship Between Soft Tissue Neck Injury and Number of Side Doors - Frontal Impacts

	Soft Tissue. Neck Injury		No Soft Tissue Neck Injury		Total
	N	%	N	%	
2-side door vehicle	274	20	1,124	80	1,398
4-side door vehicle	428	21	1,657	79	2,085
Total	702		2,781		3,483

4; Rear-end Crash Occupant, Vehicle and Collision Characteristics

4(a); Seat Belt Effectiveness - The effect of belt use on soft tissue neck injury in rear impacts was studied for front seat occupants only. Rear seat occupants were excluded from this analysis since belt usage rates over the period of the study was very low primarily because the mandatory rear seat belt wearing laws were not introduced until very late in the study period (July 1991 - as was described earlier). In each case, the occupants experienced one impact only. The results are shown in Table 10.

Males were significantly more likely to experience neck injury if the seat belt was worn in a rear impact ($\chi2 = 5.8$, df=1, $p<0.02$). However, no statistically significant association was found for females ($\chi2 = 1.77$, df=1, p=n.s.). In both cases, the overall risks could be confounded by high numbers of rear crashes where the seat belt usage was unknown.

4(b); Occupant and Seating Characteristics - In this section, seat back heights and head restraint heights in relation to occupant heights, weights and ages were assessed. The results are shown in Table 11.

For rear impacts, as can be seen from Table 11, some slight differences do occur. Male neck-injury occupants tend also to be slightly heavier and taller than males with no neck-injury. For females in rear impacts, the most discernible difference is that neck-injury occupants are somewhat younger than no neck-injury occupants. Female neck injury occupants also have higher seat back height/head restraint height combinations.

Table 10.
Seat Belt Use in Rear Impacts; STNI-Vs-All Injuries

Males							
	Used		Not Used		Not Known		Total
Injury Condition	N	%	N	%	N	%	
Soft Tissue Neck Injury	42	78	3	6	9	16	54
No Soft Tissue Neck Injury	43	46	14	15	36	39	93
Females							
	Used		Not Used		Not Known		Total
Injury Condition	N	%	N	%	N	%	
Soft Tissue Neck Injury	48	58	10	12	25	30	82
No Soft Tissue Neck Injury	33	59	13	23	10	18	56

Table 11
Occupant Height, Weight and Age In Relation to Seat Characteristics-Rear Impacts

Males		
	STNI	No STNI
	Mean	Mean
Seat Back Height and Head Restraint Height (cm)	77.5	77.7
Age (years)	41.5	38.9
Weight (kg)	79.7	74.0
Height (meters)	1.79	1.75
Females		
	STNI	No STNI
	Mean	Mean
Seat Back Height and Head Restraint Height (cm)	77.8	75.9
Age (years)	36.0	43.8
Weight (kg)	61.7	64.4
Height (meters)	1.63	1.61

4(c); Head Restraint Type and Effectiveness - A comparison was made of head restraint type on injury outcome. In each case, the occupants sustained only 1 impact and only drivers and front seat passenger were included. Males and females were studied collectively. Table 12 shows the data for head restraint effectiveness in rear impacts.

Table 12 shows no evidence that fixed or adjustable head restraints had any statistically significant effect on soft tissue neck injury. The probability that the results observed were derived by chance was at least 70%.

4(d); Vehicle Type - The incidence of soft tissue neck injury in different vehicle types was explored to establish if there was any potential relationship between seat-belt geometry (using the number of side-doors on the vehicle as a proxy) and soft tissue neck injury. Table 13 shows the results for frontal impacts.

No statistical relationship was observed between number of side doors and incidence of soft tissue neck injury ($\chi 2 = 0.208$, df. = 1, p = n.s.) although there is a very slight non-significant trend suggesting that soft tissue neck injuries are more prevalent in 2 side-door vehicles ($p>0.50$).

Table 12.
Head Restraint Type and Effectiveness

Rear Impacts						
	No Neck Injury		Neck Injury		χ^2	p
Head Restraint	N	%		%		
None	18	58	13	42	0.126	0.75
Fixed	12	63	7	37		
None	18	58	13	42	0.433	0.70.
Adjustable	69	51	65	49		
None	18	58	13	42	0.283	0.70
Fixed & Adjust.	81	53	72	47		

Table 13.
Relationship Between Soft Tissue Neck Injury and Number of Side Doors - Rear Impacts

	Soft Tissue Neck Injury		No Soft Tissue Neck Injury		Total
	N	%	N	%	
2-side door vehicle	38	52	35	48	73
4-side door vehicle	52	49	55	51	107
Total	90		90		180

Table 14.
Seat Back Damage and Neck Injury Outcome

	Seat Back Damaged		No Damage		Total
	N	%	N	%	
Neck Injury	43	39	67	61	110
No Neck Injury	61	46	72	54	133
Total	104	43	139	57	243

$\chi 2 = 1.1403$, df. = 1, $p<0.20$

5. Seat Back Yield and Soft Tissue Neck Injury

The next analysis examines seat back damage in relation to neck injury in a rear impact where there was only one impact to the vehicle. Instances of seat back damage which were generated by loading from the seat occupant were compared to examples of undamaged seats for neck-injury occupants and no neck-injury occupants. The results are shown in Table 14.

As can be seen from the table there is a statistically non-significant trend towards reduced neck injury outcomes in instances of seat back damage when there is only one rear impact to the vehicle.

DISCUSSION

Soft tissue neck injuries are still a major concern but it is a common misconception that they occur more or less exclusively in rear impacts. In this study, it has been shown that although the risk of sustaining soft tissue neck injury is greatly increased in a rear impact, over 50% of these injuries are in fact occurring in frontal impacts with a further 25% occurring in side impacts. It is perhaps therefore necessary to establish whether the more impairing neck injuries occur more in one impact type compared to another, although the data in this study do not provide scope for doing this.

What is certain is that soft tissue neck injuries can occur at comparatively low-speeds and are associated with seat-belt use. They also occur more frequently to females compared to males and are an injury that has a greater tendency to be self-reported than clinically diagnosed. The reasons for gender differences are also unclear. It is suggested that anatomical and physiological differences may imply that the biomechanical tolerance of the female neck is compromised more readily than with males. However this is confounded by the fact that there is at present only a vague notion of the precise mechanism of injury and also what exactly the injury is (indeed if the injury exists at all). Certainly increasing incidences of soft tissue neck injury would suggest that there is a need for a more reliable diagnostic procedure as there remains the possibility that the crash population is becoming increasingly sophisticated and what in fact is emerging is a trend toward increasing numbers of fraudulent claims of soft tissue neck injury. This may be represented by the fact that self-reporting does produce higher incidence of neck injury but it should be remembered that the symptoms of the injury frequently do not manifest themselves until some 12-24 hours after the crash in which case self-reporting is in fact the most accurate means of diagnosis.

The explanation of increased potential for soft tissue neck injury with seat belt usage requires some clarification. It needs to be established whether the injury mechanism is the same in the case of a restrained occupant in both a front and rear impact. If so, then this would suggest that specifically in the case of rear impacts, the injury is a phenomenon of rebound from an unyielding seat creating hyperflexion during interaction with the belt as happens in a frontal impact. The data in this study, while not conclusive, show a trend toward reduced levels of soft tissue neck injury when the seat yields and this finding agrees with data from many other studies. What is necessary in this respect now is to establish precisely how a yielding seat affords protection against neck injury. If clear evidence emerges, then it is obvious that there is very real potential for reducing the incidence of soft tissue neck injury by introducing seating which deforms rearwards in a controlled manner in rear impacts.

The introduction of frontal crash airbags to modern vehicles was greeted with optimism since it was anticipated that head ride-down on the airbag would reduce the force and extent of hyperflexion in restrained occupants. However, a preliminary study of airbag deployments in the UK by Morris et al (1996) has shown that neck injuries occur at the rate of 14% for restrained drivers in frontal crashes in airbag-deployed vehicles. This compares to the overall soft tissue neck injury rate in this present study of 16% so it would appear that airbags have only limited effect. It will be interesting to establish the soft tissue neck injury rate when more data becomes available.

A cursory examination of seat belt geometry was possible in this study. Seat belt geometry was determined here by using the number of side-doors as a proxy. This was not found to have an overall effect in determining neck injury outcome but this in itself is worthy of further exploration since the data do not take into account the actual height of the upper anchorage. Increasing numbers of vehicles now use manually-adjustable anchorage heights and any future study of seat belt geometry should take into account the actual adjustment setting during the collision. It may also be worth examining the incidence of soft tissue neck injury in vehicles with improved belt technology such as pretensioners and grabbers in order to analyse whether they are influencing the incidence of soft tissue neck injury.

While it is clear that head restraints, not unexpectedly, have no overall effect in frontal crashes in this study, it is surprising to find no evidence of benefit in rear crashes. Nevertheless, although there is no evidence in this historical data-set that either fixed or adjustable head restraints reduce STNI, it cannot be inferred that alternative designs will not be effective. The explanations for limited effectiveness of adjustable head restraints must include poor positioning of the occupant in relation to the head restraint (i.e. horizontal clearance from head restraint to head) and also poor vertical positioning of the restraint itself. This generally supports the evidence provided by Parkin et al (1993) and Viano and Gargan (1995) who found that only 5% and 10% respectively of occupants had correctly adjusted restraints. However a confounding factor here is that in this study, the mean height of female occupants with soft tissue neck injury is approximately 12cm less than their male counterparts. It therefore follows that the female occupants are in a 'better' situation in terms of head restraint height/seat back height combination yet females are still sustaining higher rates of neck injury.

Overall, the data show a clear value in conducting future work in both medical and engineering circles. There is obviously scope for a more accurate diagnostic technique and procedure and also a requirement for a more precise definition of the actual injury. However with regard to vehicle design a useful follow-up would be a clear evaluation of the current design of head restraints to assess how they compare to older designs. A more rigorous comparison of fixed and adjustable head restraints is also necessary and there is a definite requirement for a closer examination of the relationship between occupant height, head restraint height and injury. The concept of yielding seats should also be explored further. If clear evidence emerges to support the case for seat yielding, then this may have implications for alternative seat design. Consideration also needs to be made of the influence of improved restraint technology on soft tissue neck injury rates as more data become available. Furthermore, as this study has examined predominantly frontal and rear impacts, some benefit would be attained by an in-depth examination of soft tissue neck injuries in side impact and rollover accidents.

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REFERENCES

Association for the Advancement of Automotive Medicine. **'The Abbreviated Injury Scale, 1985 Revision'**. AAAM, Arlington Heights, Illinois, 1985.

Bogduk, N. **'The Anatomy and Pathophysiology of Whiplash'**. In Clinical Biomechanics Vol. 1 pp 92-101, 1986.

Cameron, M H. **'The Effect of Seat Belts on Minor and Severe Injuries Measured on the Abbreviated Injury Scale'**. In Accident Analysis and Prevention Vol. 13 No 1 pp17-28, 1981.

Galasko, C S B; Murray, P M; Pitcher, M; Chambers, H; Mansfield, M; Madden, M; Jordan, C; Kinsella, A and Hodson, M. **'Neck Sprains After Road Traffic Accidents: A Modern Epidemic'**. In Injury Vol. 24 no 3 pp155-157, 1993.

Kihlberg, J K. **'Flexion-Torsion Neck injury in Rear Impacts'**. In Proceedings of the AAAM Conference, Minneapolis, Minnesota, 1969.

Larder, D R; Twiss, M K and Mackay, G M. **'Neck Injury to Car Occupants Using Seat Belts'**. In Proceedings of the AAAM Conference, Des Plaines, Illinois, pp153-165, 1985.

Lovsund, P; Nygren, A; Salen, B and Tingvall, C. **'Neck Injuries in Rear-End Collisions Among Front and Rear Seat Occupants'**. In Proceedings of the IRCOBI Conference, Sept. 14-16, Bergisch-Gladbach, Germany, pp319-325, 1988.

Maag, U; Desjardins, D; Bourbeau, R and Laberge-Nadeau, C. **'Seat Belts and Neck Injuries'**. In Proceedings of the IRCOBI Conference, Sept. 12-14, Lyon , France, 1990.

Mackay, G M; Galer, M D; Ashton, S J and Thomas, P. **'The Methodology of In-depth Studies of Car Crashes in Britain'.** SAE Paper No. 850556, Society of Automotive Engineers, Warrendale, PA, 1985.

Melvin, J W. **'Human Neck Injury Tolerance'.** In The Human Neck - Anatomy, Injury Mechanisms and Biomechanics, Congress and Exposition, pp 45-46, 1979.

Nygren, A; Gustafsson, H; and Tingvall, C. **'Effects of Different Types of Head Restraints in Rear-End Collisions'.** In Proceedings of the 10th International Conference on Experimental Safety Vehicles, Oxford, England, pp85-90, 1985.

Olsson, I; Norin, H and Ysander, L. **'An In-depth Study of Neck Injuries in Rear-end Collisions'.** In Proceedings of the IRCOBI Conference, Sept. 12-14, Lyon , France, 1990.

Parkin, S; Mackay, G M and Cooper, A. **'How Drivers Sit in Cars'.** In Proceedings of the AAAM Conference, San Antonio, Texas, pp375-388, 1993.

Parkin, S; Mackay, G M; Hassan, A M and Graham, R. **'Rear-End Collisions and Seat Performance - To Yield or Not To Yield'.** In Proceedings of the AAAM Conference, Chicago, Illinois, pp231-244, 1995.

Pearce, J M. **'Whiplash Injury: A Reappraisal'.** J. Neurol Neurosurg Psychiatry No 52 pp 1329-31, 1989.

Rutherford, W H; Greenfield, A A and Hayes, H R M. **'The Medical Effects of Seat Belt Legislation the UK'.** Department of Health and Social Security Research Report 13, London, HMSO, 1985.

Spitzer, W O; Skovron, M L; Salmi, L R; Cassidy, J D; Duranceau, J; Suissa, S and Zeiss, E. **'Scientific Monograph of the Quebec Task Force on Whiplash-Associated Disorders: Redefining 'Whiplash' and its Management'.** in Spine Vol. 20 No. 8S, April 1995.

Svensson, M; Lovsund, P; Haland, Y and Larsson, S. **'The Influence of Seat-Back and Head Restraint Properties on the Head-Neck Motion During rear Impact'.** In Proceedings of the IRCOBI Conference, Sept. 8-10, Eindhoven , Holland, 1993.

Viano, D C and Gargan, M F. **'Headrest Position During Normal Driving: Implications to Neck Injury Risks in Rear Crashes'.** In Proceedings of the AAAM Conference, Chicago, Illinois, pp215-229, 1995.

Von Koch, M; Kullgren, A; Lie, A; Nygren, A and Tingvall, C. **'Soft Tissue Injury of the Cervical Spine in Rear-End and Frontal Collisions'.** In Proceedings of the IRCOBI Conference, Sept. 13-15, Brunnen, Switzerland, pp273-283, 1995.

Walz, F H and Muser, M H. **'Biomechanical Aspects of Cervical Spine Injuries'.** SAE Paper Number 950658, Society of Automotive Engineers, Warrendale, PA, 1995.

WHIPLASH ASSOCIATED DISORDER - FACTORS INFLUENCING THE INCIDENCE IN REAR-END COLLISIONS.

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ABSTRACT

Whiplash associated disorder, AIS1 neck injury, occurring in car accidents is an increasing problem all over the world. The injury as well as the mechanism of the injury are still in many ways unknown.

The purpose of this article is to add different factors that contribute to the knowledge of the origin of this injury.
In the present study real-life data from police records was used. The paired comparison method was used to evaluate the influence of the seat-belt geometry, vehicle weight as well as the sex of the occupant.

To study the influence of the seat-belt geometry on AIS1 neck injuries in rear-end collisions, two car models that were produced with two/three or four/five doors, were selected. There was an increased risk in the car models with four/five doors compared to the same car models with two/three doors.

The risk of whiplash injury increases with increased weight difference between the struck and the striking car. For cars of a given size the risk of whiplash injury is higher for females.

INTRODUCTION

Whiplash injuries with large risk of permanent disability are particularly frequent in low severity rear-end collisions. The accident severity is said to be in the region of less than 20 km/h change of velocity (Kahane 1982, Romilly et al 1989, Olsson et al 1990). As such accidents are common, they cause significant human suffering and high societal costs, despite the fact that theinjuries are usually classified as "minor" (AIS 1) in the Abbrevated Injury Scale (AIS) (Nygren 1984, Nygren et al 1985). A small proportion of people, 4%, exposed to injury in rear-end impacts (NASS/FARS 1981-86) actually receive an AIS 2 or more (Parkin et al 1995). In frontal collisions, as many as 90% of all neck injuries are AIS 1 (Faverjon et al 19??). In Sweden, whiplash injuries, resulting from traffic accidents have become the most common injury that causes medical impairment (von Koch et al 1994). The problem has grown in other countries as well (Kampen 1993, Ono et al 1993), especially since the enforcement of seat-belt laws (Cameron, 1981, Thomas, 1990, Larder 1985), though it is not known whether this is attributable to frontal impacts as well as to rear-end collisions.

The behaviour of the front seat seems to influence the risk of neck injury. Parkin et al (1995) reported that plastic yielding of front-seat backs is beneficial as the incidencts of AIS1 neck injuries are fewer in comparison to seats which do not yield. The same result has been presented by J.Y Foret-Bruno et al (1993). Several authors have reported a considerably smaller risk of AIS1 neck injury in the rear-seat compared to the front-seat for adult car

occupants (States et al 1972, Carlsson et al 1985, Lövsund et al 1988).

In laboratory tests it has been shown that the rebound velocity of the torso, in rear-end collisions, could increase dramatically from the initial change of velocity of the impact (von Koch et al 1995) and the hypothesis has been raised that the mechanism behind neck injuries, AIS1, both in frontal and rear-end impacts could be considered as a frontal mechanism. In other writings on this subject, most of them are said to be related to extension of the neck (States et al 1969, Svensson et al 1989, Romilly et al 1989)

Aim

The aim of this paper was to study the relationship between seat-belt geometry and the risk of AIS1 neck injuries in rear-end collisions. If the rebound velocity into the seat-belt influences the risk, this analysis could verify or recejt the theory.

The aim was also to study the influence of the change of velocity in the struck car on AIS1 neck injuries in rear-end collisions, for females as opposed males.

MATERIAL AND METHOD

Car accidents were reported to the National Bureau of Statistics (SCB) in Sweden by the police during 1985-94. The injuries were classified as minor, severe or fatal. Of these reports 9 302 accidents, involving rear-end impacts, could be identified where at least one driver was injured. Only minor injuries were selected, where the specific injury was not known. Earlier research has, however, shown that almost all injuries classified as minor occurring in rear-end accidents are soft tissue neck injuries (v Koch et al 1994, Larder et al 1985, Nygren, 1984).

In order to normalize for exposure, the paired comparison method was used in analysing the number of occupants at risk and the severity of the accident. The method was originally used by Evans (1991) for occupants in one vehicle, but has been developed by Folksam for occupants in two vehicles (Hägg et al 1992). The method is known to give adequate consideration for variations in accident severity and was used in this study to analyse the influence of sex, car weight and car model. The method is based on the fact that the risk of injury is a continous function of accident severity.

In the paired comparison method, the numbers of injuries in the struck and the striking car were compared. Ideally, if the risk of injury was the same in both vehicles, the ratio of injuries is one-to-one, whereas any deviation from that ratio indicates a difference in risk.

To investigate the influence of the seat-belt geometry of the whiplash injury, two different car models were selected. Volvo 240, 1975-94 and Saab 900 1979-93. They both were produced with two/three or four/five doors, which means that the position of the B-pillar, where the seat-belt´s upper anchorage point is, differs, and therefore alters the seat-belt geometry.
Of all police reported minor injuries that occured between 1985 and 1994 in rear-end accidents, the number of Saab 900 were 443 and the number of Volvo 240 were 1 068. As these two car models are very common in Sweden, it was beneficial to choose them for the analysis.

In the analysis, the Volvo 240 with two doors and the Saab 900 with two or three doors, were dealt with as one group. TheVolvo 240 and the Saab 900, with four or five doors, were also considered as one group.

Table 1.
The numbers of Volvo 240, 1975-94 and Saab 900, 1979-93, were distinguished by number of doors.

number of doors	Volvo	Saab
2	82	21
4	551	95
3		135
5	435	192

In a Volvo 240, the B-pillar is placed 27 cm further back in a two-door than in a four/five-door model, figure 1. In Saab 900, the B-pillar is placed 23 cm further back in a 2/3-door than in a 4/5-door model, figure 2. Apart from the position of the B-pillar (different seat-belt geometry), the construction is the same.

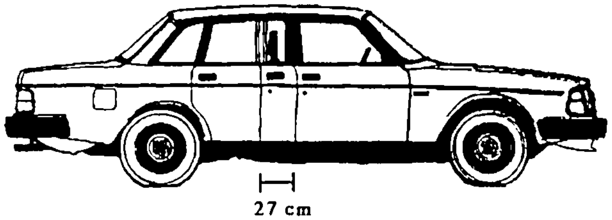

Figure 1. The position of the B-pillar in a two-, and a four-door Volvo 240, 1975-94.

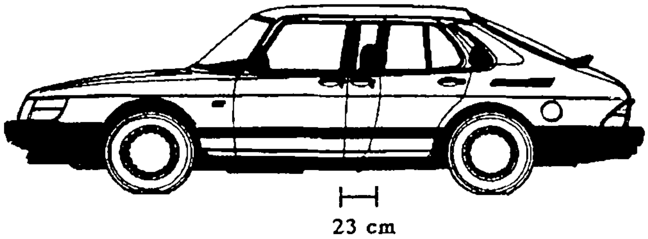

Figure 2. The position of the B-pillar in a three-, and a five-door Saab 900, 1979-93.

In figure 1 and 2, a two/three-door and a four/five-door model are plotted onto each other for elucidating the different location of theB - pillars.

In order to separate the effect of some important parameters influencing the relative risk of an injury in a rear-end collision, a multiple regression analysis with dummy variables was conducted. The dependent variable was the relative risk, generated by paired comparison, and the independent variables were sex, car model, car weight and number of doors (as an indirect measure of seat-belt geometry).

RESULTS

In table 2, the relative risk of injury in the struck car, in relation to the striking car, is shown for different weight combinations in rear-end collisions for females and males.
The same relative risk (struck/striking car) is reached when the striking car weighs on average 200 kilos less than the struck car.
The relative risk is in general at least twice as high for females as for males. The difference in relative risk in the worst case is at least 6.9 times higher in the struck car than in the striking car for females, and 3.7 times higher for males. In figure 3 the difference in the relative risk is shown for females and males, in cars of a given size (1300 kilos).

It is important to note that the injuries in the struck car almost exclusively are soft tissue neck injuries, as opposed to the striking car were there is a variety of injuries. The injuries in the police reported accidents are only coded as minor injuries, the diagnoses are not known. The relative risk of neck injuries AIS 1 is, therefore, even higher than indicated by the numbers presented in table 2.

Table 2.
The relative risk of minor injury to drivers in the struck car compared to the striking car, for females and males, in rear-end collisions.

	Striking car					
Struck car	900 kg (n)	1000 kg (n)	1100 kg (n)	1200 kg (n)	1300 kg (n)	1400 kg (n)
900kg M	0.78 (39)	1.19 (71)	2.00 (46)	2.23 (53)	2.62 (109)	2.92 (67)
F	2.60 (33)	1.83 (51)	4.25 (38)	3.44 (48)	6.33 (98)	4.40 (33)
1000 kg M	1.14 (64)	1.34 (104)	2.68 (84)	2.31 (97)	3.00 (182)	3.37 (96)
F	2.33 (46)	2.89 (71)	2.27 (50)	5.33 (59)	6.93 (120)	3.33 (66)
1100 kg M	1.21 (41)	1.06 (95)	1.58 (57)	2.50 (57)	2.35 (122)	3.72 (70)
F	1.00 (31)	2.07 (37)	2.67 (36)	2.62 (39)	3.46 (61)	3.50 (42)
1200 kg M	0.86 (68)	0.79 (94)	2.36 (91)	2.20 (87)	1.98 (179)	2.07 (99)
F	1.18 (26)	1.92 (33)	3.43 (35)	3.80 (27)	4.89 (56)	3.57 (38)
1300 kg M	0.70 (112)	0.99 (216)	1.02 (138)	1.13 (159)	1.43 (313)	1.85 (176)
F	1.74 (48)	1.86 (57)	1.46 (39)	2.46 (51)	2.60 (85)	2.26 (55)
1400 kg M	0.58 (68)	0.94 (113)	0.82 (100)	1.51 (88)	1.44 (181)	1.78 (99)
F	0.87 (26)	1.75 (38)	1.71 (22)	4.25 (25)	1.33 (50)	2.55 (27)

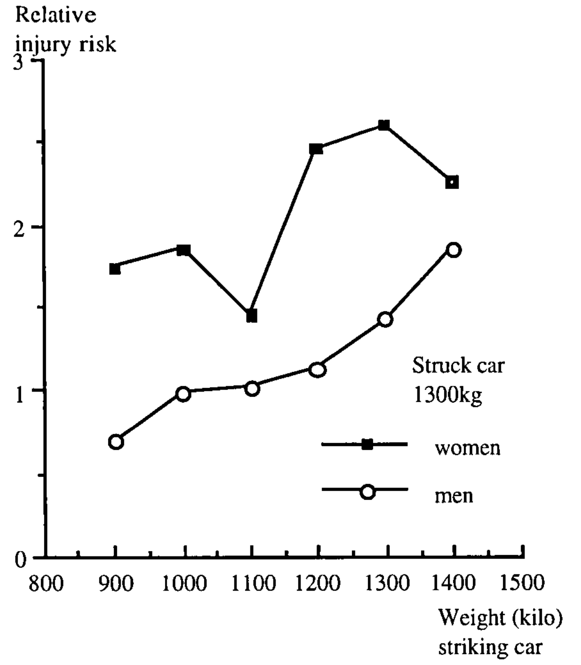

Figure 3. The relative risk of AIS1 neck injury for drivers, in rear-end collisions, distinguished by sex.

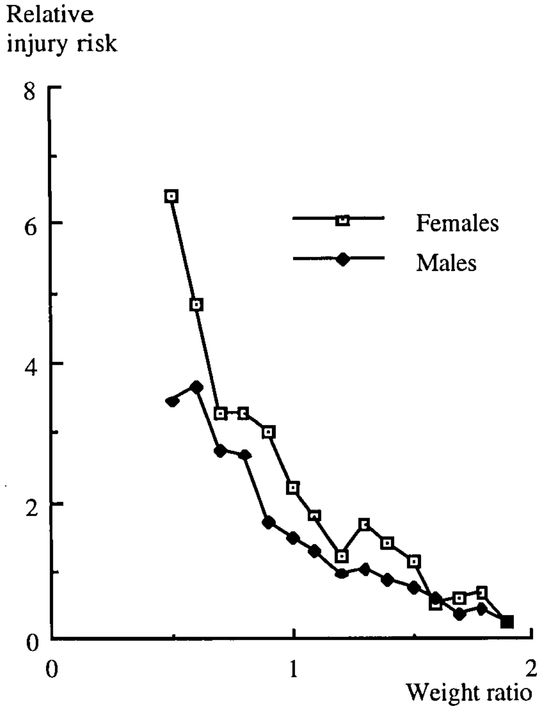

Figure 4. The relative risk of neck injury, AIS1, for different weight qouta struck/striking car.

Figure 4 shows that the relative risk of soft tissue injury to the neck, is not a linear function of the weight qouta. The risk increases considerably when the weight difference (the change of velocity) between the struck and the striking car increases.

Table 3.
Regression analysis. Regression coeff-icients and t-values for Volvo 240 and Saab 900.

	Regression coefficients	t-value
Car model	-0.111546	- 7.42
2/3-4/5 doors	0.212254	17.22
Car weight	-0.002657	-16.60
Sex	0.6560645	78.16
R square 0.849	n = 1 511	

Table 4.
The effect of different variables, based on males in a two-door Volvo 240 that weighs 1320 kilos. The relative risk of AIS1 neck injury for drivers, in struck car versus striking car was 1.165.

Volvo-Saab	9.4%
2/3-4/5 doors	18.2%
Car weight	22.8% / 100 kilo
Sex	56.3%

All regression coefficients were highly significant ($p<0.001$), which indicates that the car model, the number of doors, the weight of the car, and the sex excert an influence on the relative risk of neck injuries in rear-end impacts for drivers, table 3 and 4. Saab 900 has in relation to Volvo 240, a 9.4% higher risk. The 4/5 door cars, which have a B-pillar positioned more towards the front of the car than 2/3 door cars, have a relative injury risk that is 18% higher.
Females are at 56% higher risk than males.

Regarding weight, adding 100 kilos, gives a relative risk that is 23% lower, although this reflects not only the inherent risk in the struck car, but also the increased risk in the striking car

DISCUSSION

Injuries to the neck, AIS1, occur in different impact directions. Of all whiplash injuries causing medical impairment in Sweden, 64% occur in rear-end collisions (von Koch 1995). As much as 1/4 of the injuries are attributable to frontal impacts. Conclusions drawn from earlier research, show that the crash severity in rear-end collisions is less than 20 km/h when the AIS1 neck injury occurs (Kahane 1982, Romilly et al 1989, Olsson et al 1990).

The accident data that were used in this study were taken from police reported car accidents in rear-end collisions. Only minor injuries were selected when the specific diagnosis weas not known. However, earlier research has shown that almost all injuries occuring in rear-end accidents are soft tissue neck injuries. Because AIS1 neck injuries often occur in low-severity crashes, many of them do not reach the knowledge of the police, but the deficient quality of the data, are considered not to influence the conclusions.

In this study the number of injuries in the struck and the striking car has been compared. Ideally, if the risk of injury is the same in both vehicles, the ratio of injuries is one-to-one, and any deviation from that ratio indicates a difference in risk. The risk of an injury to the neck AIS1, is higher with a given change of velocity in the struck car than in the striking car, furthermore, the risk increases considerable in the struck car when the change of velocity is increasing.

The injury mechanism behind the whiplash injury is still unknown, but the most common explanation is related to extension of the neck (States et al 1969, Svensson et al 1989, Romilly et al 1989), at least in rear-end collisions. In those cases frontal impacts causing soft tissue injuries to the neck, hyperflexion is said to be the injury mechanism (Larder et al 1985, G.Faverjon et al 19??). The same symptoms seem to be found in both front and rear-end impacts (Jonsson 1994, Berglund 1996) but not with a common mechanism.

This study, with real-life data, showed an increased relative risk of AIS1 neck injuries in a car model with four/five doors compared to the same car model with two/three doors. Only rear-end collisions were investigated and the only parameter that distinguished the car model with two/three doors from the car model with four/five doors, was the belt geometry. In these cases, the Volvo 240 and the Saab 900 with only two doors had a seat-belt geometry that was much more beneficial. In other writings (S Parkin 1995, von Koch 1995) it has been shown that the torso can undergo a velocity change approaching twice the velocity change of the car. The seat back could effectively act as a spring which increases the velocity of the occupant significantly beyond the velocity of the striking car.This could mean that the torso accelerates to a higher velocity before it reaches the seat-belt in a four/five door Volvo 240/ Saab 900 than it does in a two/three door.

Therefore, this paper suggests that the mechanism behind AIS1 neck injuries is influenced by the frontal mechanism for the occupant, both in rear-end and in frontal collisions.

Many studies have shown that AIS1 neck injuries increased after the enforcement of seat-belt laws (Cameron 81, Thomas 1990, Larder 1985). A hospital based study in Britain indicated that a relative increase of 18% in neck sprain, coincided with the usage of seat-belts (Rutherford et al 1985). It is not known, though, if this is associated with only frontal impacts or also with rear-end collisions.

Real-life crash data always raise more questions than answers. It would be of great interest to further explore the influence of the weight of the occupant in the car seat. The present study shows that the risk of AIS1 neck injury is at least twice as high for females as for males, which has been shown in other studies as well (Larder et al 1985). Are women more vulnerable to AIS1 neck injury due to anatomical reasons or do they have a worse sitting position in the car-seat than men do? Or are women more vulnerable to AIS1 neck injury because they in general weigh less than men, and therefore reach a higher velocity before the torso is thrown into the seat-belt?

It is necessary to explain the findings regarding seat-belt geometry and the influence on neck injuries in rear-end collisions. This finding is consistent with the raised hypothesis regarding rebound velocity (von Koch 1995), and not vice versa, which means that other accident data should be analysed to verify or reject such an

hypothesis.
A hypothesis where the rebound of an occupant in a rear-end collision might cause a neck injury has a major influence on the preventative measures that will be designed, as well as test methods and injury criteria.

Conclusion

Apart from the fact that the weight of the car, both struck and striking, influences the relative risk of AIS1 neck injuries and that females are at a higher risk than males, the seatbelt geometry also is an important parameter in rear-end collisions.

REFERENCES

Abbreviated Injury Scale. 1980 and further revisions. AAAM. 1980, 1985, 1990.

Berglund A. Neck Injuries to Car Occupants - A Prospective Population - Based Study of an Insurance Material. WHO 3rd Int. Conf. Injury Prevention and Control, Melbourne, Australia, 1996.

Cameron, M.H. The effect of seat belts on minor and sevree injuries measured on the abbreviated injury scale. Accident Analysis & Prevention,Vol. 13, no 1, pp 17-28. 1981.

Carlsson G, Nilsson S, Nilsson-Ehle A, Norin H, Ysander L, Örtengren R. Neck Injuries in Rear End Car Collisions. Biomechanical considerations to improve heat restraints. Proc. Int. IRCOBI/AAAM Conf. Biomech. of Impatcts, Göteborg, Sweden, 277-289; 1985.

Evans, Leonard. Traffic Safety and the Driver. Van Nostrand Reinhold, New York,USA, 1991.

Faverjon G, Henry C, Thomas C, Tarriére C, Patel A, Got C, Guillon F. Head and Neck injuries for Belted Front Occupants involved in Real Frontal Crashes: Patterns and Risks.

Foret-Bruno J Y, Dauvilliers F, Tarriere C, Mack P. Influence of the Seat and Head Rest Stiffness on the Risk of Cervical Injuries in Rear Impact. Prox. 13th ESV Conf. in Paris,France, (1993) paper 91-S8-W-19, NHTSA, USA, DOT HS 807

Hägg A, Kamrén B, von Koch M, Kullgren A, Lie A, Malmstedt B, Nygren Å, Tingvall C. Folksam Car Model Safety Rating 1991-92. Folksam research, Stockholm, Sweden, 1992.

Jónsson Halldór Jr, Cesarini K, Sahlstedt B, Rauschning W. Findings and Outcome in Whiplash-Type Neck Distortions.Uppsala, Sweden. SPINE Volume 19, No 24, pp 2733-2743, 1994.

Kahane, C.J. An Evaluation of Head Restraints - Federal Motor Vehicle Safety Standar 202. NHTSA Technical Report, DOT HS-806 108, National Technical Information service, Springfield, Virginia 22161, USA;1982.

von Koch M, Nygren Å, Tingvall C. Impairment Pattern In Passenger Car Crashes, a Follow-up of Injuries Resulting in Long-term Consequences. ESV conference, Munchen 1994. 94-S5-O-02, p 776-781.

von Koch M, Kullgren A, Lie A, Nygren Å, Tingvall C. Soft Tissue Injury of the Cervical Spine in Rear-End and Frontal Car Collisions. IRCOBI, Brunnen, Schweiz, 1995.

4. Kampen, L.T.B.van (1993): Availability and (Proper) Adjustment of Head Restraints in the Netherlands. Int. IRCOBI Conf. on the Biomeck. of Impacts, Sept 8-10, Eindhoven, The Netherlands, pp 367-378.

Larder D R, Twiss M K, Mackay G M. Neck injury to car occupants using seat belts. 29th Annual Proceedings AAAM, Washington, D C, 1985.p 153-165.

Lövsund P, Nygren Å, Salen B.; Tingvall C. Neck Injuries in Rear End Collisions among Front an Rear Seat Occupants. Proc. Int. IRCOBI Conference Biomech. of Impacts, Bergisch-Gladbach, F.R.G., 319-325; 1988.

Nygren Å, Injuries to car occupants - some aspects of the interior safety of cars. Thesis. Acta Oto-Laryngologica, supplement 395, 1984.

Nygren Å, Gustafsson H, Tingvall C. Effects of Different Types of Headrests in Rear-End Collisions. 10th Int. Conference on Experimental Safety Vehicles, NHTSA, USA, p 85-90; 1985.

Olsson,I, Norin, H, Ysander, L. An in-Depth Study of Neck Injuries in Rear End Collisions. Proc, 1990 Int. IRCOBI Conf. on the Biomechanics of Impacts, Bron, Lyon, France, 269-282;1990.

Ono K and Kanno M Influence of the Physical Parameters on the Ris to Neck Injuries in Low Speed Rear-End Collisions, IRCOBI Proceedings, p 201-212;1993.

Parkin S, Mackay G M, Hassan A M, Graham R. Rear End Collisions And Seat Performance- to Yield or not to Yield. 39th Proc. AAAM, Chicago, Illinois, USA, 1995.

Romilly D P, Thomson, R W, Navin F P D, Macnabb M J. Low Speed Rear Impacts and the Elastic Properties of Automobiles. Proc. Twelth Int. Techn. Conf. Experimental Safety Vehicles, US Dept. of Transp., NHTSA, USA, 1199-1205; 1989.

Rutherford W H, Greenfield A, Hayes H R M. The medical effects of seat belt legislation in the United Kingdom. H.M.S.O. (in press),July, 1985.

States J D, Korn M W, masengill J B 1969. TheEnigma of Whiplash Injuries. Prox Thirteenth Ann Conf AAAm, Minnesota, USA, pp 83-108.

States J D, Balcerak J C, Williams J S, Morris A T, Babcock W, Polvino R, Riger P, Dawley R E. Injury Fequency and Head Restraint Effectiveness in Rear-End Impact Accidents. Proc. 16th Stapp Car Crsh Conf, New York. SAE, 228-245; 1972.

Svensson M Y , Örtengren T, Aldman B, Lövsund P, Seeman T. A Theoretical Model for and a Pilot Study Regarding Transient Pressure Changes in the Spinal Canal under Whip-lash Motion. Dept. of Injury Prevention, Chalmers University of Technology, Göteborg, Sweden, R 005, 1989.

Thomas,J. Road traffic accidents before and after seatbelt legislation-study in a District General Hospital. France. The Royal Society of Medicine, Volume 83, 1990.

RELATIONSHIPS BETWEEN COMPUTED DELTA V AND IMPACT SPEEDS FOR OFFSET CRASH TESTS

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ABSTRACT

The intent of crashworthiness standards and new car evaluations based on full vehicle testing is to promote designs that eliminate many, if not all, of the serious injuries in real-world crashes of equivalent or lesser severity to that used in the test. A sample of real-world frontal crashes in the United States was examined and the estimated crash severities were related to impact speeds for single-vehicle offset crashes into deformable barriers. For each of the vehicles in these tests, the postcrash vehicle deformation was measured using the procedures specified for CRASH3 and a delta V was calculated. The results of this study suggest that a 40 percent offset test into a deformable barrier at 64 km/h represents a real-world crash severity below which about 75 percent of all MAIS 3 or greater injuries and slightly less than half of all fatal injuries to passenger car occupants in frontal offset crashes occur in the United States. The fact that many deaths and serious injuries occur in higher severity crashes suggests that this test speed choice is not too high and that standards or crashworthiness evaluations in offset tests into deformable barriers at significantly lower speeds would be ignoring large numbers of real-world crashes with serious injuries.

INTRODUCTION

The use of vehicle crash testing to assess occupant protection has a long history, but such testing was not required for all new cars sold in the United States until the first federal motor vehicle safety standards were issued in the late 1960s. The crash test specified in the first federal standards was a full width, rigid barrier crash at 30 mi/h (48 km/h). It was initially used to set limits on the rearward displacement of steering columns in Federal Motor Vehicle Safety Standard (FMVSS) 204.

This test was based on the Society of Automotive Engineers (SAE) Recommended Practice J850, Barrier Collision Tests.[1] SAE J850 was issued in 1963 and specified 30 mi/h (48 km/h) impacts into a rigid barrier,

> "to provide realistic simulations of the forces which act on vehicles and occupants during accidental collisions with fixed objects. Measurements of structural loads and deflections, determinations of occupant dynamics, and photographic and post-collision observations of pertinent special events may be useful in establishing design criteria."

There are no records indicating why 30 mi/h (48 km/h) was chosen as the appropriate test speed for SAE J850 when it was issued in 1963, and it seems likely that the speed was an arbitrary choice.

Shortly after the issuance of the initial federal safety standards, the first proposal for inflatable restraints (as part of FMVSS 208) was issued in 1969. This proposal also specified 30 mi/h (48 km/h) barrier tests, but the National Highway Traffic Safety Administration (NHTSA) in 1970 also noted that,

> It is anticipated that as crash protection technology advances, the test speeds at which protection must be offered will be raised by future amendments to 40 miles per hour (head-on or fixed barrier collision) or higher, and rear impact tests will be added.[2]

As with SAE J850 there was no rationale offered for raising the impact test speed requirements from 30 to 40 mi/h beyond the unstated assumption that higher speed tests would assure better protection.

In the early 1970s NHTSA initiated the first Experimental Safety Vehicle (ESV) program. The emphasis of this program was on designs for crash protection, with a stated "near-term goal of

crashworthiness in front barrier collisions at 40-50 mph...because a significant portion of frontal injury producing accidents occur at or below this velocity range."[3] It was also anticipated that this program would lead "to an ultimate examination of feasibility for safety in crashes in the 60-70 mph range."

In 1972, NHTSA examined "the engineering and economic feasibility of inflatable restraint systems and structural modifications required to achieve passive protection for occupants in passenger car frontal collisions at 50 mph equivalent barrier speed."[4] This was one of the earliest attempts to formally justify proposed vehicle design improvements using information on the severity distributions of real-world injury producing and fatal crashes. In this report equivalent frontal barrier test speeds were used as the measure of crash severity.[5] The validity of these severity distributions, however, was challenged by Prost-Dame of Renault-Peugeot who claimed that the NHTSA method overstated the barrier equivalent speeds because it did not account for mass differences in car-to-car collisions.[6]

Crash testing became more sophisticated with dummies and injury criteria being specified in more detail throughout the 1970s. In large part this was in response to the prolonged rulemaking process for automatic crash protection, which included requirements for vehicle crash testing with instrumented test dummies. NHTSA expanded the role of crash testing in 1978 with a new program of 35 mi/h frontal barrier tests with instrumented test dummies to assess the crashworthiness of new cars.[7] This New Car Assessment Program (NCAP) was initiated to provide consumers with information on the relative crashworthiness of new cars and to encourage manufacturers to compete in terms of improved crashworthiness. The test speed of 35 mi/h (56 km/h)was chosen to provide a level of crash severity that was sufficiently higher than the 30 mi/h (48 km/h) test speed in FMVSS 208 to highlight differences in performance among new cars.

The intent of crashworthiness standards and new car evaluations based on full vehicle testing is to promote designs that eliminate many, if not all, of the serious injuries in real-world crashes of equivalent or lesser severity to that used in the test. The choice of the test speed obviously is important. If it is too low relative to real-world crashes, then few injuries will be eliminated, and if it is too high, the incremental cost associated with eliminating the relatively small numbers of injuries that occur in the most severe real-world crashes will be extremely high. Furthermore, some technologies that provide protection at high speeds may degrade protection in lower speed crashes, which are much more common. There is a clearer recognition today than there was in the 1970s that requiring protection at higher and higher crash speeds is not necessarily a good idea.

To make a rational choice of test speeds, it is necessary to have knowledge of the distributions of crash severities producing injuries of certain severity levels and the ability to relate those severities to impact test speeds. This paper examines a sample of real-world frontal crashes in the United States and shows how the estimated crash severities can be related to impact speeds for single-vehicle offset crashes into deformable barriers.

REAL-WORLD CRASH SEVERITY ASSESSMENTS

As early as the 1960s, researchers studying real-world crashes recognized the need to characterize the severity of crashes in ways that could provide useful feedback to vehicle designers.[8] After a crash, the most reliable direct evidence of the crash severity usually is the deformation of the vehicle itself, and virtually all of the accepted procedures used are based on vehicle deformation.

Early efforts to characterize crash severity essentially used simple measures of deformation but did not try to relate these scales to impact speeds.[9,10] Another approach used photographs of vehicles that had been in standard test crashes, so that the real-world crash deformation could be approximately related to that which occurred in test crashes of known speed. This latter approach led to the concept of equivalent barrier speed (EBS) (sometimes referred to as barrier equivalent velocity [BEV], because the test crashes were full-width rigid barrier crashes).[11] Even though this approach is very simple, it is valid *only* when the real-world crashes studied are actually *equivalent* to the barrier crashes producing the reference deformations. Unfortunately, the applicability of this method is constrained because so many real-world crashes are quite dissimilar to full-width rigid barrier crashes.

In the 1970s, computer programs were developed by Calspan Corporation to compute the change in velocity of a vehicle's center of gravity resulting from crash forces — referred to as delta V — from standard vehicle deformation measures.[12] Various versions of the Calspan Reconstruction of Accident Speeds on the Highway (CRASH) program have been used around the world to calculate delta V, and until recently CRASH3 was the most widely used of these programs.[13] This measure of crash severity, however, is regularly misinterpreted, especially in relation to equivalent test speeds.

In certain kinds of crashes and crash tests, delta V can be interpreted as equivalent to the impact speed, and in others, it cannot. The velocity change of a vehicle in a crash obviously begins at the time of the first contact, but the end of the velocity change can be considered to be either at the time of the maximum vehicle deformation or at the time the vehicle separates from whatever it is colliding with. Thus, in a flat barrier crash of 30 mi/h (48 km/h) the velocity change at the point of maximum

deformation is 30 mi/h (48 km/h), because at this point the vehicle velocity has reached zero. However, after maximum dynamic crush, some of the crushed structure restores itself, and the vehicle rebounds from the barrier with a negative velocity. Thus, the velocity change at the time the vehicle separates from the barrier is 30 mi/h (48 km/h) plus the rebound velocity. The CRASH3 program calculates the delta V up to the time of maximum deformation, and there is no rebound velocity component, which means that in a full-width rigid barrier crash delta V (as defined in CRASH3) is equal to the impact speed.

In these special cases, delta V is the same as equivalent barrier speed or barrier equivalent velocity. Also in the case of two identical vehicles colliding head-on (full-width) at the same speeds, each vehicle will have the same delta V as a full-width barrier crash at the same speed and the deformation will be the same.

Delta V can only be interpreted as equivalent to barrier speed for full-width impacts with rigid objects or full-width crashes with vehicles of similar stiffness. It is appropriate to relate computed delta Vs in these crashes to test speeds in full-width barrier crashes, but in other crash types, including frontal crashes where only part of the vehicle's front end is engaged, *it is not correct to* relate computed delta Vs to test speeds. Unfortunately, computed delta Vs from the complete spectrum of real-world frontal crashes have been widely misinterpreted as equivalent barrier speeds.

In part because of the widespread misinterpretation of delta V, the energy equivalent speed (EES) was developed as an alternative parameter to assess crash severity.[14] It is technically identical to equivalent barrier speed but the term was introduced to emphasize the energy-related character of this parameter rather than a barrier test equivalent. The energy equivalent speed is defined as the speed at which a particular vehicle would need to contact any *rigid* object in order to dissipate the deformation energy corresponding to the observed vehicle residual crush. Although the energy equivalent speed is a more appropriate measure for characterizing crash severity, its application has been largely confined to data collected by car manufacturers.

Despite its limitations as a measure of crash severity, delta V is the parameter that is widely used in crash data files, and, therefore, it is necessary to interpret these data in relation to impact test speeds. As already noted, this is relatively straightforward for frontal crashes between identical vehicles where the full vehicle width is directly involved in the crash. But with the growing interest in offset testing around the world, there is a need to understand how impact speeds in such tests may be related to computed delta Vs for vehicles in real-world offset tests.

RESULTS

Vehicle Crash Test Delta Vs

The Insurance Institute for Highway Safety has conducted several series of offset frontal crash tests including actual car-to-car impacts and single-vehicle crashes into deformable barriers. For each of the vehicles in these tests, the postcrash vehicle deformation has been measured using the procedures specified for CRASH3 and a delta V has been calculated. The procedures also involved applying stiffness and size codes for each vehicle and the values used in each case are the codes that would be assigned by National Accident Sampling System (NASS) field investigators if they were doing the same calculations. Table 1 shows the results of these calculations for a series of cars involved in car-to-car offset crashes conducted at nominal impact speeds of 55 and 64 km/h with nominal overlaps of 50 percent. In every case calculated, delta V is less than the test impact speed with the differences ranging from 6 to 15 km/h.

Table 2 shows the calculated delta Vs for a group of 1995-96 midsize four-door passenger cars in 64 km/h, 40 percent offset impacts with deformable barriers. Estimates of the crash energy that was absorbed by the deformable barriers were taken into account in the delta V calculations by adding the energy absorbed by the barrier to the energy absorbed by the vehicle. This procedure produces a slightly higher estimate of delta V than would be obtained from the vehicle crush measurements alone. For this group of cars, the differences between the impact speeds and the estimated delta Vs were greater than for the car-to-car crashes in Table 1. The estimated delta Vs were lower than the impact speeds by an average of 21 km/h and the range of the differences was from 16 to 27 km/h.

Table 3 shows the estimated delta Vs for several Ford Ranger pickups and Lincoln Town Cars in 64 km/h, 40 percent offset tests into deformable barriers. For every vehicle, the estimated delta V is lower than the impact speed; the differences range from 6 to 15 km/h with an average of 10 km/h.

Real-World Crash Delta Vs

NASS provides the largest database available with estimated delta Vs for the involved vehicles. Before computing delta V distributions for frontal crashes, however, it is necessary to segregate the crashes by the extent of the direct front-end damage. This was done using the coded Collisions Deformation Classification (CDC) information.[15]

Table 1
Impact Speeds and Delta V Estimates from CRASH3
Car-to-Car Impacts

Make/Model	Model Year	Vehicle Test Weight (kg)	Percent Overlap	Impact Speed (km/h)	CRASH3 Delta V (km/h)	Difference (km/h)
Lincoln Town Car	1992	1860	(46)	56	42	14
	1993	1883	(46)	57	42	15
Chrysler LeBaron Conv.	1989	1413	(48)	56	43	13
Coupe	1989	1408	(48)	57	43	14
Oldsmobile Cultlass Ciera	1985	1380	(50)	55	42	13
	1985	1431	(50)	55	40	15
	1986	1342	(52)	56	50	6
	1986	1395	(52)	56	48	8
	1989	1376	(52)	55	45	10
	1989	1376	(52)	56	45	11
	1989	1342	(57)	55	47	8
	1989	1357	(57)	55	46	9
	1989	1367	(62)	55	45	10
	1989	1371	(62)	56	45	11
Chrysler LeBaron Conv.	1989	1417	(62)	64	58	6
Coupe	1989	1426	(62)	64	58	6
Oldsmobile Cultlass Ciera	1988	1344	(55)	63	55	9
	1989	1345	(55)	64	55	9

Table 2
Impact Speeds and Delta V Estimates from CRASH3 Midsize 4-Door Passenger Cars
Single Vehicle Impacts into Deformable Barriers 40 Percent Overlap

Make/Model	Model Year	Vehicle Test Weight (kg)	Impact Speed (km/h)	CRASH3 Delta V (km/h)	Difference (km/h)
Chevrolet Cavalier	1995	1362	64	37	27
Subaru Legacy	1995	1380	64	39	25
Ford Contour	1995	1431	64	38	26
Honda Accord	1995	1452	64	40	24
Mitsubishi Galant	1995	1459	64	47	17
Saab 900	1995	1489	64	46	18
Nissan Maxima	1995	1507	64	43	21
Toyota Camry	1995	1511	64	48	16
Chrysler Cirrus	1995	1553	65	48	17
Volkswagen Passat	1995	1557	64	43	21
Ford Taurus	1995	1565	64	44	20
Volvo 850	1995	1565	65	44	21
Toyota Avalon*	1996	1584	64	45	19
Mazda Millenia	1995	1593	64	41	23
Chevrolet Lumina	1995	1645	64	42	22
Ford Taurus	1996	1651	64	42	22
				Average	21

*Stiffness code not assigned by NASS. Camry stiffness 9 used.

Table 3
Impact Speeds and Delta V Estimates from CRASH3 Single Vehicle Impacts into Deformable Barriers
40 Percent Overlap

Make/Model	Model Year	Vehicle Test Weight (kg)	Impact Speed (km/h)	CRASH3 Delta V (km/h)	Difference (km/h)
Ford Ranger	1988	1379	64	58	6
	1989	1419	64	51	13
	1990	1448	64	52	12
	1989	1495	64	52	12
				Average	**11**
Lincoln Town Car	1991	1880	64	55	9
	1990	1897	64	57	7
	1992	1924	64	49	15
				Average	**10**

The direct damage was classified as involving about one-third or less of either side of the front end, between one-third and two-thirds of either side of the front end, or distributed across the front-end. (Center impacts involving one-third or less were excluded.) Separating direct and induced damage from postcrash inspections is often difficult, and so these groupings are subject to some error. None of the three groupings exactly correspond to either full-width barrier crashes or offset crashes with overlaps of 50 percent or less; however, as a first approximation, crashes with the distributed damage are closest to full-width barrier impacts and crashes producing direct damage to one-third or less of the front-end are the closest equivalents to offset impacts involving less than half of the vehicle width. The direct damage grouping was done for all passenger cars with computed delta Vs in the 1990-94 NASS files. About 85 percent of the delta V estimates in these NASS cases were computed using the CRASH3 program; the remainder were computed using the OLDMISS program,[13] which is used when the crush measurements for the other vehicle in two-vehicle crash are not available. Then separate delta V distributions were calculated for single- and two-vehicle crashes for each direct damage grouping. The results are shown separately in Table 4 for all towaway crashes, crashes with Maximum Abbreviated Injury Score (MAIS) 2 or greater injuries, MAIS 3 or greater injuries, and fatal injuries.

For towaway crashes, the results show higher median delta Vs for single-vehicle crashes (31 km/h) compared with two-vehicle crashes (24 km/h) and lower delta Vs for crashes with direct damage involving one-third or less of the front-end (21 km/h) compared with crashes with distributed direct damage (27 km/h).

For all cars in crashes with occupant injuries of MAIS of 2 or greater, the median delta Vs are higher (34 km/h) than for towaway crashes (25 km/h) overall, but the same pattern emerges. Single-vehicle crashes have greater median delta Vs (37 km/h) than two-vehicle crashes (32 km/h) and lower delta Vs for damage involving one-third or less of the front-end (27 km/h) compared with crashes with distributed damage (35 km/h).

For cars in crashes with MAIS 3 or greater injuries, the overall median delta V is 40 km/h, which is 6 km/h higher than the median for crashes with MAIS 2 or greater injuries. In this set of more serious crashes, the differences in the median delta Vs between single- and two-vehicle crashes is less pronounced; however, the median delta Vs again are lower for the offset crashes with direct damage to one-third or less of the front-end — 34 km/h vs. 41 km/h.

For cars in crashes with fatal injuries, the overall median delta V is 51 km/h, which is 11 km/h higher than the median for crashes with MAIS 3 or greater injuries. In this set of fatal crashes, there is no clear pattern of differences between single- and two-vehicle crashes; however, there continues to be a difference between the median delta Vs for the crashes with direct damage that is distributed compared to those with direct damage to one-third or less of the front-end — 55 km/h vs. 40 km/h.

The results shown in Table 4 show interesting patterns — single-vehicle crashes typically have higher median delta Vs than two-vehicle crashes. However, in the crashes with more serious injuries — those with MAIS 3 or greater injuries — these differences disappear. Thus, these results indicate that similar delta Vs are involved for

Table 4
Median Delta Vs (km/h) for Passenger Cars
NASS 1990-94

	Crash Type		
Direct Damage	Two Vehicle	Single Vehicle	Total
All Towaway Crashes			
Distributed	26	34	**27**
Offset 2/3	23	32	**26**
Offset 1/3	18	24	**21**
Total	**24**	**31**	**25**
MAIS 2 or Greater Injuries			
Distributed	35	39	**35**
Offset 2/3	32	39	**35**
Offset 1/3	26	29	**27**
Total	**32**	**37**	**34**
MAIS 3 or Greater Injuries			
Distributed	40	44	**41**
Offset 2/3	40	42	**40**
Offset 1/3	32	34	**34**
Total	**40**	**40**	**40**
Fatal Injuries			
Distributed	55	57	**55**
Offset 2/3	51	46	**50**
Offset 1/3	34	42	**40**
Total	**52**	**48**	**51**

both single- and multiple-vehicle crashes with the more serious occupant injuries. That is, similar levels of crash severity (as indicated by delta V) are needed to produce serious injuries regardless of whether the crash is single- or multiple-vehicle.

The average differences between impact speeds and computed delta Vs for the group of 16 recent model passenger cars shown in Table 2 is 21 km/h, which means that the average delta V for this group of cars involved in 64 km/h impacts into deformable barriers is 43 km/h. In contrast, the median delta V for passenger cars involved in real-world offset crashes (direct damage to one-third or less of the front-end) is 34 km/h for crashes with MAIS 3 or greater injuries, and 40 km/h for fatal injuries. The 75th percentile delta Vs for these two groups of cars are 42 km/h and 50 km/h, respectively. Thus, based on the test results for 16 cars, frontal crashes with severities equivalent to or less than a 64 km/h impact into a deformable barrier would include about 75 percent of all MAIS 3 or greater injuries and slightly less than half of all fatal injuries occuring in real-world offset crashes.

To further illustrate the differences between test impact speeds and real-world delta Vs for offset crashes, NASS case vehicles with direct damage to one-third or less of the front-end and computed delta Vs in the 45 to 50 km/h range were identified. The postcrash crush measurements for three of these case vehicles and similar vehicles in the offset test impacts are compared in Tables 5 and 6.

Table 5
Chrysler LeBaron Crush Measurements
60 Km/H 40 Percent Offset Test vs.
Two Real World Single-Vehicle Impacts with Roadside Objects

	Crush Measurements (cm)		
		Real-World Crashes	
Crush Measurement Points	Offset Test 1989 Conv.	1990 Convertible	1988 Four-Door
C_1	97	108	75
C_2	84	81	88
C_3	74	60	64
C_4	51	44	34
C_5	30	27	14
C_6	10	15	0
CRASH3 delta V (km/h)	51	48	47

Table 6
Honda Accord Crush Measurements
64 Km/h 40 Percent Offset Test vs.
Real World Car-to-Car Offset Crash

	Crush Measurements (cm)	
Crush Measurement Points	Offset Test 1995 4-Door	Real-World Crash 1984 4-Door
C_1	84	105
C_2	64	67
C_3	49	53
C_4	30	29
C_5	16	13
C_6	7	0
CRASH3 delta V (km/h)	40	50

In Table 6 the crush measurements from a Chrysler LeBaron convertible in a 60 km/h 40 percent offset test into a deformable barrier are compared with corresponding measurements from a LeBaron convertible and four-door model, both of which were involved in single-vehicle impacts with roadside objects. The pattern of crush measurements for these vehicles are not dissimilar, and the computed delta Vs are close. These results indicate that for this particular model, real-world offset crash delta Vs are about 10-12 km/h lower than speeds that would produce similar damage in offset tests with a deformable barrier. Table 6 compares crush measurements from two Honda Accord models. In this case, there are significant design differences between the two models, the 1995 model having a longer wheelbase by about 26 cms and also heavier by about 240 kg, so the comparisons are not so clear. Again, however, the crush measurements are similar and the computed delta Vs are substantially less than the test impact speed.

DISCUSSION

There are several possible explanations for the finding that lower median delta Vs for crashes in which the direct damage involves one-third or less of the front-end compared with crashes with direct damage distributed across the front-end. It may be that offset crashes occur at somewhat lower impact speeds than crashes with distributed damage. An alternative is that the two groups of cars are in crashes with similar distributions of impact speeds, but that the computed delta Vs are systematically lower for cars in offset crashes. Or some combination of these two explanations may be occurring.

We know from its definition that delta V is equal to impact speed for full-width barrier crashes, and that in some full-width head-on crashes delta Vs indicate barrier equivalent crash speeds. The results shown in Tables 1 through 3 show that in both car-to-car and car-into-deformable barrier tests computed delta Vs for offset impacts significantly underestimate the actual impact speeds. Thus, it seems most likely that this effect -- computed delta Vs that are lower than impact speeds -- is the principal contributor to the differences in median delta Vs for distributed and offset crashes in NASS.

The systematic differences in delta Vs for distributed and offset direct damage mean that using distributions of computed delta Vs from real-world crashes to assess the relevance of impact test speeds for either new vehicle safety standards or crashworthiness assessments can be misleading. Estimated delta V distributions for frontal crashes combined together regardless of the extent of direct damage will *underestimate* equivalent test speeds. This is because delta Vs only approximate equivalent test speeds for some crashes with direct damage distributed across the full width of the vehicle's front-end. For offset crashes, the computed delta Vs are considerably lower than equivalent test speeds.

The current interest of automobile safety researchers and agencies throughout the world in offset crashes into deformable barriers, either for new car standards or for crashworthiness assessments, has focused attention on the question of appropriate speeds for this test. Because the deformable barrier absorbs some of the energy of the crash and because the initial interest in this test was for a European crashworthiness standard that was viewed as an alternative to the U.S. full-width barrier test, the initial choices for test speed were at a level somewhat higher than the 48 km/h U.S. standard. Test speeds arbitrarily tend to be considered in 5 mi/h (8 km/h) increments, and the first choice considered was 56 km/h. Initial tests at this speed, however, indicated relatively low injury measures for virtually all cars, which led to suggestions for test speeds of 60 km/h (37.5 mi/h) or even 64 km/h (40 mi/h).

The results of this study suggest that a 40 percent offset test into a deformable barrier at 64 km/h represents a real-world crash severity below which about 75 percent of all MAIS 3 or greater injuries and slightly less than half of all fatal injuries to passenger car occupants in frontal offset crashes occur in the United States. The fact that many deaths and serious injuries occur in higher severity crashes suggests that this test speed choice is not too high and that standards or crashworthiness evaluations in offset tests into deformable barriers at significantly lower speeds would be ignoring large numbers of real-world crashes with serious injuries.

REFERENCES

1. Society of Automotive Engineers. 1963. Barrier Collision Tests - SAE J850 Recommended Practice. New York, NY: Society of Automotive Engineers.

2. *Federal Register. 1970*. Occupant Crash Protection in Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses, Vol. 38, No. 214, November 3, 1970, p. 16927.

3. Edwards, H.A. 1971. *Report on the First International Technical Conference on Experimental Safety Vehicles.* Washington, DC: Department of Transportation, 21-23.

4. Carter, R.L. 1972. *Passive protection at 50 miles per hour.* (DOT HS-810-1972) Washington, DC: National Highway Traffic Safety Administration, U.S. Dept. of Transportation.

5. Cooke, C.C. 1971. *Safety Benefits of the Occupant Crash Protection Standard.* (DOT 69-07-GR-043) Washington, DC: National Highway Traffic Safety Administration, U.S. Dept. of Transportation.

6. Prost-Dame, C. 1973. *Fourth International Technical Conference on Experimental Safety Vehicles.* Washington, DC: National Highway Traffic Safety Administration, U.S. Dept. of Transportation, 197-200.

7. U.S. Department of Transportation. 1969. *News Release: DOT Car Crash Test Results Announced.* Washington, DC: U.S. Dept. of Transportation.

8. Mackay, G.M. 1968. *Injury and Collision Severity.* SAE Transactions, Vol. 77. New York, NY: Society of Automotive Engineers, Inc.

9. National Safety Council. 1968. *Vehicle Damage Scale for Traffic Accident Investigators.* Traffic Accident Data Project Bulletin No. 1. Chicago, IL: National Safety Council.

10. Cromack, J.R. 1970. Vehicle Deformation Index, CCMS-NATO Accident Investigation Workshop. Wolfsburg, Germany, October 1970.

11. Ashton, S.J., Hardy, J.L.G., Mackay, G.M. 1973. Proceedings International Accident investigation Workshop, Washington, DC: National Highway Traffic Safety Administration, U.S. Dept. of Transportation, 85-102.

12. McHenry, R.R. 1971. *Development of a Computer Program to Aid the Investigation of Highway Accidents.* Washington, DC: National Highway Traffic Safety Administration, U.S. Department of Transportation.

13. CRASH3 User's Guide and Technical Manual. 1981; revised 1982. Washington, DC: National Highway Traffic Safety Administration, U.S. Department of Transportation.

14. Zeidler, F., Schreier, H.-H., Stadelmann, R. 1985. Accident research and accident reconstruction by the EES–accident reconstruction method. *Field Accidents: Data Collection, Analysis, Methodologies, and Crash Injury Reconstructions.* Warrendale, PA; Society of Automotive Engineers, Inc., 285-299.

15. Society of Automotive Engineers. 1980. Collisions Deformation Classification – SAE J224 Recommended Practice. Warrendale, PA: Society of Automotive Engineers.

THE CRASH SAFETY OF NEW CAR MODELS - A COMPARATIVE ACCIDENT STUDY OF NEW VERSUS OLD CAR MODELS

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BACKGROUND

The differences between car models in crash safety are substantial. These differences are attributable to several characteristics of a car, such as energy dissipation, restraint system performance, and mass. Mass is more or less an important factor in a car to car collision depending on the crash mode. In i e single accidents, mass plays only a very minor role. In car to car accidents the mass distributions between the two vehicles will determine the change of velocity for the two vehicles. There might be a correlation between mass and the overall safety of a vehicle as the larger car normally has s larger interior space and more structure for energy dissipation. The producers of larger vehicles also often have had passive safety more in focus than the manufacturers of smaller vehicles.

The interest of passive safety among the consumers has started a process leading to safer cars produced. Results from crashworthiness tests show a substantial reduction in injury criteria for all types of car sizes. This increase in safety has been accompanied by an increase of mass. Cars of the same size class have had an increase in mass by more than 100kg.

From an environmental point of view, low mass vehicles are positive, since they consume less energy. The individual as well as the society is therefore interested in cars with a low mass. The society might want to stimulate a downsizing process. Often the term downsizing is used for the process aiming at decrease in mass and energy consumption. In this article we adapt to the use of the word "downsizing".

The potential mass or safety conflicts must be handled when the society more and more relies on passive safety of vehicles to reduce the number of health losses. A strategy is needed in a society where regulations are no longer the dominating tool to drive the process of generating more crashworthy cars. The development process aiming at higher crash safety is now more driven by the market than earlier. The safety level of cars is one of the most important parameters when consumers are choosing cars. The society therefore can stimulate the process towards safer vehicles by making available good consumer information as well as introducing i e economic incentives.

The objective of this paper was to:

- Study if there are any safety benefits from cars introduced 1990 and onward. These cars are often developed under higher safety demands from the market compared to older vehicles.
- Study if the newer cars have become more aggressive under the same period.
- Study the effect of large and small mass distribution in a vehicle fleet.

Material and methods

Police reported accidents in Sweden from 1/1 1994 to 15/3 1996 were used for the analysis of safety levels and aggressivity. In the material injuries are classified by the police in the field. No, minor and severe injuries as well as fatalities are registered.

In the material only car to car accidents were used. Accidents were included only if the make and model of the two vehicles were known. Only injuries to the driver were considered.

The method used for the rating was based on the paired comparison approach, where the relative risk is generated in two car collisions and the outcome in one vehicle versus the opposite car.

In order to calculate the individual risk the two car collisions were divided into probabilities of injuries with the mean probabilities for the combinations that both drivers were injured, one driver injured in one car and not in the other and vice versa. (v Koch 1992, Hägg 1992)

It is well known that police reported accidents and injuries suffer from large quality problems both in terms of coverage as well as the quality in the data collected. This could have an influence of the results and safety levels found in the report, but used in the illustration of the problem dealt with, it was considered not to change major findings.

To illustrate the effect of mass distribution synthetic fleets were used. One fleet contained only vehicles with a mass of 1300kg. Another fleet had an average mass of 1300kg and a standard deviation in the mass of 100kg and the third fleet had the same average mass but a standard deviation of 200kg. The fleet masses were normally distributed.

A set of synthetic accidents having collision closing speed distribution collected from a real life material was used to generate collisions. (v Koch 1992)

The change of velocity for every vehicle in every accident was calculated.

The fatality risk for every synthetic accident was calculated and summed if the change of velocity was over 40km/h, equivalent to less than 1% fatality risk. The fatality risk function used come from FARS data and is calculated by Evans. (Evans) An important assumption made is that all vehicles have the same fatality risk to change of velocity function.

Results

In table 1. the relative injury risk is shown for vehicles of different year models. Both the risk for any injury, including minor injuries, and the risk for a severe or fatal injury is shown. It can be seen that while the relative safety level was reasonably constant during the 80-ties, the risk of an injury has decreased during the 90-ties and the risk for severe of fatal injuries has decreased substantially. At the same time the mass of the vehicles has increased.

Table 1.
Relative injury risk and average mass for cars of different year model

model year	risk any injury	risk severe/fatal	average mass (kg)
85	1,04	1,00	1169
86	0,96	0,92	1189
87	1,06	1,00	1166
88	1,07	1,07	1194
89	1,05	0,89	1228
90	0,97	1,17	1255
91	1,07	0,88	1293
92	0,93	0,89	1313
93	0,79	0,79	1348
94	0,87	0,79	1353
95	0,89	0,53	1398

In order to differentiate between cars that was introduced as new models during the recent years ("new cars"), and cars with older construction but in production ("old cars"), a grouping was performed. Only "old" cars of model year 1991-96 were included.

It can be seen in table 2. that while there is no sign of a reduction of all kind of injuries, the relative risk for serious and fatal injuries has dropped by more than 35%. The reduction is significant. The average weight of the "new" cars was not higher than in the older vehicle models in the studied sample.

Table 2.
Relative risk for injuries for newer and older car models of model year 1991-96

	risk any injury	risk severe/fatal	average mass (kg)
"new" cars	0,85	0,61	1331
"old" cars	0,94	0,91	1331

In order to study the risk reduction for "new" cars a separation of the relative risks were calculating according to fig. 1 and 2.

Fig 1.
Risk calculation model

		Study population		
		Driver injured	Driver not injured	
Other vehicle	Driver injured	$N\bar{p}_1\bar{p}_2$	$N(1-\bar{p}_1)\bar{p}_2$	$N\bar{p}_2$
	Driver not injured	$N\bar{p}_1(1-\bar{p}_2)$		
		$N\bar{p}_1$		
		$\bar{p}_1 = \frac{N\bar{p}_1\bar{p}_2}{N\bar{p}_2}$	$\bar{p}_2 = \frac{N\bar{p}_1\bar{p}_2}{N\bar{p}_1}$	

$\bar{p}_1$ = mean risk of injury in study population
$\bar{p}_2$ = mean risk of injury in opposite vehicles
N = Number of accidents with injuries

The separation of risks can only be done and compared with other study populations under the assumption that the accident severity distribution is identical. This assumption is made for the "new" car and "old" car constructions of same year models.

Table 3.
Separated risks for the two study groups, "new" and "old" car models. Serious and fatal injuries

	Study population	Opposite vehicles	Average mass study	Average mass other (kg)
"new" cars	0,36	0,59	1331	1209
"old" cars	0,51	0,56	1331	1237

It can be found, that the relative risk for newer cars and older ones, are a result of a reduced risk for the newer cars and not by an increased risk for the opposite cars. This is an indication that "new" cars have an inherent safety level. The inherent safety development is not achieved by higher aggressivity. As the weight of the

study population and the opposite vehicles are more or less identical, the mass is not an explanation in any sense to the results.

The generally increased masses of cars might have a negative effect on the crash safety level of the total vehicle population. In table 4. the fatality outcome of three synthetic fleets is given. The fleets vary in mass distribution and the lower the distribution the lower the fatality outcome.

Table 4.
The number of fatalities depending on mass distribution. Average mass always 1300kg. Standard deviation 0kg, 100kg and 200kg

	SD 0	SD 100	SD 200
Fatalities (relative)	1,00	1,03	1,23

If the average fatality risk per accident is used the risk in different mass groups in the fleets can be studied. In table 5. the fatality risk in different mass classes in the synthetic fleets. It can be seen that the risk difference in groups relatively close to the average can differ significantly when the standard deviation in vehicle mass increases.

Table 5.
The average fatality risk in the car depending on mass group

Mass	SD 100	SD 200
1000-1199	0,040	0,044
·1200.1399	0,029	0,030
1400-1600	0,022	0,020

Discussion

The crash protection of vehicles has become increasingly focused during the last years, as an effective tool to reduce health losses in road traffic. While safety regulations earlier were used as the major tool for increasing crash protection, safety has become more and more a market issue where the consumers gradually have increased their interest in buying cars on the basis of their safety level. New technology has been introduced mainly on the basis of increased competition, and the distance between what is specified in regulations and the actual safety level with best practice has grown rapidly. The society today discuss more and more the benefit of consumer information and economic incentives as complementary tools to regulations in order to encourage a more rapid technological development and promote sales of crashworthy cars. Environmental aspects have lead to that safety and energy consumption is more combined in the discussion.

In this study the safety benefits from the newly introduced cars have been compared to cars produced at the same time but with older constructions. It is clearly demonstrated that driver of the newer cars, regarding fatal and severe injuries, have a significantly lower risk compared to the drivers of the older cars. This is an important finding set in relation to the predictions made in the society regarding the benefit from increased crash protection.

The increased crash protection has been achieved only on the benefit of the occupants of the newer car, and not as a higher aggressiveness to other car occupants. This was also clearly demonstrated in this study.

The lack of effects on minor injuries can, at first sight, be negligible. It must though be understood that injuries classified as minor can be severe in the sense that they might lead to long term consequences. Neck soft tissue injuries, often as a result from rear end impact, is an injury with major health losses due to impairment. It is important that, in the future safety work, such injuries are focused in i e safety rating.

The mass of cars has increased as a result of the better crash protection. Mass is not the only explanation to the better crash protection. Increased mass is a consequence of more structure, etc. The higher mass might though be a problem if it results in a wider mass distribution in the car population. A wider mass distribution will result in more injuries in the population even if all cars have the same inherent safety. In this study such an effect was studied using an empirically derived risk versus change of velocity function, an empirically derived accident distribution and a synthetic car mass distribution. The risk function itself, characterized as an exponentially increasing risk, is enough to understand that a widespread car population, in terms of mass, is negative and produces more injuries even if the inherent safety of all cars is identical. Any downsizing process must take this into account, so that the goal of such a downsizing does not contradict high demands on safety levels for the full fleet. As much focus must be set on the heavier vehicles as on the low mass vehicles.

REFERENCES

Evans, Leonard. Car size and safety, a review focused on identifying causative factors. In Proceeding ESV Experimental safety vehicle, München 1994, Paper No. 94 S4 W28 pp 721-733.

Hägg A, Kamren B, v Koch M, Kullgren A, Lie A, Malmstedt B, Nygren Å, Tingvall C. Car model safety rating 1991-92. Stockholm 1992 and Proc. of Comparative crash tests within the EU 1993.

v Koch M, Korner J, Norin H, Nygren Å, Tingvall C. Injury severity assessment for car occupants using disability scaling. AAAM 1992, pp 252-268

v Koch M, Kullgren A, Lie A, Tingvall C. Car model safety rating - Further development using the paired comparison method. In proceeding ESV Experimental safety vehicle, Paris 1991. Vol. 1 pp 78-83.

THE DEVELOPMENT OF VEHICLE CRASHWORTHINESS RATINGS IN AUSTRALIA

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ABSTRACT

The paper reviews the history of the production of vehicle crashworthiness ratings, based on real crash data, in Australia since 1990. The methods used in Europe and the USA are described, as well as their influence on the Australian developments. The Australian ratings published in 1992 and 1994 are summarised and the vehicle manufacturers' and importers' reactions to them are described.

The paper then outlines the preparation of new crashworthiness ratings of 1982-94 model Australian cars crashing during 1987-94 in the States of New South Wales and Victoria. The data covers over 305,000 cars involved in tow-away crashes in New South Wales, and around 64,000 drivers injured in crashes in the two States. The crashworthiness rating for each make/model measures the risk of a driver being killed or admitted to hospital when involved in a tow-away crash, derived from separate estimates of the driver injury risk and driver injury severity when injured. Logistic regression was used to take into account a number of factors which have been found to be strongly related to injury risk and severity, namely the driver sex and age, the speed limit at the crash location, and the number of vehicles involved.

The relationship of the crashworthiness ratings with the tare mass of each make/model was investigated. Previous research has suggested that the effect of vehicle mass is likely to be greater on the driver's risk of injury than on his/her injury severity. It has been suggested that the driver's injury severity reflects vehicle design to a greater extent. The results of the analysis support these propositions.

INTRODUCTION

During 1990, the New South Wales Roads and Traffic Authority (RTA) decided to develop ratings of car safety. In the same year, the NSW Road Safety Prize was awarded to the idea that a system of "Car Safety Rating" should be initiated. This led to a joint project between the NSW RTA and NRMA Ltd. with the objective of using vehicle crash records and injury data to develop comparison tables of the relative safety of vehicles.

During the same year, the Victorian Parliamentary Social Development Committee (SDC) in its report on its Inquiry Into Vehicle Occupant Protection recommended that ways should be investigated for Victorian consumers to give high priority to motor vehicle occupant protection in the vehicles they purchase (SDC 1990).

In the second half of 1990, the Monash University Accident Research Centre (MUARC) commenced a project to develop consumer advice on vehicle safety performance from mass accident data. The development of crashworthiness ratings (the relative safety of vehicles in preventing severe injury in crashes) was given priority in the project because of their potential to find significant differences between makes and models.

Methods for Measuring Vehicle Safety

As part of the project, a review was conducted of methods of mass data analysis to measure the safety performance of vehicle safety features or vehicle models. Evans' (1986) "double pair comparison" method was recognised as an important concept which could be extended to measure the relative risk of injury to occupants of a particular model, compared with occupants of the other cars in two-car collisions. This was relevant because the initial data files on which the MUARC project was based covered only crashes in which someone was injured, making it impossible to measure the risk of occupant injury directly. Subsequently, Gustafsson et al (1989) extended Evans' method to address the same problem which was also confronting Folksam Insurance in preparing the Swedish car safety ratings.

A comprehensive review of methods used to rate the safety performance of cars from mass data analysis was prepared (Cameron 1991). This review has been updated and Table 1 summarises the methods used by the Highway Safety Research Centre (Campbell and Reinfurt 1973), the Insurance Institute for Highway Safety (IIHS 1994) and the Highway Loss Data Institute (HLDI 1994)

in the USA, Folksam Insurance (Folksam 1992) in Sweden, the U. K. Department of Transport (DOT 1995), and the University of Oulo (Tapio, Pirtala and Ernvall 1995) in Finland. The most recent method used by Monash University Accident Research Centre is included for completeness.

Table 1.
Summary of Published Vehicle Safety Ratings Based on Mass Crash Data

Publishing organisation	Rating measures used in the publication	Dimensions covered by the measure: . Crash involvement (CI) . Crashworthiness (CW)	Factors used to adjust the ratings before comparison between models	Factors used to categorise the [adjusted] ratings into car groups
Highway Safety Research Centre (USA)	Rate of driver death or serious injury per involvement in crashes with damage exceeding $100	CW	Impact speed Point of impact on car Accident type	Crash type (single-vehicle versus car-to-car crashes)
Insurance Institute for Highway Safety (USA)	Driver death rate per 10,000 registered vehicle years	CI and CW	None [previously: Car wheelbase Driver age Driver sex]	Car wheelbase Body style
Highway Loss Data Institute (USA)	1. Occupant injury rate per insured vehicle year a) any injury b) injury costs > $500 2. Vehicle damage payments per insured vehicle year	1. CI and CW 2. CI	1. Driver age 2. Driver age Deductible amount (excess)	Car wheelbase Body style
Folksam Insurance (Sweden)	1. Relative risk of driver injury in two-car crashes 2. Risk of death or permanent disability to front seat occupants who were injured 3. Combination: 1 by 2	1. CW 2. CW 3. CW	1. Car weight 2. Nil 3. Car weight	Car weight
Department of Transport (UK)	Rate of driver injury [and severe injury] in two-car crashes with at least one injured driver	CW	Speed limit Point of impact Driver sex Driver age	Size of car
University of Oulo (Finland)	1. Relative risk of driver injury in two-car crashes in built-up areas 2. Total number of drivers injured in two-car crashes in built-up areas relative to expected 3. Total driver injury rate per 100 million km	1. CW 2. CW (includes a measure of aggressivity of the make/model focused on) 3. CI and CW (includes aggressivity)	1 and 2: Driver age Driver sex Car mass (in second set of results) 3. Kilometres driven by type of area and driver age	1 and 2: Car mass 3. Crash type

Table 1 (continued).
Summary of Published Vehicle Safety Ratings Based on Mass Crash Data

Publishing organisation	Rating measures used in the publication	Dimensions covered by the measure: . Crash involvement (CI) . Crashworthiness (CW)	Factors used to adjust the ratings before comparison between models	Factors used to categorise the [adjusted] ratings into car groups
Monash University Accident Research Centre (Australia)	1. Rate of driver injury in tow-away crashes 2. Rate of death or hospital admission for injured drivers 3. Combination: 1 by 2	1. CW 2. CW 3. CW	1 and 2: Driver sex Driver age Speed limit Number of vehicles involved in crash 3. As 1 and 2	Market group (related to mass, size and cost)

The seven published vehicle safety ratings based on mass crash data have each used different measures of vehicle safety performance. While the general tendency is for the measures to cover crashworthiness aspects (perhaps reflecting a perception that the biggest differences between cars should emerge in this dimension), some of the measures embody the risk of crash involvement as well. The vehicle safety ratings published by IIHS and HLDI are based on measures which combine crash involvement risks with crashworthiness.

Development of Australian Methods

Initially, the MUARC project was based on data on the injury outcomes of drivers of cars manufactured during 1982-88 which crashed in Victoria during 1983-88 and who made an injury compensation claim to the Transport Accident Commission, the monopoly "no fault" transport injury insurer for the State. The claims were matched with Victoria Police accident reports on the same crashes, thus providing information on injured and uninjured drivers of the "other" cars in multi-vehicle collisions.

The occurrence of injury to each of the drivers in 5,455 two-car crashes was used to estimate the *relative injury risk* of drivers of specific makes and models manufactured during 1982-88, using the method developed by Gustafsson et al (1989). The proportion of injured drivers of the specific models who were killed or admitted to hospital, based on 7,832 injured drivers, was used to measure the *injury severity*. Again following Gustafsson et al (1989), the crashworthiness of each make and model was measured by multiplying the relative injury risk by the injury severity measure in each case.

Prior to the final calculation, the relative injury risk was normalised for the driver sex distribution, and the driver injury severity was normalised for both the distribution of driver sex and the speed limit at the crash location. This normalisation procedure ensured that, before crashworthiness estimates of the car models were compared, they each had exactly the same mix of male and female drivers (and speed limits). Normalisation is also used by HLDI (1994) to adjust for driver age differences.

The initial methods and data available were able to produce crashworthiness estimates for 40 makes and models, of which eight had estimates which were statistically significantly different from average. However the results were not considered sufficiently reliable to publish, except in a form in which the specific makes and models were not identified (Cameron 1991). It was recommended that additional data be added from Victoria and another State, preferably one with a property damage criterion for Police reports of road crashes, such as New South Wales (NSW).

The provision of data from NSW Police accident reports was an important development for the project. Crashes are reported to the Police in NSW if a person is killed or injured or a vehicle is towed away. As well as providing additional crash and injury data to make the crashworthiness ratings more reliable, it also provided the opportunity to measure the risk of driver injury directly, rather than make use of the relative injury risk method.

In 1992, the first published crashworthiness ratings of Australian passenger cars were produced based on crash and injury data from Victoria during 1983-90 and NSW during 1989-90 (Cameron et al 1992a,b; 1994a). The ratings were based on data for 22,964 drivers injured in crashes in the two States, plus data for 73,399 drivers

involved in tow-away crashes in NSW. The ratings covered cars manufactured during 1982-90. For these and all subsequent ratings, crashworthiness was measured using the following two components, which were subsequently multiplied together:

1. Rate of injury for drivers involved in tow-away crashes (*injury risk*)
2. Rate of serious injury (death or hospital admission) for injured drivers (*injury severity*).

As in the previous estimates (Cameron 1991), the components were each normalised for the distributions of male and female drivers and the speed limit at the crash location, prior to final calculation of the crashworthiness rating. Standards were set for the reliability of each rating and 62 makes and models were considered to have reliable ratings. Of these, eight had ratings which were significantly different from average.

In 1994, the second published crashworthiness ratings of Australian passenger cars were produced based on crash and injury data from Victoria and NSW during 1987-92 (Cameron et al 1994b; 1995). The ratings were based on data for 45,070 drivers injured in crashes in the two States, plus data for 221,971 drivers involved in tow-away crashes in NSW. The ratings covered cars manufactured during 1982-92.

Unlike previous estimates, the components of the ratings were calculated using a different method to take into account differences between makes and models related to driver characteristics and the crash circumstances. Logistic regression modelling of the driver injury risk and injury severity components, separately, was used to adjust for differences in the driver age and sex, number of vehicles involved in the crash, and the speed limit at the crash location (Hosmer and Lemeshow 1989). Based on a comparison of methods applied to the previous data, the new method produced crashworthiness ratings with proportionately smaller variability, thereby improving the reliability and sensitivity of the results (Cameron et al 1994c). Further details of the new method are given later in this paper.

The 1994 ratings covered 87 makes and models considered to have reliable estimates, and 26 of these had ratings which were significantly different from average.

Publication of the Ratings, and Car Manufacturers' Responses

On each occasion during 1992 and 1994, the rating figures were widely distributed throughout Australia in the form of a "Driver Protection Ratings" brochure, with over 400,000 copies being produced. The ratings were widely republished in daily newspapers throughout the country. MUARC produced a summary technical report, available on request, to support each set of ratings (Cameron et al 1992a, 1994b).

Some manufacturers and importers have responded to the ratings in the advertising of their products. In 1992, Volvo importers were quick to point out that "a Volvo has just topped an independent study on safety by Monash University" in advertisements for their 940 model (which has replaced the 700 Series models rated in the project). Ford Australia in their advertisements for the EB Falcon noted that "recently released government statistics reveal Falcon's superiority in terms of crash safety. In an accident, you are safer in a Falcon sedan than in any other Australian-made large car on the market today". SAAB importers, reacting to the absence of Australian rating scores for their specific models in 1992, pointed out in their advertisements that the SAAB 9000 displayed the best ratings in the systems published by Folksam (undated) and Great Britain's Consumers' Association (1991).

In 1994, the BMW 5-Series had the highest rating (lowest estimated risk of serious driver injury in a tow-away crash). BMW Australia produced a press advertisement showing a crash test dummy reading MUARC's summary technical report (Cameron et al 1994b) and the caption "If it comes to the crunch there's only one choice. A BMW 5-Series". This and the above reactions to the published figures suggest that the car industry has recognised that at least some consumers are taking crashworthiness rating scores into consideration in choosing a car to buy.

DATA FOR THE 1996 CRASHWORTHINESS RATINGS

The crash and injury data used for the 1996 crashworthiness ratings were identical in format to that used and described previously (Cameron et al 1994b,c; 1995), but also covered crashes during 1993 and 1994. The Victorian data were derived from 20,814 Transport Accident Commission claims for injury compensation by drivers of 1982-94 model cars and station wagons which crashed during 1987-94, and whose claim records could be matched with Victoria Police accident reports.

The NSW data covered 305,263 drivers of 1982-94 model light passenger vehicles involved in Police reported crashes during 1987-94 which resulted in death or injury

or a vehicle being towed away. As well as cars and station wagons, the files covered four-wheel drive vehicles, passenger vans, and light commercial vehicles. Of the 305,263 drivers involved in tow-away crashes, 43,105 were injured. When the data on the injured drivers from the two States was combined, there was data on 63,919 injured drivers available for analysis.

The makes and models of the crashed vehicles manufactured during 1982-94 were derived by processes which involved matching the crash records with the State vehicle register using the registration number, and then decoding information held on the register. The processes were essentially the same as those described previously (Cameron et al 1994c).

ANALYSIS

Overview

The crashworthiness rating (C) is a measure of the risk of serious injury to a driver of a car when it is involved in a crash. This risk can be considered to be the product of two probabilities:

i) the probability that a driver involved in a crash is injured (*injury risk*), denoted by R;

ii) the probability that an injured driver is killed or admitted to hospital (*injury severity*), denoted by S.

That is $C = R \times S$.

To produce the crashworthiness ratings, each of the two components of the rating were obtained by logistic regression modelling techniques. Such techniques are able to simultaneously adjust for the effect of a number of factors (such as driver age and sex, number of vehicles involved, etc.) on probabilities such as the injury risk and injury severity.

Logistic Model

The logistic model of a probability, P, is of the form:

$$\log it(P) = \ln\left(\frac{P}{1-P}\right) = \beta_o + \beta_1 X_1 + \ldots + \beta_k X_k = f(X)$$

That is, the log of the odds ratio is expressed as a linear function, f, of k associated variables, $X_i, i = 1,\ldots,k$. Estimates of the parameter coefficients of the logit function, ie. the $\hat{\beta}_i$, can be obtained by maximum likelihood estimation (Hosmer & Lemeshow, 1989). The extension of this model to include interaction terms is straightforward.

Logistic Models for Each Component

To obtain crashworthiness ratings reflecting vehicle factors alone, it was necessary to develop logistic models of each of the crashworthiness components separately to identify possible factors, other than vehicle design, that might have influenced the crash outcomes. This was done initially without considering the make/model of car in the models as the aim was to determine which other factors were most likely to have an influence across a broad spectrum of crashes.

Logistic models were obtained separately for injury risk (R) and injury severity (S) because it was likely that the various factors would have different levels and directions of influence on these two probabilities. The factors considered during this stage of the analysis for both injury risk and injury severity were:

- *sex:* driver sex (male, female)
- *age:* driver age (≤25 years; 26-59 years; ≥60 years)
- *speedzone:* speed limit at the crash location (≤75 km/h; ≥80 km/h)
- *nveh:* the number of vehicles involved (one vehicle; >1 vehicle)

These variables were available in both the Victorian and NSW crash data. Other candidate variables (eg. whether or not the vehicle collided with a fixed object) were highly correlated with these variables, or were only available from one source and their inclusion would have drastically reduced the number of cases that could have been included in the analysis.

All data were analysed using the LR procedure of the BMDP statistical package (BMDP, 1988). Estimates of the coefficients of the logit function, $\hat{\beta}_i, i = 1,\ldots,k$, together with their associated standard errors, were obtained by maximum likelihood estimation. For both injury risk and injury severity, a stepwise procedure was used to identify which factors and their interactions made a significant contribution to these probabilities. All possible first order interactions were considered. A hierarchal structure was imposed so that if an interaction between two variables was included in the model then the corresponding main effects would also be included. The resultant logistic regression models were referred to as the "covariate" models.

Assessing Car Model Differences

Injury risk and injury severity for individual vehicle models were estimated after adding a variable representing car model to the respective logistic "covariate" models. The car model variable was forced into the logistic equation and individual car model coefficients were computed to represent deviations of that car from the average.

It was important to ensure that the logistic model adequately described the data and did not yield individual car model coefficients that were imprecise or unstable. For this reason, individual car models with small frequencies were pooled with similar car models, if appropriate, or they were excluded from the analysis. Car models were excluded if, after pooling models, either there were less than 100 involved vehicles or there were less than 20 injured drivers.

After exclusion, the regression analyses were performed on 109 individual car models (or pooled similar models). The variable representing car model was therefore categorical with 109 nominal levels. The choice of the design for the logistic model allowed the injury risk and injury severity estimates for each car model to be compared with the overall (average) rating for all models considered.

Combining Injury Risk and Injury Severity Components

For a given model of car, j, the crashworthiness rating, C_j, was calculated as:

$$C_j = R_j \times S_j$$

where

R_j denotes the injury risk for car model j

S_j denotes the injury severity for car model j.

The 95% confidence interval for each combined rating was also calculated. Because each of the two estimated crashworthiness components have been adjusted for the effect of other factors by logistic regression prior to their incorporation into the combined ratings, the resultant crashworthiness rating is also adjusted for the influence of these factors.

RESULTS

Estimating Injury Risk

The logistic regression model of the injury risk component of the crashworthiness ratings of 1982-94 model vehicles was estimated from the data on 305,263 drivers involved in tow-away crashes in NSW. Because of missing values of some factors included in the logistic regression, the analysis was performed on data for only 288,612 drivers.

All of driver sex and age, speedzone and number of vehicles, along with first order interactions between speedzone and number of vehicles, sex and number of vehicles, age and sex, speedzone and age and speedzone and sex, and second order interactions between sex, speedzone and number of vehicles and sex, speedzone and age, were significantly associated with injury risk and were included in the logistic model. No other interaction term significantly improved the fit of the logistic model.

Estimating Injury Severity

The injury severity component was based on 63,919 drivers of 1982-94 model vehicles who were injured in crashes in Victoria or NSW during 1987-94. Because of missing values of some of the crash factors, logistic regression was performed on data relating to only 62,725 injured drivers.

The analysis identified a number of important factors affecting injury severity, namely driver sex and age, speedzone and number of vehicles. In addition, significant interactions were found between sex and age, speedzone and age, speedzone and number of vehicles, and age and number of vehicles. No other interaction term significantly improved the fit of the logistic model.

Crashworthiness Ratings

The crashworthiness rating for each car model was obtained by multiplying the individual injury risk and injury severity estimates. The appendix gives the crashworthiness ratings and the associated 95% confidence intervals for the 109 car models included in the analyses. The appendix also indicates the overall ranking of the crashworthiness ratings from 1 (lowest or best crashworthiness rating) to 109 (highest or worst crashworthiness rating).

Each crashworthiness rating is an *estimate* of the true risk of a driver being killed or admitted to hospital in

a tow-away crash and, as such, each estimate has a level of uncertainty about it. This uncertainty is indicated by the confidence limits. There is 95% probability that the confidence interval will cover the true risk of serious injury (death or hospital admission) to the driver of the particular model of vehicle.

The ratings in the appendix exclude those models where the width of the confidence interval exceeded 7, or the ratio of the confidence interval width to the rating score exceeded 1.6. This second criterion was necessary because smaller confidence intervals tended to occur for the lower rating scores, but the confidence intervals were relatively wide in proportionate terms. It is also more stringent than that used by Cameron et al (1994b,c), reflecting the greater precision available in the 1996 ratings as a result of larger quantities of data.

Comparisons With the All Model Average Rating

The confidence limits can be used to judge whether the true risk of death or hospital admission for a driver of a specific model car involved in a tow-away crash is significantly different from the overall average for all models, ie. 2.59 per 100 involved drivers. An upper limit below the average is indicative of superior crashworthiness, whereas a lower limit above the average suggests inferior crashworthiness. Other models also have crashworthiness ratings at the low or high end of the scale, but their confidence limits overlap the all model average. Although such models may also have superior or inferior crashworthiness characteristics, the data base did not contain sufficient numbers of these models for the data to represent scientific evidence that this is the case.

Thirteen models had ratings representing evidence of superior crashworthiness because their upper confidence limits were less than the average rating. Five of these were large cars and a further five were luxury models. Two were classified as medium cars. The remaining model was a large four-wheel-drive vehicle. The specific models were (in order, from lowest to highest, of estimated risk of serious driver injury in a crash):

- Mitsubishi Magna TR/TS and Verada KR/KS (1991-94 years of manufacture)
- Volvo 700 Series (1984-92)
- Toyota Crown/Cressida (1989-93)
- Honda Accord (1986-90)
- Peugeot 505 (1982-90)
- Subaru Liberty (1989-94)
- Volvo 200 Series (1982-92)
- Ford Maverick / Nissan Patrol (1988-94)
- Toyota Crown/Cressida (1982-85)
- Ford Falcon EA/EB Series I (1988-March 1992)
- Ford Falcon X-Series (1982-91)
- Mitsubishi Magna (1985-90)
- Holden Commodore VN/VP (1987-93) / Toyota Lexcen (1989-92).

Twenty three models had ratings representing evidence of inferior crashworthiness because their lower confidence limits were greater than the average rating. Thirteen were small cars, four were light commercial vehicles, two were families of passenger vans, two were medium cars, one was a small four-wheel-drive vehicle, and the remaining model was a sports car. The specific models were (in order, from highest to lowest, of estimated risk of serious driver injury in a crash):

- Subaru Sherpa/Fiori (1982-92)
- Suzuki Mighty Boy (1985-88)
- Daihatsu Handivan (1982-90)
- Honda City (1983-86)
- Holden Scurry (1985-86) / Suzuki Carry (1982-90)
- Toyota Supra (1982-90)
- Daihatsu Charade (1982-86)
- Subaru Brumby (1982-92)
- Suzuki Hatch (1982-85)
- Mazda 121 (1987-90) / Ford Festiva (1991-93)
- Nissan Gazelle (1984-88)
- Holden Barina (1985-88) / Suzuki Swift (1985-88)
- Hyundai Excel (1982-89)
- Mitsubishi passenger vans (1982-94)
- Honda Civic (1984-87)
- Daihatsu Charade (1988-92)
- Nissan passenger vans (1982-92)
- Holden Astra (1984-86) / Nissan Pulsar/Vector (1982-86)
- Suzuki Sierra (1982-94) / Holden Drover (1985-87)
- Toyota Hiace/Liteace (1982-94)
- Mitsubishi Colt (1982-90)
- Holden Camira (1982-89)
- Mazda 323 (1982-88) / Ford Laser/Meteor (1982-89).

RELATIONSHIP OF CRASHWORTHINESS WITH CAR MASS

The crashworthiness rating score of each of the models listed in the appendix was compared with its tare mass (Figure 1). Unlike previous analysis (Cameron et al 1992c), the comparison was not limited to cars and station wagons, and Figure 1 also includes models of four-wheel-drive vehicles, passenger vans and light commercial vehicles.

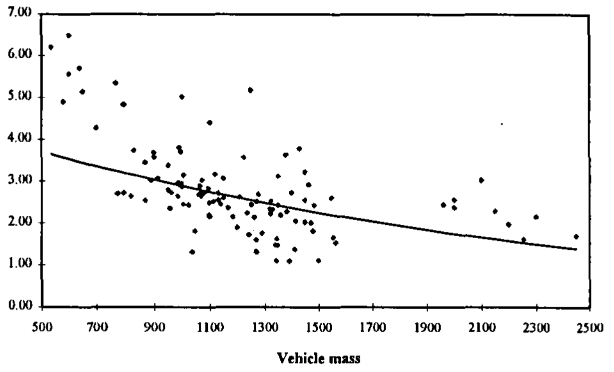

Figure 1. Crashworthiness rating score versus tare mass of car model

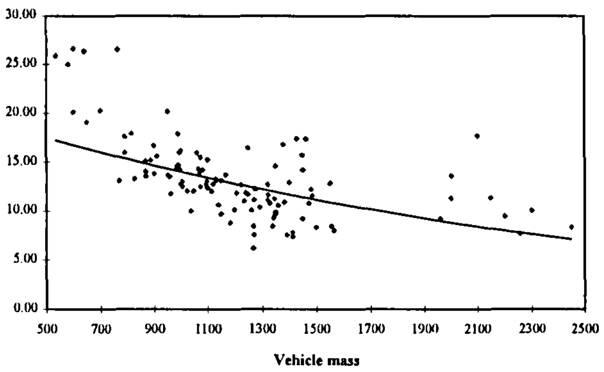

Figure 2. Driver injury risk versus tare mass of car model

A logistic regression relationship was fitted between the rating score and the mass of the models. Each model was weighted in the regression by the sum of the number of drivers involved in tow-away crashes in NSW and the number of drivers injured in the two States. The coefficient of vehicle mass in the regression was statistically significant ($p < 0.001$). The curvilinear nature of the hypothesised relationship contrasts with the linear functions assumed in previous similar research (Cameron et al 1992c, Broughton 1994, U. K. Department of Transport 1995). A curvilinear function, asymptoting with zero as mass increases, would seem to be an intuitively more appropriate relationship.

Broughton (1994) has suggested that an unweighted regression may be preferable, ie. giving each model equal weight unrelated to the number involved in crashes or drivers injured. When this was done the estimated coefficient of vehicle mass was somewhat greater, but not substantially different from that estimated by the weighted regression.

The relationships between vehicle mass and each of the two components of the rating score were also investigated (Figures 2 and 3). A weighted logistic regression was fitted between the driver injury risk and vehicle mass, using the number of drivers involved in tow-away crashes as the weighting factor. The coefficient of vehicle mass was statistically significant ($p < 0.001$). In contrast, when a regression between driver injury severity and vehicle mass was fitted, weighted by the number of injured drivers, the mass coefficient was not statistically significant ($p = 0.47$). For this reason, no fitted relationship is shown in Figure 3.

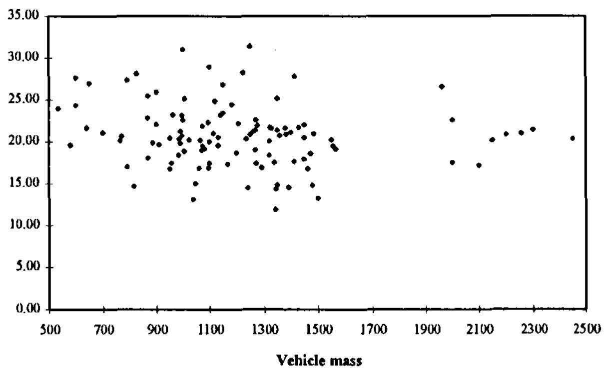

Figure 3. Driver injury severity versus tare mass of car model

Previous research on a more limited range of models and masses (Cameron et al 1992c) also suggested that the effect of vehicle mass is greatest on the driver's risk of injury compared with the effect on the injury severity of the injured driver. It was suggested that the driver's injury severity reflects the effects of vehicle design to a greater extent than the driver's injury risk. The results presented in this paper support these propositions.

CONCLUSIONS

A system of measuring crashworthiness ratings of makes and models of passenger vehicles in Australia has been developed and refined, and rating scores were published and widely distributed during 1992 and 1994. The reactions of the car industry in the advertising of its products suggests that it recognises that at least some

consumers are taking the rating scores into consideration when choosing a car to buy.

A new set of crashworthiness ratings has been prepared, based on crashes and driver injuries in Victoria and NSW during 1987-94. The ratings and their associated confidence limits have identified 36 models of passenger cars, four-wheel drive vehicles, passenger vans and light commercial vehicles which have superior or inferior crashworthiness characteristics compared with the average vehicle. Statistically significant relationships between crashworthiness and the tare masses of these vehicles have also been found.

The results and conclusions presented in this paper are based on a number of assumptions and qualifications. In particular it should be noted that other factors not collected in the data (eg. crash speed) may have differed between the makes and models, and thus may have affected the results.

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REFERENCES

BMDP (1988), "BMDP Statistical Software Manual Volume 2" (W. J. Dixon, chief editor). University of California Press, Berkeley.

BROUGHTON, J. (1994), "The theoretical basis for comparing the accident record of car models". Project Report 70, Safety and Environment Resource Centre, Transport Research Laboratory, Crowthorne, Berkshire, U.K.

CAMERON, M.H. (1991), "Vehicle Crashworthiness Ratings from Mass Crash Data". Proceedings of Seminar *Road Trauma: The Medical-Engineering Link*, Association for the Advancement of Automotive Medicine, in cooperation with the Royal Australasian College of Surgeons, Melbourne, July 1991.

CAMERON, M.H., MACH, T., and NEIGER, D. (1992a), "Vehicle Crashworthiness Ratings: Victoria 1983-90 and NSW 1989-90 Crashes - Summary Report". Report No. 28, Monash University Accident Research Centre.

CAMERON, M.H., MACH, T., NEIGER, D., GRAHAM, A., RAMSAY, R., PAPPAS, M., and HALEY, J. (1992b), "Vehicle Crashworthiness Ratings In Australia". Proceedings, International Conference on the Biomechanics of Impacts, Verona, Italy, pp. 105-119.

CAMERON, M.H., MACH, T., NEIGER, D., GRAHAM, A., RAMSAY, R., PAPPAS, M., and HALEY, J. (1992c), "Vehicle Crashworthiness Ratings from Victoria and New South Wales Crash Data". Road and Transport Research, Vol. 1, No. 3, pp. 4-18.

CAMERON, M.H., MACH, T., NEIGER, D., GRAHAM, A., RAMSAY, R., PAPPAS, M., and HALEY, J. (1994a), "Vehicle Crashworthiness Ratings In Australia". Accident Analysis and Prevention, Vol. 26, No. 4, pp. 521-533.

CAMERON, M.H., FINCH, C.F., and LE, T. (1994b), "Vehicle Crashworthiness Ratings: Victoria and NSW Crashes During 1987-92 - Summary Report". Report No. 55, Monash University Accident Research Centre,

CAMERON, M.H., FINCH, C.F., and LE, T. (1994c), "Vehicle Crashworthiness Ratings: Victoria and NSW Crashes During 1987-92 - Technical Report". Report No. 58, Monash University Accident Research Centre.

CAMERON, M.H., FINCH, C., NEWSTEAD, S., LE, T., GRAHAM, A., GRIFFITHS, M., PAPPAS, M., and HALEY, J. (1995), "Measuring Crashworthiness: Make/Model Ratings and the Influence of Australian Design Rules for Motor Vehicle Safety." Proceedings, International Conference on the Biomechanics of Impacts, Brunnen, Switzerland, pp. 297-310.

CAMPBELL, B.J., and REINFURT, D.W. (1973), "Relationship between Driver Crash Injury and Passenger Car Weight." Highway Safety Research Center, University of North Carolina, Chapel Hill, USA.

CONSUMERS' ASSOCIATION LTD. (1991), "Which? Guide to New and Used Cars". Association for Consumer Research, Great Britain.

DEPARTMENT OF TRANSPORT (1995), "Cars: Make and Model: The Risk of Driver Injury and Car Accident Rates in Great Britain: 1994". Transport Statistics Report. London: Her Majesty's Stationery Office.

EVANS, L. (1986), "Double Pair Comparison - A New Method To Determine How Occupant Characteristics Affect Fatality Risk in Traffic Crashes". Accident Analysis and Prevention, Vol. 18, No. 3.

FOLKSAM (undated), "Safe and Dangerous Cars 1989-90". Division for Research and Development, Folksam, Stockholm.

FOLKSAM (1992), "Safe and dangerous cars: 1991-1992". Folksam Research, Folksam Insurance Group, Stockholm.

GUSTAFSSON, H., HAGG, A., KRAFFT, M., KULLGREN, A., MALMSTEDT, B., NYGREN, A., and TINGVALL, C. (1989), "Folksam Car Model Safety Rating 1989-90". Folksam Insurance Group, Stockholm.

HIGHWAY LOSS DATA INSTITUTE (1994), "Injury, Collision, and Theft Losses by Make and Model". Highway Loss Data Institute, Arlington, Virginia, USA.

HOSMER, D.W., and LEMESHOW, S. (1989), "Applied Logistic Regression". Wiley, New York.

INSURANCE INSTITUTE FOR HIGHWAY SAFETY (1994), "Special Issue: Driver Death Rates by Vehicle Make and Series". Status Report, Vol. 29, No. 11. Insurance Institute for Highway Safety, Arlington, Virginia, USA.

SOCIAL DEVELOPMENT COMMITTEE (1990), "Inquiry into Vehicle Occupant Protection". Parliament of Victoria.

TAPIO, J., PIRTALA, P., and ERNVALL, T. (1995), "The Accident Involvement and Injury Risk Rates of Car Models". Report No. 30, Road and Transport Laboratory, University of Oulu, Finland.

APPENDIX: CRASHWORTHINESS RATINGS OF 1982-94 MODELS OF CARS INVOLVED IN CRASHES DURING 1987-94

Make	Model of Car	Year of Manufacture	CRASHWORTHINESS RATINGS: Serious injury rate per 100 drivers involved	Overall rank order	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Width of Confidence Interval	Ratio of Confidence Width to rating
ALL MODEL AVERAGE			2.59					
4-Wheel Drive Vehicles			2.52		2.31	2.74	0.43	0.17
Ford Nissan	Maverick Patrol	88-94 88-94	1.70	15	1.13	2.56	1.43	0.84
Toyota	Landcruiser	90-94	1.97	21	1.18	3.29	2.11	1.07
Nissan	Patrol	82-87	2.16	27	1.34	3.47	2.12	0.99
Mitsubishi	Pajero	82-94	2.29	34	1.65	3.17	1.53	0.67
Toyota	Landcruiser	82-89	2.56	53	2.05	3.19	1.15	0.45
Toyota	4Runner/Hilux	82-94	2.60	56	2.25	3.00	0.75	0.29
Suzuki	Vitara	88-94	2.69	62	1.60	4.50	2.90	1.08
Daihatsu	Rocky F70/75/80	84-94	3.03	80	1.76	5.21	3.44	1.14
Holden Suzuki	Drover Sierra	85-87 82-94	3.38	87	2.61	4.39	1.78	0.53
Commercial Vehicles			2.88		2.66	3.13	0.48	0.17
Ford	Falcon Panel Van	82-94	1.81	18	1.26	2.60	1.35	0.74
Ford Nissan	Falcon UTE XFN UTE	82-94 88-90	2.19	29	1.75	2.74	0.99	0.45
Nissan	Navara	86-94	2.34	36	1.66	3.30	1.64	0.70
Daihatsu	Delta	82-94	2.38	39	1.50	3.77	2.26	0.95
Holden	WB Series	82-85	2.43	41	1.72	3.44	1.72	0.71
Holden	Rodeo	82-94	2.55	52	1.83	3.55	1.71	0.67
Nissan	720 UTE	82-85	2.73	67	1.91	3.89	1.98	0.72
Holden	Shuttle	82-87	2.92	75	1.53	5.58	4.05	1.39
Toyota	Hiace/Liteace	82-94	3.22	86	2.71	3.84	1.13	0.35
Subaru	Brumby	82-92	5.02	102	3.81	6.62	2.81	0.56
Holden Suzuki	Scurry Carry	85-86 82-90	5.34	105	3.36	8.48	5.11	0.96
Suzuki	Mighty Boy	85-88	6.19	108	4.13	9.28	5.15	0.83
Large Cars			2.26		2.16	2.37	0.21	0.09
Mitsubishi	Verada KR/KS Magna TR/TS	91-94 91-94	1.10	1	0.67	1.79	1.12	1.02
Holden Toyota	Apollo JM Camry SDV 10	93-94 93-94	1.47	8	0.77	2.82	2.05	1.39
Holden Toyota	Commodore VR Lexcen	93-94 93-94	1.62	13	0.93	2.84	1.91	1.18
Ford	Falcon EA Falcon EB Series I	88-Mar 92	2.01	22	1.74	2.32	0.58	0.29
Ford	Falcon EB Series II Falcon ED	Apr 92-94	2.02	23	1.45	2.83	1.39	0.68
Ford	Falcon X Series	82-91	2.23	31	2.06	2.41	0.35	0.16
Mitsubishi	Magna	85-90	2.24	32	1.99	2.53	0.54	0.24
Holden Toyota	Commodore VN/VP Lexcen	87-93 89-92	2.28	33	2.02	2.57	0.54	0.24
Holden	Commodore VH-VL	82-88	2.44	44	2.25	2.65	0.40	0.16
Nissan	Skyline	82-90	2.52	50	2.01	3.17	1.16	0.46

APPENDIX: CRASHWORTHINESS RATINGS OF 1982-94 MODELS OF CARS INVOLVED IN CRASHES DURING 1987-94

Make	Model of Car	Year of Manufacture	CRASHWORTHINESS RATINGS: Serious injury rate per 100 drivers involved	Overall rank order	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Width of Confidence Interval	Ratio of Confidence Width to rating
ALL MODEL AVERAGE			**2.59**					
Luxury Cars			**1.96**		**1.79**	**2.15**	**0.36**	**0.19**
Volvo	700 Series	84-92	1.10	2	0.54	2.24	1.70	1.54
Toyota	Crown/Cressida	89-93	1.10	3	0.55	2.22	1.67	1.52
Honda	Accord	86-90	1.31	4	0.78	2.20	1.42	1.08
BMW	5 Series	82-94	1.31	5	0.66	2.61	1.95	1.48
Toyota	Crown/Cressida	86-88	1.38	7	0.66	2.86	2.20	1.60
Mercedes Benz	300-600 Series	82-93	1.53	10	0.89	2.63	1.74	1.14
Volvo	200 Series	82-92	1.60	11	1.12	2.30	1.18	0.74
Range Rover	Range Rover	82-93	1.61	12	0.93	2.77	1.84	1.14
Ford	Fairlane N & LTD D	89-94	1.65	14	1.00	2.71	1.71	1.04
Toyota	Crown/Cressida	82-85	1.72	16	1.18	2.51	1.32	0.77
SAAB	900	82-93	1.76	17	0.93	3.31	2.38	1.36
Mercedes Benz	100 Series	83-94	1.90	20	0.93	3.87	2.94	1.55
Mercedes Benz	200 Series	82-94	2.05	24	1.17	3.60	2.44	1.19
Honda	Accord	82-85	2.36	37	1.66	3.35	1.70	0.72
Ford	Fairlane Z & LTD F	82-87	2.42	40	1.95	3.02	1.07	0.44
Jaguar	Jaguar	82-94	2.44	43	1.36	4.40	3.04	1.24
BMW	3 Series	82-94	2.47	46	1.79	3.39	1.60	0.65
Mazda	929	82-94	2.62	57	1.96	3.51	1.54	0.59
Medium Cars			**2.67**		**2.54**	**2.81**	**0.27**	**0.10**
Peugeot	505	82-90	1.32	6	0.69	2.55	1.86	1.41
Subaru	Liberty	89-94	1.48	9	0.88	2.50	1.62	1.10
Ford Mazda	Telstar 626/MX6	88-91 88-91	2.14	25	1.63	2.80	1.17	0.55
Ford Mazda	Telstar 626/MX6	92-94 92-94	2.15	26	1.20	3.83	2.63	1.22
Ford Nissan	Corsair Pintara	89-91 89-92	2.33	35	1.77	3.05	1.28	0.55
Mitsubishi	Nimbus	84-91	2.37	38	1.30	4.30	3.00	1.27
Toyota	Corona	82-87	2.44	42	2.14	2.77	0.63	0.26
Subaru	1800/Leone	82-94	2.45	45	2.02	2.98	0.96	0.39
Nissan	Pintara	86-88	2.51	48	1.93	3.28	1.36	0.54
Mitsubishi	Sigma/Scorpion	82-85	2.56	54	2.27	2.89	0.63	0.24
Nissan	Stanza	82-83	2.64	59	1.53	4.55	3.02	1.14
Holden Toyota	Apollo JK/JL Camry SV21	89-92 88-92	2.69	61	2.32	3.11	0.80	0.30
Nissan	Bluebird	82-86	2.72	64	2.38	3.10	0.71	0.26
Ford Mazda	Telstar 626/MX6	83-87 83-86	2.89	73	2.56	3.25	0.68	0.24
Holden	Camira	82-89	3.02	79	2.71	3.36	0.65	0.22
Toyota	Camry	83-86	3.17	85	2.16	4.65	2.50	0.79
Nissan	Prairie	84-86	3.70	94	1.97	6.95	4.97	1.34
Nissan	Gazelle	84-88	4.40	99	3.00	6.47	3.48	0.79

APPENDIX: CRASHWORTHINESS RATINGS OF 1982-94 MODELS OF CARS INVOLVED IN CRASHES DURING 1987-94

Make	Model of Car	Year of Manufacture	CRASHWORTHINESS RATINGS: Serious Injury rate per 100 drivers involved	Overall rank order	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Width of Confidence Interval	Ratio of Confidence Width to rating
ALL MODEL AVERAGE			**2.59**					
Passenger Vans			**3.50**		**3.14**	**3.91**	**0.78**	**0.22**
Toyota	Tarago	83-89	3.13	83	2.48	3.94	1.45	0.46
Nissan	Passenger Vans	82-92	3.63	92	2.77	4.76	2.00	0.55
Mitsubishi	Passenger Vans	82-94	3.78	96	3.17	4.51	1.34	0.35
Small Cars			**3.09**		**2.95**	**3.24**	**0.29**	**0.09**
Daihatsu	Applause	89-94	2.16	28	1.13	4.13	3.00	1.39
Holden Toyota	Nova Corolla	89-93 90-93	2.52	49	2.08	3.06	0.99	0.39
Toyota	Corolla	82-84	2.54	51	2.17	2.98	0.81	0.32
Holden	Gemini RB	86-87	2.64	58	1.52	4.58	3.06	1.16
Hyundai	Excel	90-94	2.65	60	1.85	3.80	1.95	0.74
Honda	Civic	82-83	2.70	63	1.64	4.44	2.80	1.04
Mazda	323	90-93	2.72	65	1.72	4.30	2.59	0.95
Holden Suzuki	Barina Swift	89-93 89-94	2.72	66	2.08	3.57	1.49	0.55
Holden Nissan	Astra Pulsar/Vector	88-92 88-91	2.73	68	2.29	3.25	0.96	0.35
Honda	Civic	88-91	2.73	69	1.91	3.90	1.99	0.73
Toyota	Corolla	86-88	2.79	70	2.43	3.21	0.78	0.28
Nissan	Pulsar/Vector	92-94	2.82	71	1.64	4.85	3.21	1.14
Holden	Gemini	82-84	2.92	74	2.47	3.44	0.97	0.33
Mitsubishi	Lancer	86-93	2.95	76	2.13	4.09	1.95	0.66
Mitsubishi	Cordia	82-88	2.96	77	2.09	4.21	2.12	0.72
Ford Mazda	Laser/Meteor 323	82-89 82-88	3.02	78	2.78	3.28	0.50	0.16
Mitsubishi	Colt	82-90	3.07	81	2.68	3.52	0.85	0.28
Ford	Laser/Meteor	91-93	3.15	84	2.37	4.18	1.81	0.57
Holden Nissan	Astra Pulsar/Vector	84-86 82-86	3.45	88	3.03	3.93	0.90	0.26
Mazda	121	91-94	3.45	89	2.21	5.41	3.20	0.93
Daihatsu	Charade	88-92	3.69	93	2.86	4.75	1.89	0.51
Honda	Civic	84-87	3.74	95	2.88	4.86	1.97	0.53
Hyundai	Excel	82-89	3.81	97	2.89	5.02	2.13	0.56
Holden Suzuki	Barina Swift	85-88 85-88	4.28	98	3.50	5.23	1.74	0.41
Ford Mazda	Festiva 121	91-93 87-90	4.83	100	3.24	7.19	3.95	0.82
Suzuki	Hatch	82-85	4.90	101	3.53	6.79	3.26	0.67
Daihatsu	Charade	82-86	5.14	103	4.08	6.48	2.41	0.47
Honda	City	83-86	5.56	106	3.15	9.81	6.67	1.20
Daihatsu	Handivan	82-90	5.69	107	3.66	8.87	5.21	0.91
Subaru	Sherpa/Fiori	82-92	6.47	109	4.38	9.57	5.19	0.80

APPENDIX: CRASHWORTHINESS RATINGS OF 1982-94 MODELS OF CARS INVOLVED IN CRASHES DURING 1987-94

Make	Model of Car	Year of Manufacture	CRASHWORTHINESS RATINGS					
			Serious injury rate per 100 drivers involved	Overall rank order	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Width of Confidence Interval	Ratio of Confidence Width to rating
ALL MODEL AVERAGE			**2.59**					
Sports Cars			**2.59**		**2.25**	**2.97**	**0.72**	**0.28**
Honda	Prelude	84-91	1.81	19	1.20	2.74	1.54	0.85
Mazda	RX7	82-85	2.20	30	1.28	3.76	2.47	1.12
Toyota	Celica	82-85	2.48	47	1.75	3.52	1.77	0.71
Toyota	Celica	90-93	2.60	55	1.33	5.06	3.73	1.44
Honda	Integra	86-88	2.88	72	1.58	5.25	3.67	1.27
Toyota	Celica	86-89	3.07	82	2.09	4.52	2.43	0.79
Ford	Capri	89-94	3.58	90	1.99	6.43	4.45	1.24
Alfa Romeo	33	83-92	3.58	91	2.00	6.40	4.40	1.23
Toyota	Supra	82-90	5.17	104	2.86	9.34	6.48	1.25

CORRELATION OF RESULTS FROM THE AUSTRALIAN NEW CAR ASSESSMENT PROGRAM WITH REAL CRASH DATA

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ABSTRACT

In recent years, several major initiatives have been undertaken in Australia to assess relative vehicle occupant protection performance for consumer information. Two of these initiatives undertaken were the New Car Assessment Program (NCAP) and the Driver Protection Ratings (also known as Vehicle Crashworthiness Ratings). The first of these measures the relative occupant safety of current model vehicles by measuring dummy responses in controlled crash testing, following the methods of a similar program undertaken in the United States. The second initiative estimates the relative risk of severe driver injury for individual models of vehicles involved in real crashes by analysing mass crash data using logistic regression techniques.

This paper assesses the relationship between Australian NCAP test results and data from real crashes by comparing the results of crashworthiness ratings to the outcomes of NCAP testing for vehicle models which have been assessed in both programs. Existing crashworthiness ratings based on all crash types have been used in the comparison, as well as crashworthiness ratings derived from crashes of specific types which are thought to be more typical of the crash types the NCAP program claims to represent. Comparison has been made not only with the raw NCAP measures but also with transformations and combinations of these which claim to estimate the probability of severe injury to a vehicle occupant in an NCAP type collision. The effect of vehicle mass in the relationship has also been investigated.

A second stage of the study has examined the relationship between detailed injury data by body region recorded in insurance claim data and the corresponding measurements taken from the various body regions of the crash test dummies in the NCAP procedures.

INTRODUCTION

In recent years, motor vehicle occupant protection has come to the fore as an issue not only for Government authorities concerned with road safety, but also for motor vehicle consumers and manufacturers. Two initiatives undertaken in response to this were the New Car Assessment Program (NCAP) and the Driver Protection Ratings (also known as Vehicle Crashworthiness Ratings).

The NCAP Program

Australia's New Car Assessment Program (NCAP) commenced testing in 1992, building upon the procedures established in NCAP in the USA. The Australian NCAP program involves laboratory crashes of current model cars into a concrete barrier in two configurations : (1) Full Frontal - 100% of the front of the vehicle impacting with a solid concrete barrier at a speed of 56.3 km/h (the first 10 large car models tested in Australia were subject only to this configuration) and (2) Off-set Frontal - 40% of the driver's side front of the car impacting a concrete barrier with a crushable aluminium front at 60 km/h. Instrumented "Hybrid III" dummies placed in the driver and front left passenger seating positions, restrained by the vehicle's seat belts, measure the severity of impacts to various body regions of the dummy with the measurements Head Injury Criterion (HIC), Chest Deformation (CD), chest loading (in Gs) and right and left femur and lower leg loadings being published. Comparative performance of each car tested in the NCAP program is based on the measurements taken from the instrumented driver and front passenger dummies used in the test. (see NCAP 1993, 1994a,b)

Crashworthiness Ratings And Real Crashes

Crashworthiness ratings rate the relative safety of vehicles by examining injury outcomes in real crashes, in contrast to NCAP which uses laboratory crash tests. The crashworthiness rating of a vehicle is a measure of the risk

of serious injury to a driver of that vehicle when it is involved in a crash. This risk is estimated from large numbers of records of injury severity to drivers of that vehicle type involved in real crashes on the road.

In 1996, the Monash University Accident Research Centre (MUARC) produced vehicle crashworthiness ratings based on crash data from Victoria and New South Wales during 1987-94 (Cameron et al., 1996). These ratings updated an earlier MUARC set produced by Cameron et al. (1994a,b). Crashworthiness was measured in two components: (1) Rate of injury for drivers involved in tow-away crashes (injury risk) and (2) Rate of serious injury (death or hospital admission) for injured drivers (injury severity). The crashworthiness rating was formed by multiplying these two rates together; it then measured the risk of serious injury for drivers involved in crashes. Measuring crashworthiness in this way was first developed by Folksam Insurance which publishes the well-known Swedish ratings (Gustafsson et al 1989).

Aims

The aim of this study was to investigate the relationship between NCAP test results and data from real crashes in assessing relative occupant protection. This as been achieved by comparing the results of crashworthiness ratings to the outcomes of NCAP testing for the 20 vehicle models whose design had not changed for a number of years and for which sufficient real crash experience had accumulated for a reliable crashworthiness rating to be calculated. A second stage of the study has examined the relationship between injury severity patterns by body region and corresponding NCAP test results.

LITERATURE REVIEW AND STUDY DESIGN

A number of studies comparing the results of NCAP testing with real crash outcomes have been documented in the literature. These raise a number of important issues which must be addressed in designing a study of this type are raised in previous studies examining the relationship between NCAP results and real crashes. The major issues raised are :

Crash Type : By its own description, NCAP is concerned with assessing relative occupant protection performance in frontal impacts, both full width of the vehicle and offset towards the driver side. This is recognised in many of the studies of the relationship between NCAP and real crashes carried out to date, most of which consequently focus specifically on certain crash types. For example, Zador et al. (1984) examines the probability of fatal injury in front to front, two car crashes and finds a strong relationship with NCAP test results. Kahane et al (1993) and Langweider et al (1994) also consider two car front to front crashes. It is also of interest to see how representative NCAP is of relative occupant protection in all crash types. Crashworthiness ratings for both front to front two car collisions and all collision types have been compared here with both full frontal and offset NCAP test results.

The Effect of Vehicle Mass : A number of previous studies have noted a strong relationship between vehicle mass and risk of occupant injury, with increasing mass being associated with decreasing occupant injury risk (Zador et al 1984, Evans 1994, Langweider et al 1994 and Viano 1994). NCAP also notes the influence of mass in real crash outcomes in guiding interpretation of its results which are said to be independent of vehicle mass. The role of vehicle mass in determining real crash outcomes has been investigated here, with a method of adjusting NCAP scores to include the effects of vehicle mass developed and applied.

Single Index Rating From NCAP Scores : Combining the results of NCAP testing into a single rating has been used by a number of authors as a means of summarising the results of a number of separate readings on a single dummy obtained from a crash test. Australian NCAP uses a single index rating following methods of Viano & Arepally (1994) who derived injury risk functions using logistic probability analysis of biomechanical data to calculate the probability of life threatening injury to the chest and head, and severe injury to the legs, from crash test dummy response data. These individual risk probabilities by body type are combined into an overall risk for the particular NCAP crash configuration. The results of full frontal and offset testing for driver and front passenger separately are then combined into a single figure. This is achieved by weighting the combined probabilities of injury for full frontal and right offset crashes by the ratio for which these crash types occur on the road resulting in injury to driver or front passenger. Both the single index rating and its components have been considered in the analysis presented here

DATA

The data used for estimating vehicle crashworthiness covered 20,814 drivers of 1982-94 model vehicles injured in crashes in Victoria during 1987-94 and 305,263 drivers of 1982-94 model vehicles involved in tow-away crashes

in NSW over the period 1987-94, of which 43,105 were injured. Of the combined Victorian and NSW data, 31,422 were drivers of vehicle models tested under NCAP and involved in crashes in NSW, whilst 5,233 drivers of vehicle models tested under NCAP were injured in crashes in Victoria or NSW. For estimation of two car head on crashworthiness ratings, 16,684 drivers of vehicles were identified as being involved in this crash configuration in NSW whilst 14,122 drivers from Victoria and NSW were injured in this crash configuration.

Two methods were used to determine the models of the crashed vehicles appearing in the combined data file. For the data from NSW and part of the 1994 data from Victoria, vehicle model was determined by decoding the vehicle identification number (VIN) recorded for each vehicle on the NSW vehicle register (Pappas 1993). Model details for the remaining vehicles registered and crashing in Victoria were obtained by a process of decoding the power, mass, make, body type and year of manufacture information appearing on the Victorian vehicle register.

Data from NCAP for use in this study was taken straight from the published brochures (NCAP 1994a,b, NCAP 1995). This data included the measurements of HIC, CD, Chest loading and femur loading from both the driver and passenger side dummies in full frontal impacts for all 20 tested cars, as well as the results from offset impacts for the 13 cars with sufficient real crash data for which these results are available.

METHODS

Crashworthiness Ratings

The crashworthiness rating (C) is a measure of the risk of serious injury to a driver of a car when it is involved in a crash. It is defined to be the product of two probabilities (Cameron et al, 1992):

I) the probability that a driver involved in a crash is injured (injury risk), denoted by R; and
ii) the probability that an injured driver is hospitalised or killed (injury severity), denoted by S.

That is $C = R \times S$.

For the estimation of crashworthiness each of the two components of the crashworthiness rating were obtained by logistic regression modelling techniques using a stepwise procedure in the statistical package BMDP (BMDP, 1988). Such techniques are able to simultaneously adjust for the effect of a number of factors on the probabilities of injury risk and injury severity for each vehicle model. The factors considered in the analysis for both injury risk and injury severity were driver sex and age, speed zone of crash and number of vehicles involved. Crashworthiness ratings for two car head-on crashes were also produced using these methods. Factors adjusted for when considering this crash type were driver age and sex and speed zone of collision.

Comparison Of NCAP And Crashworthiness

The primary analysis method used here in assessing the relationship between NCAP and real crash outcomes was correlation analysis, estimating Pearson's correlation co-efficient. Correlations have been made against not only the final crashworthiness measure (*injury risk* x *injury severity*) but also against the injury risk and injury severity components separately. This has been carried out for crashworthiness ratings based on all crash types as well as for crashworthiness ratings for two vehicle, head on crashes.

Correlations have been calculated for crashworthiness against the NCAP measures; Head Injury Criteria (HIC), Chest compression/deflection (CD) and femur loading as well as their injury risk probability transforms; Probability of serious head injury (P_{head}), Probability of serious chest injury (P_{chest}), Probability of serious leg injury (P_{femur}), Probability of head and/or chest injury (P_{comb2}), Probability of head and/or chest and/or leg injury (P_{comb3}). These correlations have been calculated for both full and offset NCAP results separately as well as combined (P_{real}) using the methods of NCAP (1994b).

Mass Effects And Crashworthiness Ratings

The effect of vehicle mass in crashworthiness has been investigated using logistic regression techniques, regressing crashworthiness against vehicle tare mass. Using the estimated logistic curve the NCAP probability measures summarising the overall risk of serious injury to the vehicle occupant have been adjusted to reflect the relative weight of the vehicle compared to the fleet average. The details of this procedure are also given in Newstead et al (1995). The mass adjusted NCAP measures were again compared to the real crash outcome measures using correlation analysis.

Comparison Of Injury Patterns With NCAP Scores

There is detailed information on the particular injuries of those drivers involved in crashes recorded in the Transport Accident Commission (TAC) claims records (the TAC is the sole motor Vehicle accident inury insurer in the state of Victoria). By extracting the TAC claims by drivers of the NCAP models involved in relevant crashes, it is possible to make a comparison between real-life crash injuries and NCAP scores by the injury levels of each body region. This analysis requires two steps;

(i) The TAC records the injuries of drivers using the ICD-9 coding system. This injury data from TAC must be converted into a form that measures the level of injury incurred from each accident. A dBase III Plus program, called ICDMAP, was run to estimate these injury levels. ICDMAP (MacKenzie et al 1989, ICDMAP 1988) is a computerised conversion table that maps injury diagnoses that are coded ICD-9-CM onto (AIS) severity scores by body region.

(ii) Having estimated maximum AIS scores by body region using the ICDMAP program on the TAC claims data, comparison of these scores with the corresponding NCAP score for each body region was made. Analysis centres around comparison of the average maximum AIS score by body region for each of the NCAP tested vehicle model with the relevant NCAP score. Correlation analysis was used to assess the relationship between the average AIS scores and NCAP test results.

RESULTS

Crashworthiness Ratings

The crashworthiness ratings of Cameron et al (1996) describe real crash outcomes for all crash types and have been used here. For two car head on crashes, new crashworthiness ratings were estimated from 16,684 drivers of vehicles in tow away crashes in NSW and 8112 drivers injured in two vehicle head on crashes identified in the Victorian and NSW data. Logistic regression analysis found injury severity to be influenced by driver sex and age and speed zone of crash along with interactions between sex and age and sex and speed zone. Injury risk was found to be significantly influenced by speed zone and driver sex and age, as well as all first order interactions between speed zone and age and sex and age. The resulting crashworthiness ratings covered 53 light vehicle models, including the 20 NCAP tested models.

Mass Effects And Crashworthiness Ratings

Logistic regression analyses found vehicle mass to have a statistically significant relationship with crashworthiness for both all crash type and two car head on crashes with higher mass being associated with better crashworthiness. Further analysis of the injury risk and severity components of the crashworthiness rating showed the mass effect in the crashworthiness ratings to stem from statistically significant mass effects in the injury risk component for both crash types. Using the estimated association of crashworthiness with mass, the combined NCAP injury probability estimates were adjusted to include this effect (see Newstead et al. 1995 for a full description of the mass adjustment techniques).

Correlation Of NCAP With Crashworthiness Ratings

Table 1, parts (A) - (C), summarise the main results of the correlation analyses performed. Each of the correlations presented in Table 1 has been tested for statistically significant difference from 0 (ie. the null hypothesis of no association). Correlations statistically significantly different from zero are indicated by shading, with darker shading for greater significance according to the key shown on the table. PheadD, PchestD and Pfemload are the injury risk probabilities derived from the NCAP readings of HIC, Chest Loading and Femur Loading respectively. Pc1 and Pc2 refer to the combined probability of injury to head and/or chest and head and/or chest and/or femur respectively. Preal1 and Preal2 are the associated combined probability of injury derived from both full frontal and offset NCAP test scores.

Part (A) of Table 1 shows the correlations of each of the full frontal NCAP test measures with the crashworthiness ratings and its components for each of the three crash types considered. Analysis presented covers all 20 models covered by both the crashworthiness ratings of Cameron et al (1996) for all crashes and NCAP, and also included is the two car head-on crash analysis. Part (B) of Table 1 gives analogous information for offset NCAP test results. This analysis covers the 13 models for which offset NCAP results were available.

Examination of Table 1 parts (A) and (B) reveals some indication of the relationships between NCAP scores and real crash outcomes. Firstly, Table 1 shows a much stronger association of real crash outcome measures with the offset NCAP results and than with the full frontal NCAP results. This is the case when considering either all crash types or two car head-on crashes. In general, there

is a somewhat stronger correlation between the NCAP test results and two car head on crashes than with all crash types. This is perhaps expected given the configuration of the NCAP tests. For the full frontal NCAP test results and the offset NCAP test results in relation to all crashes, the NCAP scores show strongest relationship to the injury severity component of the crashworthiness rating, with this association being reflected in the crashworthiness ratings themselves. When considering two car head on crashes, the injury severity component of the crashworthiness rating also shows strong association with the offset NCAP results.

When considering individual NCAP measures, the full frontal NCAP test femur loading measure shows strongest association with real crash measures whilst HIC and chest loadings show the strongest associations for the offset NCAP test results. In each instance in Table 1 parts (A) and (B), the combined measures of injury risk across all body regions (Pc1, Pc2 and Preal) derived from the NCAP scores show strong association with crashworthiness and its injury severity component demonstrating the worth of these measures as a summary of NCAP test results. Mass adjustment of these combined NCAP measures of injury risk consistently increases their correlation with real crash measures. This demonstrates the role that vehicle mass plays in real crashes and reinforces the need to consider this when interpreting NCAP results.

Because the results of correlation of the offset NCAP scores with real crashes relate to only 13 of the 20 available for analysis, Table 1 part (C) gives the results of correlation of the full frontal NCAP scores for the same 13 cars as analysed in Table 1, part (B), with the real crash measures. The correlations in Table 1 part (C) are then directly comparable with those in part (B). Generally, the patterns of relationship observed in part (C) of Table 1 are consistent with those in Part (A), validating the comparisons of parts (A) and (B) made above.

In summary, the results of correlation of NCAP test results with real crash outcomes as measured by crashworthiness ratings suggest a number of relationships. Firstly, the results from offset NCAP testing have a much stronger association with real crash outcomes than do the results of full frontal NCAP testing. For both NCAP test configurations, the NCAP test results and their associated measures have the strongest association with the injury severity component of the crashworthiness rating. Correlations were generally stronger between NCAP results and two car head on crashes than with all crash types but this difference was not large. Mass adjustment of the NCAP probability measures also improved their relationship with real crash outcomes.

Table 1.
Correlation of NCAP test results with real crash outcomes. Summary of Correlation Analyses.

(A) FULL FRONTAL NCAP TEST RESULTS

	All Crashes (20 Models)			2 Car Head-on Crashes (20 Models)		
	Crash-worthiness Rating	*Injury Severity*	*Injury Risk*	*Crash-worthiness Rating*	*Injury Severity*	*Injury Risk*
HIC	0.291	**0.510**	-0.050	**0.332**	**0.349**	0.164
Chest G	0.177	0.110	0.180	**0.307**	0.300	0.226
Femload	**0.459**	**0.309**	**0.355**	**0.403**	0.233	**0.364**
PheadD	0.292	**0.505**	-0.044	**0.326**	**0.346**	0.162
PChestD	0.177	0.086	0.208	**0.302**	0.276	0.227
PFemload	**0.366**	0.291	0.243	**0.331**	0.235	0.290
Pc1(full)	**0.331**	**0.447**	0.074	**0.414**	**0.423**	0.243
Pc2(full)	**0.351**	**0.462**	0.089	**0.417**	**0.419**	0.246
Mass Adj. Pc1	**0.426**	**0.444**	0.202	**0.605**	**0.640**	**0.440**
Mass Adj. Pc2	**0.446**	**0.457**	0.217	**0.609**	**0.641**	**0.443**

Table 1. (continued)
Correlation of NCAP test results with real crash outcomes. Summary of Correlation Analyses.
(B) OFFSET NCAP TEST RESULTS

	All Crashes (13 Models)			2 Car Head-on Crashes (13 Models)		
	Crash-worthiness Rating	*Injury Severity*	*Injury Risk*	*Crash-worthiness Rating*	*Injury Severity*	*Injury Risk*
HIC	0.686	0.762	0.245	0.625	0.524	0.542
Chest G	0.819	0.755	0.464	0.748	0.578	0.716
Femload	0.668	0.562	0.430	0.592	0.592	0.499
PheadD	0.764	0.775	0.332	0.628	0.595	0.527
PChestD	0.706	0.735	0.310	0.731	0.564	0.678
PFemload	0.399	0.435	0.154	0.425	0.471	0.311
Pc1(offset)	0.832	0.800	0.413	0.667	0.612	0.580
Pc2(offset)	0.843	0.787	0.445	0.673	0.622	0.588
Preal1	0.755	0.834	0.279	0.721	0.664	0.560
Preal2	0.776	0.845	0.303	0.725	0.673	0.564
Mass Adj. Pc1(offset)	0.860	0.763	0.486	0.737	0.693	0.663
Mass Adj. Pc2(offset)	0.869	0.747	0.516	0.739	0.701	0.668
Mass Adj. Preal1	0.832	0.760	0.451	0.880	0.855	0.755
Mass Adj. Preal2	0.849	0.766	0.473	0.880	0.863	0.756

(C) FULL FRONTAL NCAP TEST RESULTS
FOR THE SAME 13 MODELS AS TABULATED IN TABLE 1 (B)

	All Crashes (13 Models)			2 Car Head-on Crashes (13 Models)		
	Crash-worthiness Rating	*Injury Severity*	*Injury Risk*	*Crash-worthiness Rating*	*Injury Severity*	*Injury Risk*
HIC	0.326	0.695	-0.205	0.375	0.358	0.178
Chest G	0.241	0.007	0.361	0.474	0.387	0.415
Femload	0.544	0.543	0.296	0.448	0.396	0.369
PheadD	0.324	0.698	-0.210	0.366	0.354	0.172
PChestD	0.232	-0.024	0.389	0.469	0.371	0.410
PFemload	0.337	0.423	0.096	0.291	0.292	0.223
Pc1(full)	0.385	0.569	0.015	0.522	0.484	0.330
Pc2(full)	0.399	0.594	0.014	0.513	0.480	0.319
Mass Adj. Pc1	0.504	0.546	0.199	0.749	0.740	0.582
Mass Adj. Pc2	0.518	0.569	0.200	0.743	0.742	0.572

NNN = Statistically significant at the 1% level
NNN = Statistically significant at the 5% level
NNN = Statistically significant at the 10% level

Injury Patterns In TAC Claims

Interrogation of the Victorian crash data revealed 1028 observations of driver injury in the 20 NCAP tested vehicles. Five of the 20 models were subsequently excluded from the analysis because there were too few cases in the data. The ICDMAP program was used to produce maximum AIS scores by body region from the coded driver injury data for each of the cases available for analysis. For each model, the average maximum AIS score for each of the head, chest and leg regions was calculated using a simple arithmetic average over the drivers injured in each model. The results were correlated with the NCAP scores for head injury criterion (HIC), chest loading (CG) and femur loading (FL).

Table 2 summarises the correlation between each NCAP measure, both full frontal and offset, and the

corresponding average injury scores by body region observed in real crashes. Examination of Table 2 shows association between full frontal NCAP femur loading readings and average maximum AIS to the leg region in real crashes. There is also a weak association between HIC and real crash head injury severity for this NCAP test configuration. Table 2 shows a much stronger association between the offset NCAP scores and average maximum AIS scores recorded in real crashes for the 13 car models for which offset scores are available. The two measures show strongest association in the head regions, with weaker association in both the chest and leg regions. These results are generally consistent with the results of the correlation analyses presented above, confirming those results with a more detailed and specific method of analysis.

Table 2.
Correlation between Full Frontal and Offset NCAP Test Results and
Average Maximum AIS Scores By Body Region Observed in Real Crashes.

BODY REGION	HEAD	CHEST	FEMUR
CORRELATION BETWEEN	**HIC WITH AV. MAX. AIS TO HEAD**	**CG WITH AV. MAX. AIS TO CHEST**	**FL WITH AV. MAX. AIS TO LEGS**
FULL FRONTAL NCAP (16 Models)	0.36 (*p=0.082*)	0.25 (*p=0.172*)	0.61 (*p=0.006*)
OFFSET NCAP SCORES (9 Models)	0.81 (*p=0.006*)	0.58 (*p=0.052*)	0.53 (*p=0.072*)

CONCLUSIONS

The analysis presented in this paper indicates a number of relationships between the results of NCAP testing and the outcomes of real crashes. Firstly, the results from offset NCAP testing have a much stronger association with real crash outcomes than do the results of full frontal NCAP testing. For both NCAP test configurations, the NCAP test results and their associated measures have the strongest association with the injury severity component of the crashworthiness rating which measures the risk of serious driver injury given any injury. Correlations were generally stronger between NCAP results and two car head on crashes than with all crash types. Mass adjustment of the NCAP probability measures also improved their relationship with real crash outcomes.

Detailed analysis of injury data by body region generally confirmed the results of the correlation analysis using a more detailed and specific method of analysis. Full frontal NCAP femur loading readings showed strong association with average maximum AIS to the leg region in real crashes. There was also weak association between HIC and real crash head injury severity for this NCAP test configuration. Offset NCAP scores and average maximum AIS recorded in real crashes show strongest association in the head regions, with weaker association in both the chest and leg regions.

REFERENCES

BMDP Inc. (1988), "*BMDP statistical software manual*", Chief Ed: W.J. Dixon, University of California Press, Berkeley.

CAMERON, M.H., MACH, T., and NEIGER, D. (1992), "Vehicle Crashworthiness Ratings: Victoria 1983-90 and NSW 1989-90 Crashes - Summary Report". Report No. 28, Monash University Accident Research Centre.

CAMERON, M.H., FINCH, C.F., and LE, T. (1994a), "Vehicle Crashworthiness Ratings: Victoria and NSW Crashes During 1987-92 - Summary Report". Report No. 55, Monash University Accident Research Centre.

CAMERON, M.H., FINCH, C.F., and LE, T. (1994b), "Vehicle Crashworthiness Ratings: Victoria and NSW Crashes During 1987-92 - Technical Report". Report No 58, Monash University Accident Research Centre.

CAMERON, M.H., NEWSTEAD, S.V. and SKALOVA, M. (1996) "The development of vehicle crashworthiness ratings in Australia" Proceedings of the Fifteenth International Conference on the Enhanced Safety of Vehicles, Paper Number 96-S9-0-14.

EVANS, L. (1994) 'Car size and safety: a review focused on identifying causative factors', Paper No. 94 S4 W 28, Presented to the 14th ESV Conference, Munich, Germany.

GUSTAFSSON, H., HAGG, A., KRAFFT, M., KULLGREN, A., MALMSTEDT, B., NYGREN, A., and TINGVALL, C. (1989), "Folksam Car Model Safety Rating 1989-90". Folksam, Stockholm.

ICDMAP (1988) "ICDMAP. Determining injury severity for hospital discharges : A program to map ICD-9CM diagnoses into AIS and ISS severity scores" Johns Hopkins Health Research and Development Centre, Johns Hopkins University.

KAHANE, C.J., JAMES, R.H., BERKOWITZ, A.M., (1994) 'Correlation of vehicle performance in the New Car Assessment Program with fatality risk in actual head-on collisions.' Paper No. 94 S8 O 11, Presented to the 14th ESV Conference, Munich, Germany.

LANGWIEDER, K., BAUMLER, H. (1994) 'Priorities of real car crashes and the agreement of real accidents with results from crash testing', Accident, Motor Vehicle and Legal Protection Insurers, Germany.

MACKENZIE, E.J., STEINWACHS, D.M. & SHANKAR, B. (1989) "Classifying trauma severity based on hospital discharge diagnosis. Validation of an ICD9-CM to AIS-85 conversion table" Medical Care, Vol 27, No.4, pp 412-422, April 1989.

NEW CAR ASSESSMENT PROGRAM (1993) : "Crash rating report", Vol 1, Number 1, April 1993.

NEW CAR ASSESSMENT PROGRAM (1994a), "Crash test report", Vol 1, Number 2, April 1994.

NEW CAR ASSESSMENT PROGRAM (1994b), "Crash test report. Technical summary", Vol 1, Number 3, November 1994.

NEW CAR ASSESSMENT PROGRAM (199b), "Buyer's guide to vehicle crash tests", Number 2, March 1995.

NEWSTEAD, S.V., CAMERON, M.H., SKALOVA, M. MULLAN, N.G. (1995), "Correlation of results from the New Car Assessment program with real crash data : Interim report", Monash University Accident Research Centre.

PAPPAS, M. (1993), "NSW Vehicle Occupant Protection Ratings Documentation". Report to NRMA Ltd. and Road Safety Bureau, Roads and Traffic Authority, NSW.

VIANO, D.C. (1994) 'Analysis of a safety advertising claim on vehicle crashworthiness', Paper No. 94 S5 W 18, Presented to the 14th ESV Conference, Munich, Germany.

VIANO, D.C., AREPALLY, S. (1990) 'Assessing the safety performance of occupant restraints systems', SAE Paper No. 902328, 38th Car Crash Conference, Florida, USA.

ZADOR, P.L., JONES, I.S., GINSBURG, M. (1984) 'Fatal front-to-front car collisions and the results of 35 mph frontal barrier impacts', Presented to the 28th Annual Conference of AAMM, Denver.

HARMONISATION OF EUROPEAN REAL-WORLD CRASH INJURY DATA COLLECTION SYSTEMS

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ABSTRACT

This paper describes the role of real-world crash injury data in the development of safety strategies or regulations. It highlights the difficulties in combining or comparing data from several teams or countries. Areas are indicated where a harmonised approach could allow a more general view of vehicle safety issues. Current European activity towards data harmonisation is described.

Crash Injury data and the vehicle safety cycle

The reduction of injuries to road users in crashes is widely recognised as a major objective in societies in many parts of the world. National governments are introducing targets for reductions in fatalities and other casualties. Manufacturers also aim to reduce injuries sustained in their vehicles and sometimes see a marketing advantage in being able to demonstrate the safety of their products.

Injury reduction can be achieved by measures that prevent the crash occurring or by design elements in the vehicle that reduce the crash forces on road users.

The vehicle design process, and that of development of associated national legal requirements, is highly complex. Design or performance requirements to reduce injury have to be incorporated within a rigorous cycle involving problem identification, changes to model designs or regulations followed by evaluauon of the solutions. Real-world crash injury data plays a key role in this process.

The process is illustrated in Figure 1 and starts with an analysis of crash injury data to identify outstanding problems and to rank them according to the costs to society. A manufacturer is likely to be interested in the performance of individual models while a regulator will probably take a more generic approach.

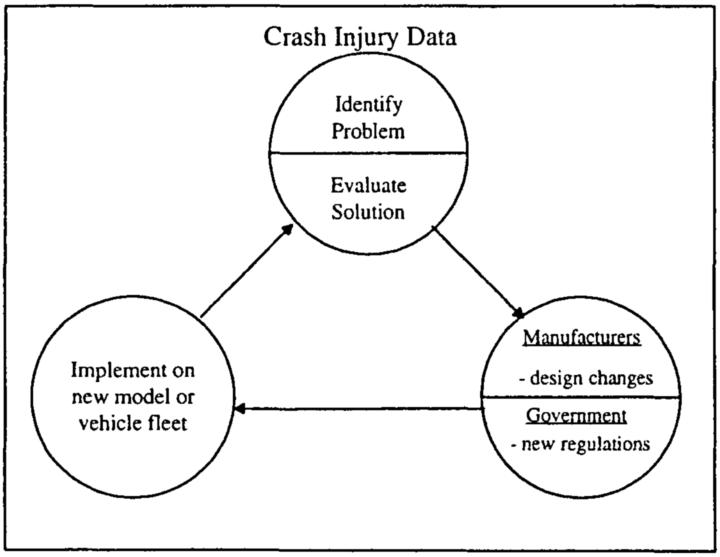

Figure 1: The Vehicle Safety Cycle

The data can frequently be used to describe problems in sufficient detail so as to indicate the likely nature of any changes although only simple solutions will normally drop out readily. The engineering process is needed to redesign a vehicle or component and to include, for example, biomechanical considerations. The regulatory process has to develop a suitable test condition to measure a range of vehicle performance indicators. These new model designs or regulations are then introduced into the vehicle fleet resulting in changes in injury patterns.

Frequently other issues affect the implementation of new vehicle designs. A vehicle has to be capable of being constructed at a price that will mean it is popular. A vehicle with extremely high safety levels will not reduce injuries much if it not sold in any numbers.

Similarly other issues unrelated to safety, such as consumer or industry needs will influence the nature and timing of safety regulations. It is therefore vital that the effect of new designs and new regulations on safety levels is evaluated and the effectiveness of countermeasures contrasted with the initial expectations. Real-world crash injury data is an essential component in a data driven vehicle safety cycle. The main functions of crash injury data are:-

- To support research driven safety policy making;
- To evaluate the effectiveness of safety designs and regulations;
- To identify the need for new safety systems or performance requirements;
- To identify areas requiring more detailed research.

These functions are illustrated in Figure 2.

Current difficulties in crash injury data use

Vehicles are increasingly designed for sale in a global market and manufacturers find it advantageous to minimise the variation in design necessary to sell, for example, in the US, Europe and Asia. Similarly there is pressure upon Governments to harmonise the legal performance requirements for vehicles. As a consequence decisions on legislation and vehicle design need to be based on the safety problems across markets. The crash injury data that is used to support safety strategies correspondingly needs to be representative of the wider markets and regulatory areas.

At present crash injury data is collected by a range of groups that may be based at universities, car manufacturers, insurance groups or government institutions. Each of these groups has individual objectives for the research reflecting the needs of the funding body. There is normally no co-ordination in research methods employed, vehicle types examined or the data collected. It is not straightforward to combine data from several sources to base decisions on a composite data set. Regulatory groups, in particular, find it difficult to assess the relevance of the variety of datasets used to support arguments on safety policy.

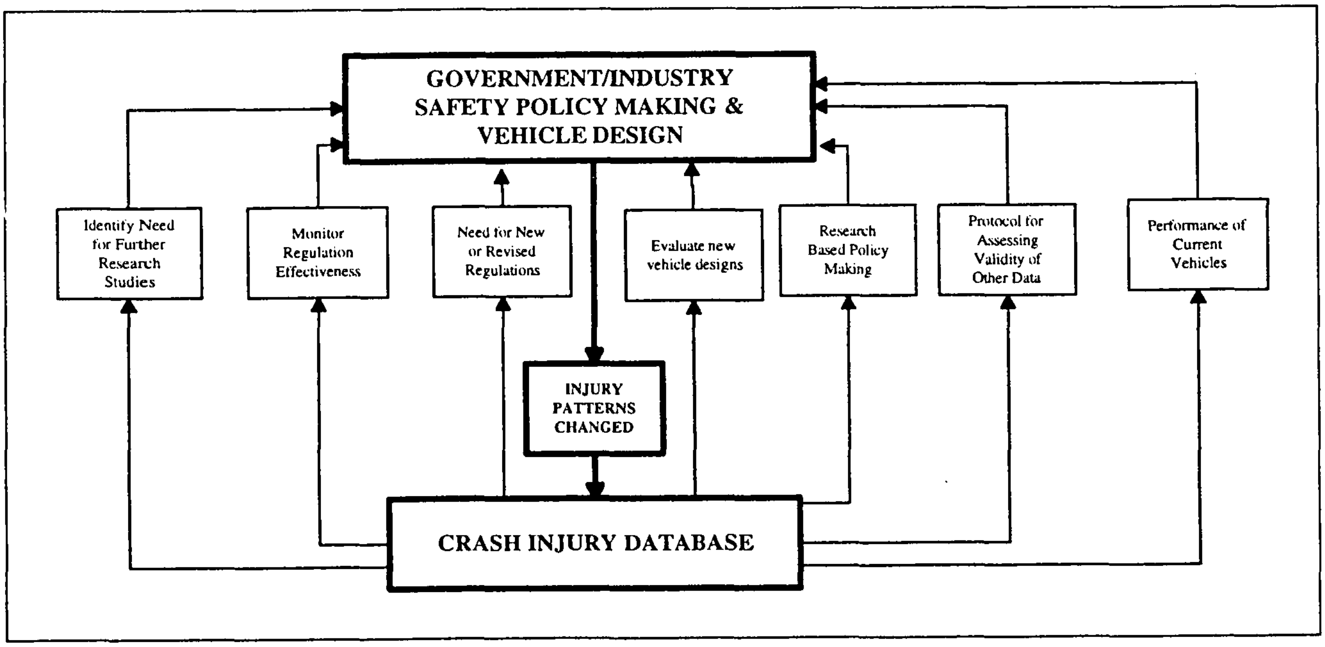

Figure 2: Functions of Crash Injury Data

Additionally the process of harmonisation will involve identifying the whole set of needs of the funding groups. Frequently there is a significant level of duplication between groups within an organisation that collects accident data. There can often be a significant financial benefit obtained from distilling the requirements together and implementing a single co-ordinated study. For example in government some responsibility for aspects of vehicle safety could be within the remit of the health, industry, transport, research or environment departments. While there may be a spread of needs across such groups there will also often be a degree of common needs reflecting, in part, the wide issue of crash injuries as a public health problem.

A degree of harmonisation between crash injury studies will have considerable benefits of synergism from combining or otherwise comparing several datasets from several countries.

Areas for harmonisation

The injury investigation studies that are being conducted in Europe have many differences of detail. They are each designed to address the needs of the project sponsors and have developed different ways of doing similar functions. There is a need for these basic activities of data collection to become harmonised to lead to the possibility of a combined system. The first step is to decide on the harmonised approaches to be used so as to define a basic system that will fulfil the needs of both government and industry. The system must allow the flexibility for local enhancement and accommodate local limitations. The key areas for harmonisation are:-

1. Selection of crashes for study
2. Relationship between these crashes and the population from which they are drawn.
3. Link to the European crash database (CARE)
4. Data to be collected - methodology and recording techniques
5. Terminology
6. Data quality, consistency and validation
7. Data processing
8. Methods for combining data to ensure European representivity
9. Confidentiality and ethical considerations

Selection of crashes for study - The selection of crashes to be used for the investigation of injuries and their causes is the first step in data collection. Past data collection systems have used haphazard or biased techniques which restrict the applicability of the data. The database should be able to describe the problems associated with injury in some detail but it should ideally also permit risks to be calculated so there also needs to be data on crashes where no serious or fatal injuries were sustained.

The harmonisation process must define the ideal manner in which the sample of crashes will be selected from the population to ensure representative results. For example the UK Co-operative Crash Injury Study utilises a stratified sampling procedure which results in approximately half of the sample of crashes being serious or fatal and half involving just slight injury. It can be shown statistically that this spread of crashes can be the most cost effective way to produce a sample that is optimised for accuracy. Weighting factors can be calculated for analysis that will statistically undo the special selection techniques employed and produce a close representation of the underlying population of crashes. However this method has the disadvantage that the selection requires some knowledge about the injury outcome so it is clumsy and inefficient if used for on-the-spot studies where response time is critical.

Alternatively a random sample can be made from the crash population. The Medical University of Hanover operates a sampling system where a fixed known of crashes are investigated. this proportion is determined on a pragmatic basis according to crash availability. The system is straightforward to operate but many crashes are low energy with low injury risk and low information value.

Some studies that use retrospective techniques limit the vehicles studied to those that have been towed away from the crash so that fewer crashes with very low energies will be examined.

There may be alternative methods to increase the usefulness of the sample, this should be evaluated during the harmonisation process.

It is very likely that different investigating groups will not be able to work to the ideal selection system, particularly at an earlier stage of a harmonisation process. For example some systems operate on a call-out basis and attend the scene of the crash while the vehicles are still in place. It is difficult to pre-select crashes as the emergency services often do not know the full details of

any crash before they attend the scene so on-the-spot studies will find it difficult to operate a stratified selection procedure. It is also likely that there will be local restrictions on the manner in which investigating groups can operate crash notification procedures. The harmonisation process must examine these restrictions and find a common sampling system that will result in equivalent datasets.

The sampling procedures used are a fundamental aspect of the validity of the data and a high level of quality control should be exercised in case selection. This means that the crash sampling systems should be well defined and rigorously operated. The manner in which the system is meant to operate should be well documented. In practise there are often deviations from the ideal that occur because of local effects so the system should also evaluate the real relation between the sample and the population. The weighting factors should then be based on this real relationship rather than the intended relationship. The harmonisation process should define the quality control process to be employed in crash sampling.

Relationship between the sample of crashes and the population from which they are drawn.- The relationship between the sample of crashes and the whole crash population is a fundamental part of the injury data collection process. There needs to be a well controlled and documented link between the two. A clear method of crash selection is essential to the data collection process, it is not an option. Until this link is defined any data collected cannot be considered statistically representative.

Figure 3 shows the links between crashes investigated and the populations from which they are drawn.

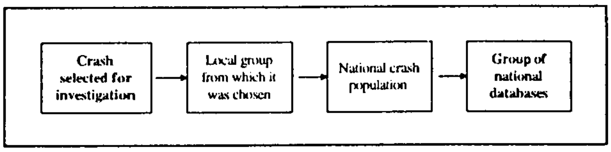

Figure 3: Relation between Crashes and International Crash Population

Each data collection group should continue to have its own way of choosing crashes for investigation that has been developed in response to local limitations and possibilities. There are many possible definitions of the crash population. Each group may select cases from its own locally defined crash population which in turn will have its own links with the national crash population. For example some groups may select crashes where vehicles have been towed away from the crash, others may select crashes where a casualty attended hospital. The national populations in each European country will have their own characteristics that will have to be related to each other. Each of the links between the crashes selected for study and the European crash population will have to be evaluated. If this is not done then any combined database can only be viewed as several datasets in the same place rather than a single harmonised system.

There will be problems in harmonisation because of differences in national systems. For example some countries count fatalities as being those people who die within 24 hours of the crash while other countries have a 30 day limit. Crash sampling systems that are based upon these different definitions will themselves be different. These national differences may be difficult to work around and the harmonisation process needs to consider interim steps before a combined database can be produced. The existing databases will probably have to converge with time to a harmonised format.

Data to be collected - methodology and recording techniques. - Like sampling issues, the data collection and recording is a fundamental part of the crash investigation process. The stages include:-

- definition of data concepts to be collected
- definition of a core data set to meet user needs
- definition of data collection methodologies

The first stage of data harmonisation will be to identify the basic concepts of data to be collected. These will include basic items such as crash configuration, vehicle types, safety components, occupant characteristics, injury outcomes and injury causation. There will also be other data that will relate closely to current or intended regulatory policy and to vehicle design issues. So for example there may be items that relate to the future front and side impact requirements of cars and also items that concern pedestrian protection.

The second stage of data harmonisation will be to define precisely the variables that will be coded. This will include standard fields such as the Collision Damage Classification[1] and the Abbreviated Injury Scale[2] and variables detailed in the above paragraph. It can also include data that is linked to the future regulatory and vehicle design evaluation needs of the government and industry. This means that there will need to be close liaison over the likely future needs. There should also be items to allow the database to be

augmented with data from other systems. For example there should also ideally be a cross-reference between each case and the national data and with the CARE database, the Vehicle Identification Number (VIN) should be recorded to allow special information from manufacturers to be linked. The manner of coding some of the variables will be relatively unambiguous but experience indicates that much will inevitably be open to individual interpretation at the point of crash investigation.

The third stage of data harmonisation will be to define the methods to be used for interpreting and coding the data. For example it may be necessary to describe the damage to the bonnet of a car from pedestrian contact. A coding system will have to developed that describes the location of the contact, the depth of crush and other factors that will relate to any future regulation. There will need to be a data collection handbook that describes in detail how the damage to vehicles and road user injuries should be interpreted into the coded format. This handbook should be developed within the harmonisation stage but it should also be updated regularly during data collection to clarify data collection problems that will inevitably occur.

The harmonisation process should be conducted by a responsible group with considerable experience both in crash injury data collection and the application of the data to vehicle safety design and regulatory issues. The same group should continue to be involved in any ongoing implementation of a data collection system.

The harmonised data collection procedures should be viewed as a minimum system to meet the general needs of government and industry. There will probably be special interests of the data collection groups that will mean that additional data will be collected. This is to be encouraged because the basic system will be directed for one particular purpose, the enhancements will assist in the identification of new issues and help other research and development activities. These enhancements should only marginally affect the costs of the study as the most expensive part involves setting up a study and getting to the vehicles and casualties involved. An extra 30 minutes used to record additional data costs very little in comparison.

There is one particular data item that will have to be addressed by the harmonisation process that will involve special problems of methodology. A measure of impact severity is a fundamental item, severe injuries that are sustained in a high speed crash may be less unacceptable than severe injuries at low speeds. It is important that an accurate measure of the speed is routinely coded. There is a considerable variation between groups in selecting and evaluating impact severity measures. Some groups measure pre-impact velocities while others measure the velocity change during the collision. A variety of methods are used to calculate these values including some developed for the US vehicle fleet. The data harmonisation process should address this issue with some vigour but there is the need for some separate research. A series of staged collisions should be conducted and the different methods compared to establish the most accurate measure to relate to injury outcome. This process should address the impact severity of all types of crash that will be covered within the data collection - cars, pedestrians and motor-cyclists.

<u>Data quality, consistency and validation.</u> - The data harmonisation process will define a standard manner in which the data will be collected. This needs to be supported by procedures to ensure that the data that is finally produced is accurate, consistent between groups and of high quality. This will involve procedures such as the checking of injury cases by co-workers, electronic error checking procedures, exchange of crash injury case files, exchange of personnel between sites and feedback to groups of problem areas. A thorough set of documentation will be needed.

A regular feature should be the provision of feedback to teams of the progress of the work. Data collection for the purposes of regulation is a professional activity and thought should also be given to ways of ensuring that skilled investigators remain motivated and stay within the system.

<u>Data processing and exchange</u> - Once the procedures for collecting and recording the data have been defined the requirements and structure of the electronic database should be established. There will need to be procedures that describe the format of the electronic data and the methods of data exchange. It is possible that the harmonisation group may consider that there is value to have visual images of the vehicles in the database. As mentioned previously there will also need to be a system of electronic error checking of the data. The harmonisation group may decide that there is an advantage in constructing a standard set of data analysis routines although this may be better done by each group analysing the data. The content of the data may impose special requirements of the computer systems to service the data e.g. CD-ROMs, optical disks etc. As the system develops the dataset will grow and the size may also impose special hardware requirements.

The harmonisation process should define the structure, content and exchange format of the electronic data.

Link to national and international crash databases. - An earlier section has discussed the link between the sample of crashes investigated and the population from which they are drawn. In the same way there should be a known link between the population and the group of crashes in national and international databases. The population the crash sample is taken from may be based on police reported crashes, hospital admissions or other systems. Some groups may have an inherent link to the national crash database and hence to the national database while others may not. The harmonisation process should define the needs of these links which allow wider judgements to be made based on data that has a known link to the European data.

The links to the international databases should ideally include crash identification fields as well as descriptions of e.g. vehicle and casualty types, severities of injury, local conditions at the time of the crash. This means that there will need to be a set of harmonisation procedures in common with those being conducted for international crash databases. The harmonisation process should include a stage where these links are established.

The CARE database currently comprises national data from each EU country. There is a continuing process of convergence of these datasets and the system will evolve. A harmonised in-depth injury database will also evolve with time. There will need to be a continuous process to ensure that the two datasets do not diverge as they each develop. This will require further action after the initial harmonisation process. A working group consisting of members from both CARE and the crash injury study should be involved in the supervision of the developing datasets.

The harmonisation process in Europe should ensure that there are links with the CARE database, these links will include a statistical link and also common variables.

This linkage can be applied to other types of crash or injury data that might be needed on a European scale. As long as suitable fields are included in each database and the selection of cases is well defined and executed then European representivity can be validated.

Statistical methods for combining data from several sources - A final harmonised database will probably include data collected in several countries by different groups. This data could then be combined on a single computer file to achieve the purposes of government and industry. If one of the component datasets is large it may influence analysis of the complete dataset to an extent beyond that merited by the size of the national casualty data. There are problems to be solved when combining a small amount of injury data from a country with a large casualty problem with a large dataset from a country with a smaller problem. One objective of a harmonised database is to be able to accurately represent the injury problem across Europe so a representative European database is needed. These issues are related to those of national sampling and representivity and it is possible that the CARE database can be of use.

Statistical methods for analysing data from several sources - The combined dataset will be complex as a result of its diverse origins. The data may have been collected to a variety of protocols that have converged through the links with national data. This complexity will place restrictions on the manner in which the data can be analysed. Data analysis can take two forms. It can be used as a resource that describes the links between injury outcomes and the performance of vehicles, cases can be combined to do this with little reference to the sampling methods. The data can also be used to present a picture of the European crash population and to answer questions such as "how many drivers sustain fatal head injuries from the steering wheel" or "what is the risk of pedestrian pelvis fracture at 50 kph". These questions imply that the case selection process must be untangled to produce representative data through the use of weighting factors, they are complex issues statistically. A harmonisation process should include the development of guidelines concerning methods that should be used for analysis. This should be done in consultation with professional statisticians.

Confidentiality and Ethical Considerations - The preservation of confidentiality of individual identities places an important responsibility on all groups dealing with personal data. None of the individual injury databases examined have identifying details within the electronic database but knowledge of identities is a necessary part of the data collection process. Final databases are normally sanitised to remove all identifying data, photographs of damaged vehicles or injuries are normally taken with licence plates obscured. The harmonisation procedure should include the need to preserve the confidentiality of the data. A set of guidelines should be drawn up to demonstrate compliance with data collection ethics.

One particular issue of confidentiality concerns access to medical records and post-mortem reports. Some countries require that the permission of the patient be obtained before access can be granted, others do not. This means that some countries may have accurate injury data on less than half of the casualties while others may have full data. This restriction may extend to access to post-mortem reports, some countries accept ready access while others do not even conduct routine examinations. This means that individual datasets may have missing data which may affect its usefulness. The harmonisation procedure should include an evaluation of the extent of this problem and identify methods to minimise the effects on analysis of combined data. There may also be the need to develop government and industry backed guidelines to facilitate the use of personal information for research purposes.

Terminology - There is a need for as closer degree of harmonisation in the terminology used to describe the variables collected in crash injury research as well as the published results. Terms such as "accident severity", "accident type", "crash severity" and "frontal impact" can take a variety of meanings and interpretations depending on the research group. The recent work by ISO SC22/TC12/WG 7 concerning terminology should help resolve a number of these issues if the definitions established are conformed with. Until then there will continue to be confusion over the language and meaning of the technical terms employed.

Next steps

This paper has described the value in harmonisation of crash injury data and the areas where it will most usefully be achieved. The harmonisation process is one step along the path towards a harmonised system. Once areas of harmonisation have been agreed the whole process must be implemented.

Implementation of a European Crash Injury Database - It is considered that a crash injury database that can reliably be used to assess vehicle safety issues in Europe will be a benefit to the European Commission and the European vehicle industry. There are a range of short, medium and long term actions that are needed to implement a European Injury Database. The first step comprises the sampling and data harmonisation processes including the comparison of existing data sets to prioritise solutions. This step will make available a set of procedures that can then be put into action. It is unlikely that there will be any existing groups that collect data that complies exactly with the harmonised specification but this should lead into a pilot phase where a small number of datasets are combined to form a prototype database. The construction and analysis of this pilot database will throw up further teething troubles that will have to be solved before the system can be enlarged.

Once the pilot database has been validated it will be usable for the objectives of research driven policy making. There will need to be a management process that involves the groups collecting the data and the funding groups to control the analysis and development of the database as an active tool.

Following the pilot phase further datasets can be included within the database. Before each can be included within the main database the data collection procedures must be reviewed to ensure they comply with the harmonised requirements.

The processes are summarised in the Figure 4.

There will be gaps in the data collected by the existing groups, the need for more data on pedestrian and motor-cyclist accidents has been high-lighted earlier. The harmonisation procedure should include an evaluation of the likely data gaps and recommend additional data collection needs to the project sponsors.

Time-Scales And Sample Sizes

The harmonisation process will probably take at least 2 years work by a steering group of data collection groups with dedicated personnel working on the task. Once the harmonisation protocols have been developed it will be possible to evaluate the extent to which existing databases can be combined. The decision to proceed with the pilot database can then be made. The process of converting the existing data into a combined system and then performing a set of validation analyses will probably take about a year. The addition of each further database will involve a review process which can be done on a copy of the main database used as a pilot. It is recommended that a single group take responsibility for the management of the combined dataset to ensure that the high standards of data quality are consistently met and access to all groups is maintained.

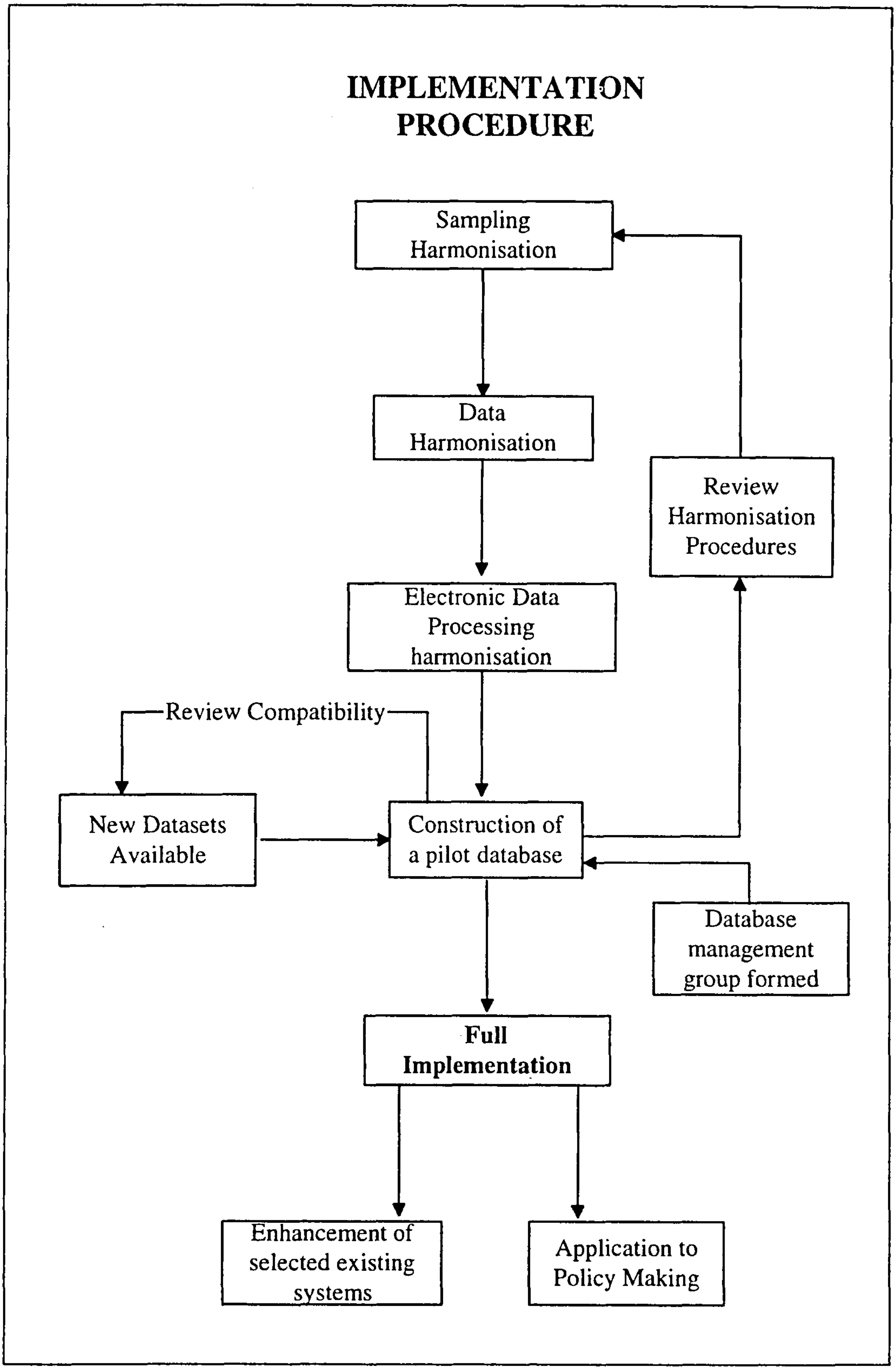

Figure 4. Implementation of Harmonised Crash Injury Database

European Representation

One objective of the database is to describe the causes of injury in European road accidents. This means that it is desirable to include representative data from each country of the European Union. Some countries, such as the UK, Germany and France, conduct nationally funded in-depth injury causation studies while others do not. There are also independent studies funded by the car industry or insurance groups in the UK, France, Germany, Sweden and Finland. There are no identified data collection teams in any of the remaining EU countries.

It is likely that in general the crash performance of a vehicle is much the same in any country but it is suspected that different countries might have slightly different accident characteristics. For example there are indications that southern European countries have lower rates of seatbelt and helmet use. The UK has mostly right hand drive vehicles and the car fleets in some countries may contain more small cars than others. Travel speeds may be higher in some countries so biases may be introduced if data is not included from these countries.

It is probable that the objectives of the database can be achieved using data from just a few countries but it is recommended that new data collection groups are encouraged, particularly in the Southern European countries where seat-belt and helmet use may be lower.

Participation in an In-depth Injury Database

Existing data has been collected for the specific purposes of those funding the work. These funding bodies may be government or industry and they may not be prepared to share their data with other groups that make a lower level of input. If this data is to be included in a harmonised system there will need to be a process of negotiation over the use and ownership of this data. Informal discussions with some of the groups indicate that some groups may not be prepared to share their data unless they can receive an equivalent amount in return. They may also place restrictions on the public availability of the data they have funded.

This is a critical issue that will need to be resolved before a pilot database can be established. The harmonisation process should identify a small number of datasets that could be used for the pilot. It is recommended that there be discussions with the owners of this data at an early stage in the harmonisation process.

If the owners of the data are not prepared to let it be used for Commission purposes the Commission may need to fund data collection teams completely.

Access To Data

It is likely that the negotiation process referred to above will give access to the combined data set to those groups that fund the data collection. A question that will have to be resolved concerns the more open access to the data. There will have to be some consideration whether access to the data should be freely available to all, whether access should be limited to specific groups or whether it should be unavailable to all. Consideration should also be given to restrictions on the type of use of the data.

The database is likely to be complex and it is recommended that any public access should be supported by information systems to ensure that users understand the limits and requirements of analysis. It is the experience of the authors that datasets that are statistically complex can frequently be complex to analyse. A set of statistical tools may be necessary to untangle complex case selection criteria and this will require some level of expertise on the part of the analyst. More importantly every dataset has its strengths and weaknesses and they are often limited by the data collection process - the investigator knows that some data elements are easily determined while others may be difficult to collect. This means that some fields in the data are highly reliable while others are more speculative. The best analysis practise will ensure that the analysts have a sound crash investigation experience. In a similar manner it is desirable that the data collectors have a good understanding of the intended purpose of data items

Industry Involvement in the Harmonisation Process

Vehicle manufacturers, insurance groups and other industrial groups have an interest in the collection of injury data. Many already collect data to meet their own needs and some are among the most experienced in the world and can play a valuable role. They may wish to add their own data to the aggregate dataset and receive other data back in turn, this is likely to be a matter of negotiation as described above. One issue concerns commercial confidentiality over any data they donate. They may also wish to use their own data to make representations for revised regulations in which case they

might like to ensure that their own data conforms to the protocols established in the harmonisation process. This means that the harmonisation process should involve the industry either in a consultative or other capacity. The key stages include the harmonisation of sampling and the core data set.

The experience of non-independent groups should be sought for the sampling and data harmonisation process which should also include a wider consultation with all interested groups. This could involve paper consultation, workshops or other means.

European data harmonisation activities

The first phase of the harmonisation of European crash injury data has begun. The development of the harmonised protocols is being undertaken within the EC Fourth Framework Research Programme. A group based on the Loughborough Vehicle Safety Research Centre (UK), INRETS (Fr.), CETE (Fr.), Medical University of Hanover (D), TRL (UK) and BAST (G) will develop a harmonised protocol for all aspects of crash injury data collection. The project acronym is STAIRS (STandadrisation of Accident and Injury Registration Systems). Associated with this project is another that addresses the similar issues concerning the harmonisation of European national accident databases under the CARE programme under the acronym CAREPLUS. The work will start in summer 1996 and take approximately 2 years. The subsequent implementation is a matter for separate negotiations and decision making.

It is planned that there will be an extensive consultation process during the STAIRS programme including the organisation of a workshop to attract the participation of all those involved in or associated with the collection of real-world crash injury data.

The main focus of the harmonisation process is on European crash injury data but an input will be actively sought from all concerned groups. The initial contacts to obtain information or make comment on the process are given below.

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REFERENCES

[1] Collision damage classification J224b Society for Automotive Engineers 1996
[2] Association for Automotive Medicine, 1991 Abbreviated Injury Scale 1990.

AUTOMATIC RECORDING SYSTEM AND TRAFFIC ACCIDENTS AT UNCONTROLLED INTERSECTIONS

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ABSTRACT

The purpose of this paper is to assess the usefulness of a new automatic recording system called "TAAMS" for traffic accident, which can saves the pre- and post accident scenes, in determining the cause of accidents and near misses.

The study was conducted to assess the dynamics of traffic accidents and near misses using TAAMS installed at two unsignalized intersections. Some cases recorded by TAAMS are analyzed focusing on misjudgments of drivers including road condition and the pre-accident behavior of vehicles. In some cases, mail interviews also made for the drivers involved in accidents as a mean of examining the role of human factors.

Analysis of accidents and near missed recorded by TAAMS and driver interviews reveal some kinds of misjudgments caused by habitual driver behavior and lack of concentration under certain situations. Misjudgments on drivers involved accidents are classified into three categories, which are caused by under traffic congestion, overlooking and gap distance, are demonstrated in this paper.

INTRODUCTION

A great deal of effort has been made on traffic accident mechanism including human errors. What seems to be lacking, however, is to make clear processes of inducing human error at traffic accident. In addition to this, the most important point is that nobody knows the fact and detail of the accidents in the real word. The studies have been conducted mainly based on police reports and documents, which resulted from investigations carried out after the accidents. The police investigations tend to put much focus on the human behavior involved in traffic accidents, assuming a simple factor induces accidents, because of judgment of professional negligence. As a results, many traffic accidents have been accordingly attributed to human errors of individuals involved. Human behavior, however, is complicated; the influence of external factors including environmental situation must be considered to understand the human behavior and/or error leading to accidents. It is essential to find mechanism of accident in terms of human behavior as common factors of traffic accidents, and to investigate the way to estimate the factors, while assuming human errors are unavoidable.

This paper described how to know the facts and process of the accidents. A new recording system "Traffic Accident Auto-Memory System (TAAMS)"[1),2)] was developed to record the scene before and after a traffic accident on real time. It offers, in fact, the key to an understanding of mechanism of traffic accident including causes and factors on human error.

GENERAL DESCRIPTION OF TAAMS

The configuration of the TAAMS is shown schematically in Fig.1, which comprises a detector with a camera and microphone, a main unit consisting of sound discriminator, image and sound memory, and a video tape recorder. When sound received by the microphone is determined as that of an accident including near miss by the discriminator, TAAMS saves the pre- and post accident scenes as digital data in the systems memory. After this data is converted to analog format and recorded on videotape, the system automatically resets. Approximately 1,000 accident cases can be recorded by TAAMS on a 120 minute videotape, with 40

pictures (20 pre- and 20 post-accident) recorded per single accident process. Figure 2 illustrates some typical frequency characteristics patterns (time - frequency) of sound and noise collected from actual traffic stream.

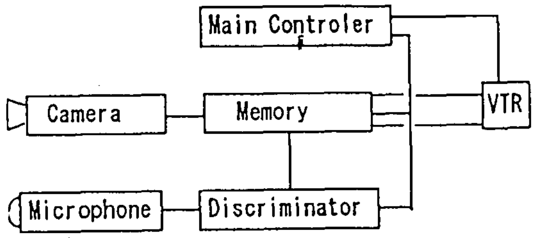

Fig.1 Schematic view of TAAMS

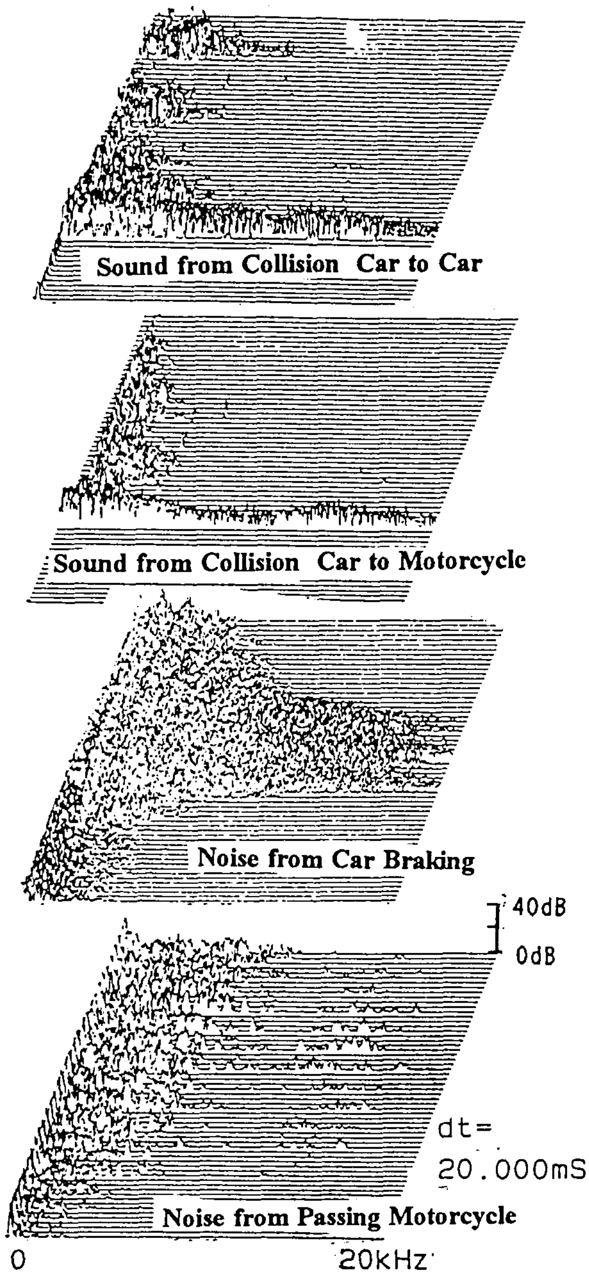

Fig.2 Frequency Characteristic Patterns of Traffic Noise

FIELD MEASUREMENTS BY TAAMS

TAAMSs installed at two intersections without signal control in down town of Metropolitan Tokyo as shows in Figure 3. . The road way represent as arrow are regulated with temporarily a stop sign and stop line marking with "とまれ or 止まれ" on the road surface. Accordingly, any vehicles running to the roadway must stop temporarily on the stop line before entering to the intersection by Japanese traffic law.

Data of accidents and near misses are collected from 1994, and we classified the data into some main groups focusing on driver behavior immediately before accident. In some cases, the police documents reported to the police department are collected and analyzed . Also, mail interviews with the drivers involved in accident are carried out to examine the human factors on the accident.

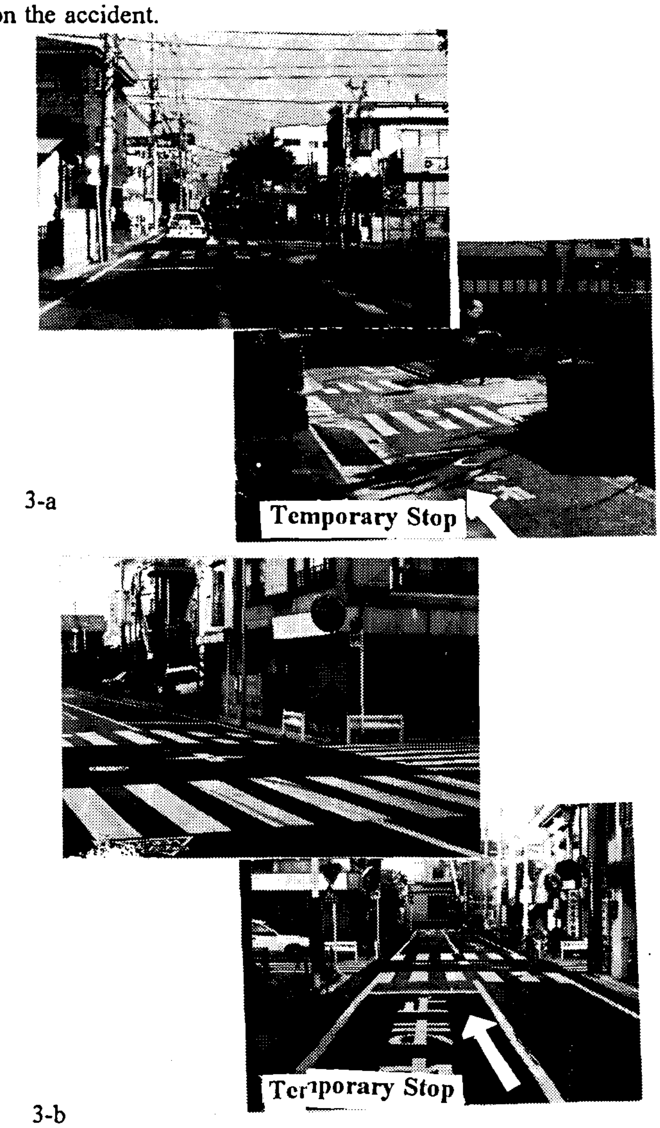

Fig. 3 The intersections installed TAAMSs

MECHANISM OF MISJUDGMENT

We would like to focus attention on why drivers and riders involved in accidents misjudge under a certain situation in analyzing the data recorded by TAAMS. TAAMS pictures may be informative for traffic accident mechanism of intersections at which a number of accident occurs. In this paper, three main groups are classified on trial basis as following.

MISJUDGMENT UNDER TRAFFIC CONGESTION - Two cases are accident and a near miss under traffic congestions in the intersection of Figure 3-a, are illustrated as follows: The first is an accident of a moped to a passenger car (Case No.1); second is a near miss of a bicycle to truck (Case No.2). In both cases, similar behavior between rider of moped and bicycle can be observed .

Case No.1 - Many cars were stopping beyond the intersection because of traffic congestion as shown in Figure 4. And then a passenger car was waiting on the pedestrian crossing. At that time, a moped coming along the passenger car, entered into the intersection in spite of the situation. The rider of moped perceived a approaching passenger car on the crossing roadway at high-speed from his right, and he stopped the moped near the center of the intersection, panicked. Immediately after then, the passenger car collided at the back of the moped and the rider was thrown out onto the street.

Figure 5 illustrates the speed changes of the both vehicles, with time resulted from picture analysis. The speed of the moped is approximately 50km/h, while that of passenger car 15km/h, respectively.

The accident scene suggests the possible misjudgment of the moped rider; he may have judged that no other approaching vehicle would enter the intersection. But the judgement is quite groundless misapprehension. The analysis results also suggest that the misjudgment of the driver, who entered the intersection at high-speed, extremely asserting the right of way, and totally neglecting the possible misjudgment of the other vehicle coming on the crossing street due to traffic congestion. Further, this accident shows the difficulty to take adequate response in an emergency, convincing us of the importance of preventive measures before panicked.

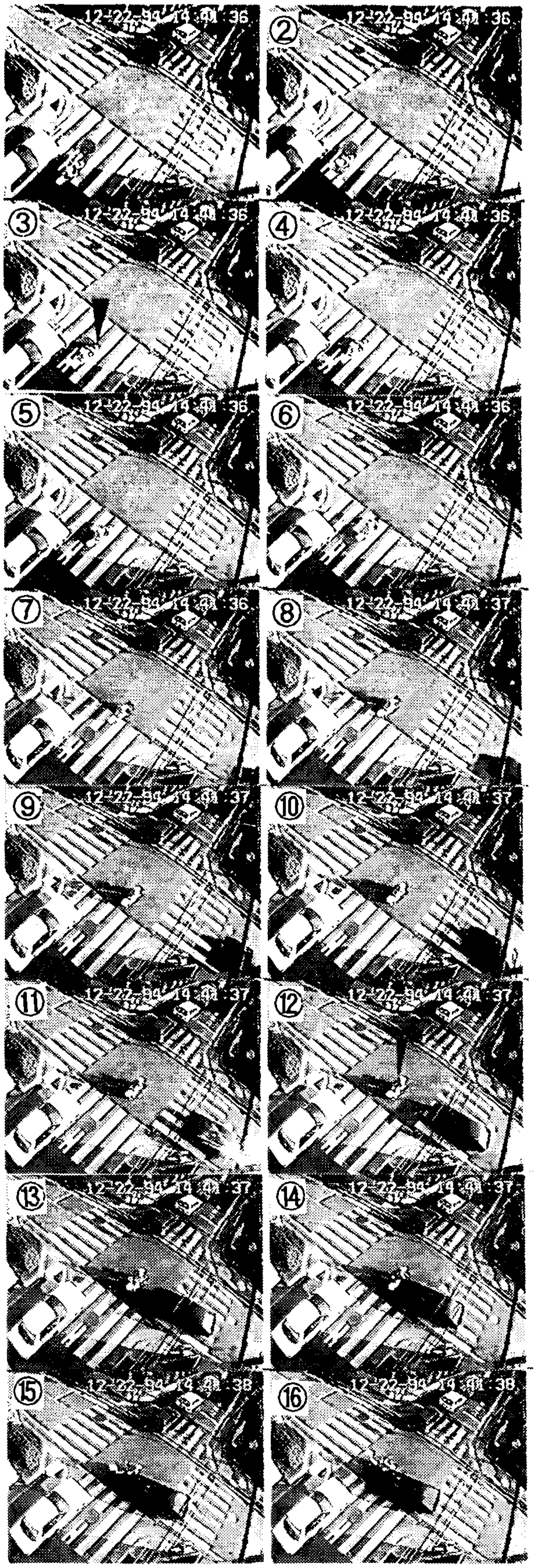

Fig. 4 Accident Scene recorded by TAAMS.

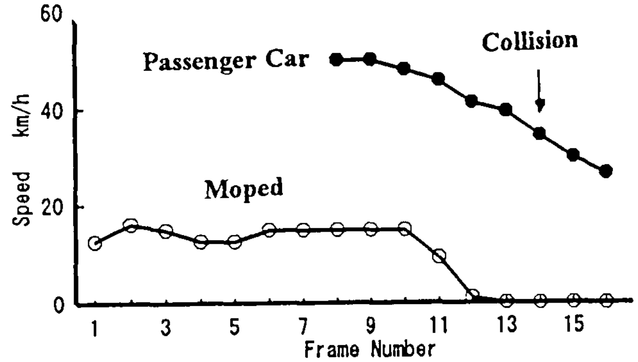

Fig. 5 Vehicle Speed v. Frame Number.

Case No.2 - The near miss of a bicycle to a truck happened under the similar situation in the same intersection in Case No.1. Figure 6 illustrates the near miss scene of the bicycle to the truck. A passenger car was waiting on the pedestrians crossing for the traffic congestion.

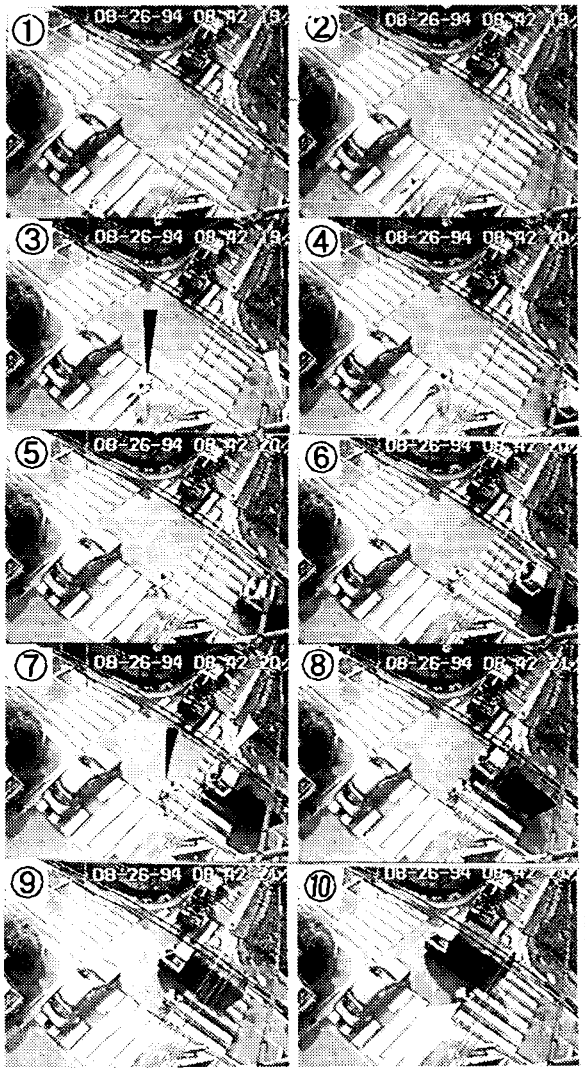

Fig.6 Near Miss Scene recorded by TAAMS.

The behavior of bicycle rider is similar as the rider of the moped in Case No.1. Probably, the bicycle was going to turn right. On the other hand, the truck didn't slowdown entering the intersection in this case. The speeds of the truck and the bicycle were approximately 45km/h and 5km/h respectively according to speed analysis. The bicycle could stop immediately before passing the truck. The driver might judge no coming vehicle from the crossing way under this situation. Also, he ignored the bicycle because it was hardly visible and was aprroching with a low speed

These examples show typical accident pattern caused by misjudgments of riders of moped or bicycle in intersections under traffic congestion. In both cases, the important point to note is approaching speeds of the crossing vehicles are extremely high. In this intersection, speed limit is 30km/h. In two cases the speeds are approximately 50km/h and 45km/h, respectively.

The reason why the drivers drove with such high speed is that the drivers anticipated no crossing vehicle for the traffic congestion on the crossing way. On the other hand, a rider of moped or bicycle would think that he can freely run in any time and any situation, even under this situation, which is characteristic of riders of moped and bicycle. However, it is very dangerous behavior of riders of moped or bicycle to pass the intersection under the traffic congestion like as these cases mentioned previously.

Case No.3 - To behavior of bicycle we may add, for instance, another near miss case recorded by TAAMS as shown in Figure 7. Although this case didn't occur under traffic congestion, it is an interesting case regarding to judgments of riders. Two different ways on behavior of bicycles riders can be observed at the same situation in Figure 7. In this case, one rider judged it should have stopped, while the other judged it was able to pass on safety. In a very short time, they decided completely different judgements in the same situation. We must look more carefully into how these decisions come from, and what is important (particularly from the safety point of view). Most of people realize that judgment on safety mind is important. What is not so widely understood, however, is occurrence of misjudgment and difficulty of instantaneous judgment.

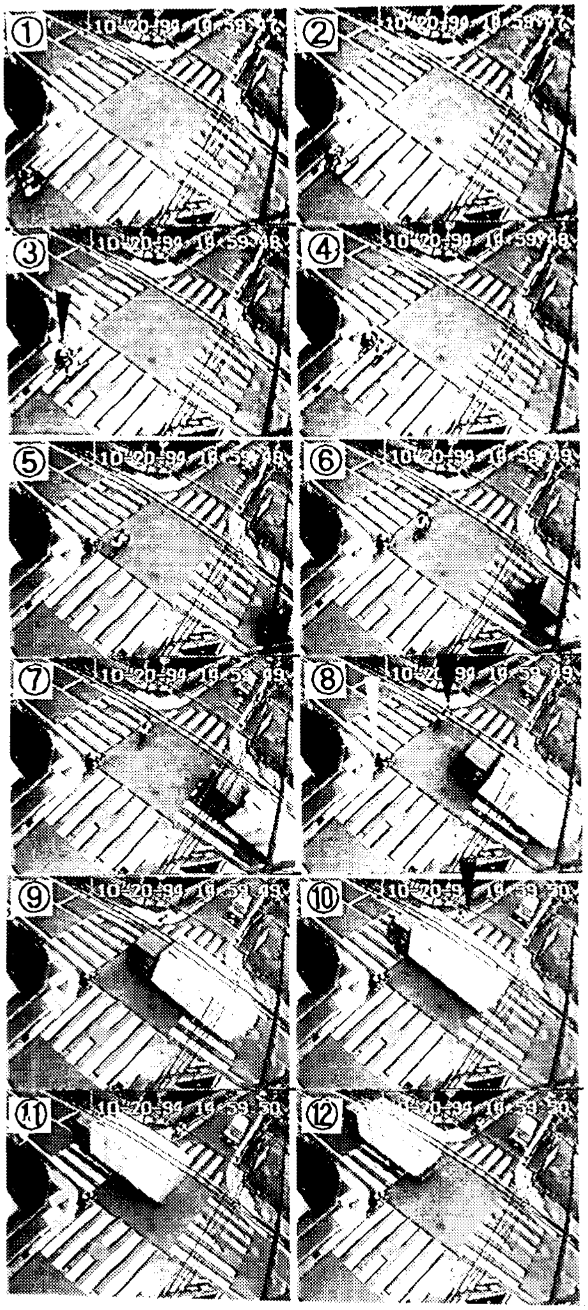

Fig. 7 Near Miss Scene recorded by TAAMS.

In these cases mentioned previously, riders of moped and/or bicycle tend to run freely at their own convenience neglecting the certain situations such as the traffic congestion, whereas the approaching vehicles on crossing way run faster than usual speed because of no coming vehicle. If moped or bicycle stopped before entering into the intersection according to the traffic law, they could avoid the accidents. Also, the crossing vehicle should slowdown surely before the intersection in spite of under traffic congestion for the traffic safety .

ACCIDENT CAUSED BY OVERLOOKING -

Three typical accidents caused by overlooking are described as follows: The first case is an accident in early morning, in which a truck collided against a passenger car (Case No.4)., the second one occurred in the daytime, in which a moped collided to a passenger car (Case No.5). the last is an accident in midnight, that is, a moped to wagon car case (Case No.6). These cases are examples of decline in driver vigilance levels due to individual factors.

Case No.4 - A truck impacted with passenger car at early morning (7:11 AM) as shown in Fig.3-a. Fig. 8 shows the accident scene recorded by the TAAMS.

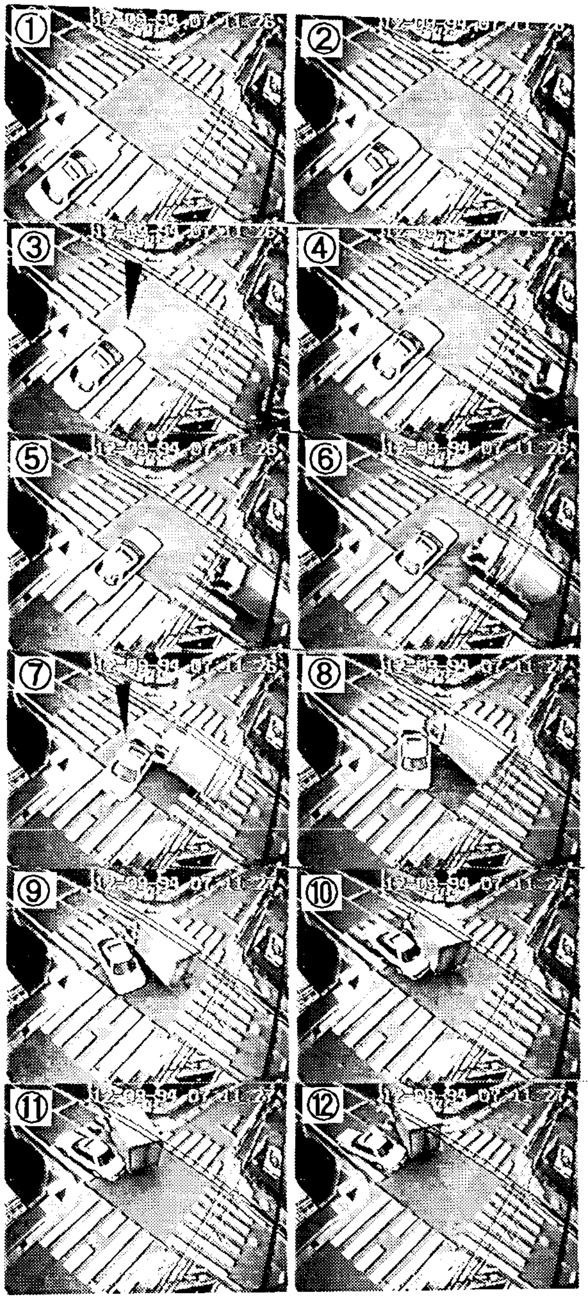

Fig.8 Accident Scene recorded by TAAMS.

Both vehicles entered without deceleration. The truck was driven with extremely high speed of approximately 60km/h as shown in Figure 9. The driver, who was professional driver belong to a transportation company, related that he was hurry because he should have arrived by 8:00 AM at the place of work for loading. On the other hand, the driver of the passenger car also was hurry to his office to be in time to his business hour. He related that he uses this intersection every morning for going to the office. Also since he knew that there is few vehicle around the intersection at that.hour, his neglect of the duty of a halt, overlooking the stop sign and stop line. The driver said that it resulted from his failure in duty of safety check at the intersection through decelerating before enter.

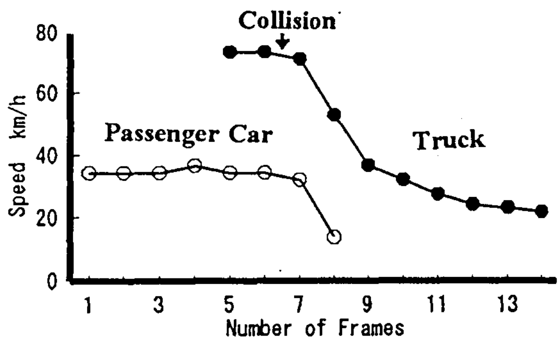

Fig.9 Vehicle Speed v. Frame Number.

Case No.5 - A moped and a passenger car collided at daytime when they passed in the intersection as shown in Figure 3-b. Fig. 10 and Fig.11 illustrates their behavior and the speed change recorded by the TAAMS, respectively.

The passenger car and the moped, entering the intersection at the speed of approximately 25km/h and 35km/h, perceived each other and put on a sudden break, respectively. The car collided against the moped near the center of the intersection while decelerating.

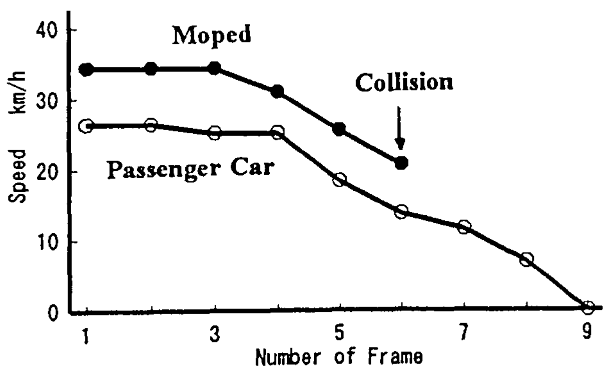

Fig.11 Vehicle Speeds v. Frame Number.

The moped's rider relates that the collision resulted from his neglect of the duty of a halt, overlooking the traffic sign. The car driver said that it resulted from his failure in duty of safety check at the intersection through decelerating before enter.

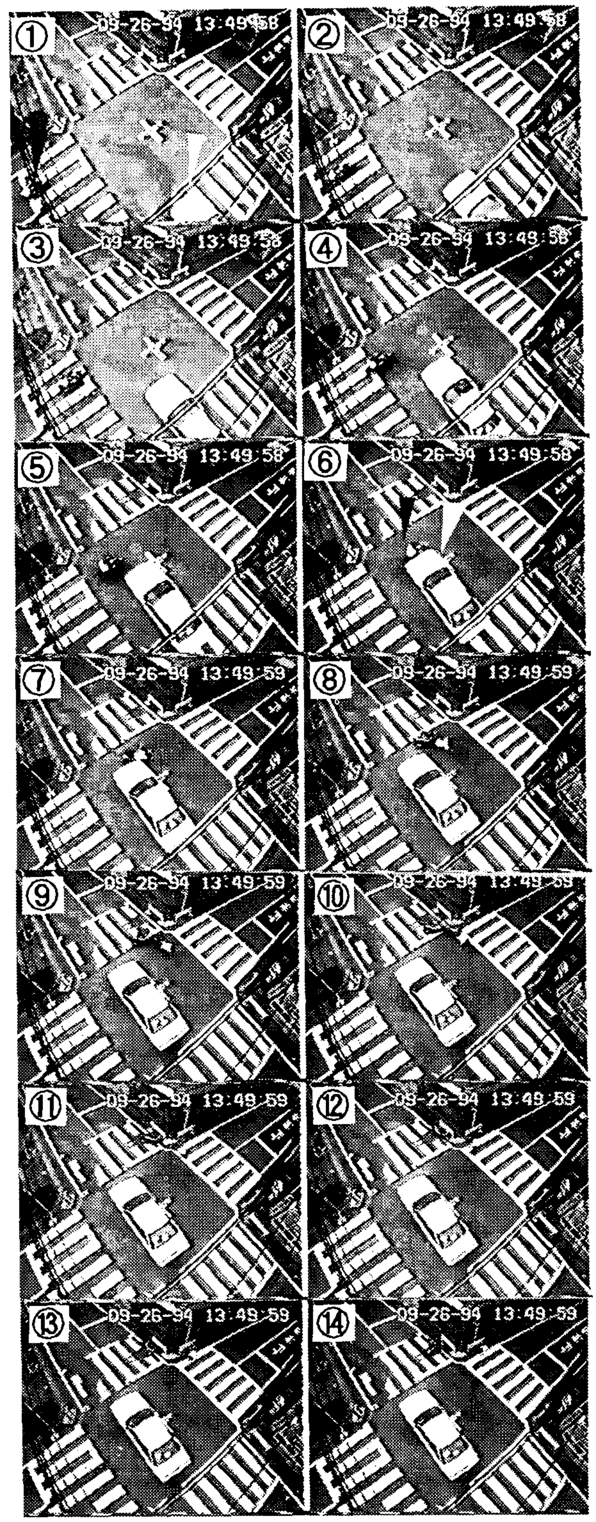

Fig.10 Accident Scene recorded by TAAMS.

Case No.6 - A moped and a wagon typed one box car collided each other in the intersection as shown in Figure 3-b, at midnight while they were passing. Fig.12 shows the accident scene. The moped collided with the wagon on the left-side front and the moped rider was hurled against the street.

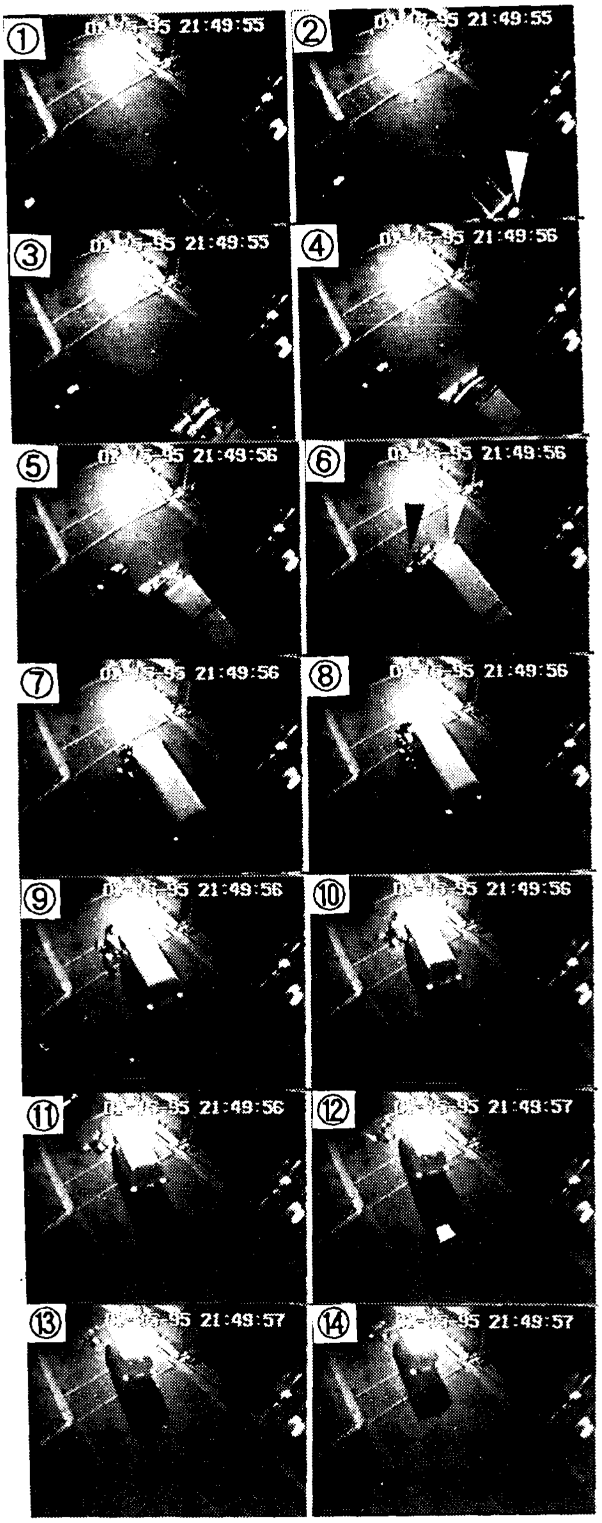

Fig.12 Accident Scene recorded by TAAMS.

Fig.13 illustrates the speed changes of the moped and the wagon. The moped entered the intersection as the speed of approximately. 35km/h without making a halt. The moped was slightly decelerated just before the collision. The wagon entered the intersection at the speed of approximately 40km/h and was quickly braked (approx. 0.7g) immediately after the collision. The moped rider was seriously injured, suffering a bruise on the head, a sprain in chest and a fracture of a rib.

The analysis of the data suggests that both the moped and wagon car perceived each other just before the collision. The moped rider, absorbed in his thought (emotional stress: family and job), did not make a halt and deceleration before the intersection. The driver in the wagon insists that he believed the moped would make a halt because of traffic law. However, the traffic law say that when any vehicle on the right-of-way entering intersections should slowdown and check a safety.

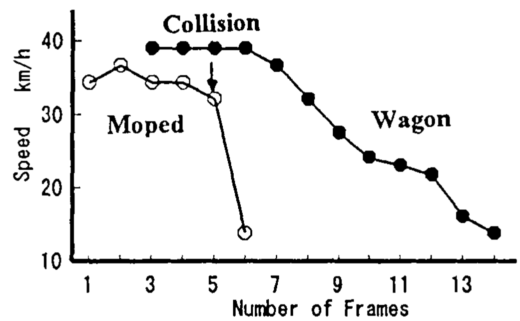

Fig.13 Vehicle Speed v. Frame Number.

MISJUDGMENT ON GAP DISTANCE - For the present, it may be useful to look more closely at one of the more important features of accident in uncontrolled intersections. It appears that many accidents happen frequently caused by misjudgment of gap distance (or including approach vehicle speed) at the intersections. It is difficult task to judge safe gap distance for approaching oncoming vehicle in the real world. In this section, three examples of accidents and near miss are illustrated to examine accident mechanism with relation to judgments of gap distance in some detail below.

Case No.7 - Figure 14 illustrates an accident scene recorded by TAAMS in the intersection as shown in Figure 3-a. A passenger car "Car A (Black) " in the roadway regulated with stop sing, entered at a low speed into the intersection after deceleration around stop marking, while passenger car "Car B (White)" in the right-of-way approaching to the intersection lately.

Figure 15 shows a result of speed analysis from the TAAMS pictures. Speed of Car A is increasing from at 15km/h to 20km/h after entering the intersection. Assuming that the driver of Car A judged a safe gap distance from his position to approaching Car B.

As a result an accelerative maneuver appeared in this situation as shown in Figure 15. On the other hand, since the driver of Car B recognized that the scene is unsafe, the brake was depressed (approx. 0.6g) for avoidance the dangerous situation.

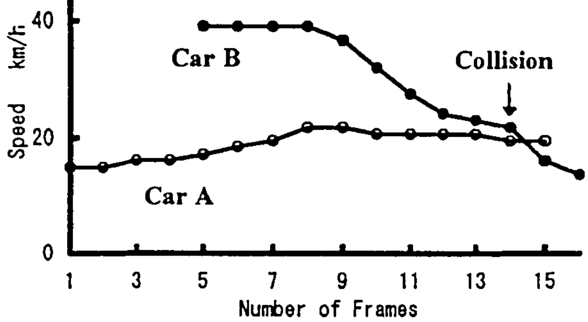

Fig.15 Vehicle Speed vs. Frame Number.

Figure 16 illustrates a frequency characteristic patterns analyzed the sounds collected from this accident. Emergency brake started at 1,100ms before impact against Car A, and it was working for the duration of 1,100ms. The scene of Frame No.1 in Figure 14 indicates the situation . The duration time of collision and tire skid time are approximately 300ms and 400ms, respectively.

Assuming that a los time for brake effect is 1 second, when the driver of Car A recognized unsafe situation on the process (Frame No.1), the location of Car B is approximately 20m ~25m from the intersection. Note the position of Car A in the Frame No.1, it is worth while examining the driver judgements more closely, for safety decisions under like these situations.

Fig. 14 Accident scene recorded by TAAMS.

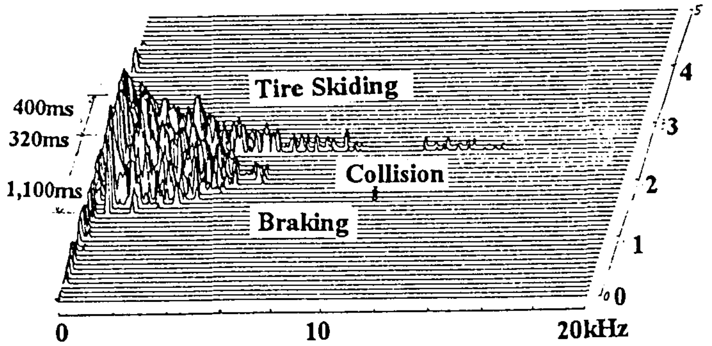

Fig.16 Frequency Characteristic Pattern.

Case No.8 - In the midnight, two taxies collided each other in the middle of intersection in Figure 3-a. Figure 17 illustrates the accident scene recorded by TAAMS.

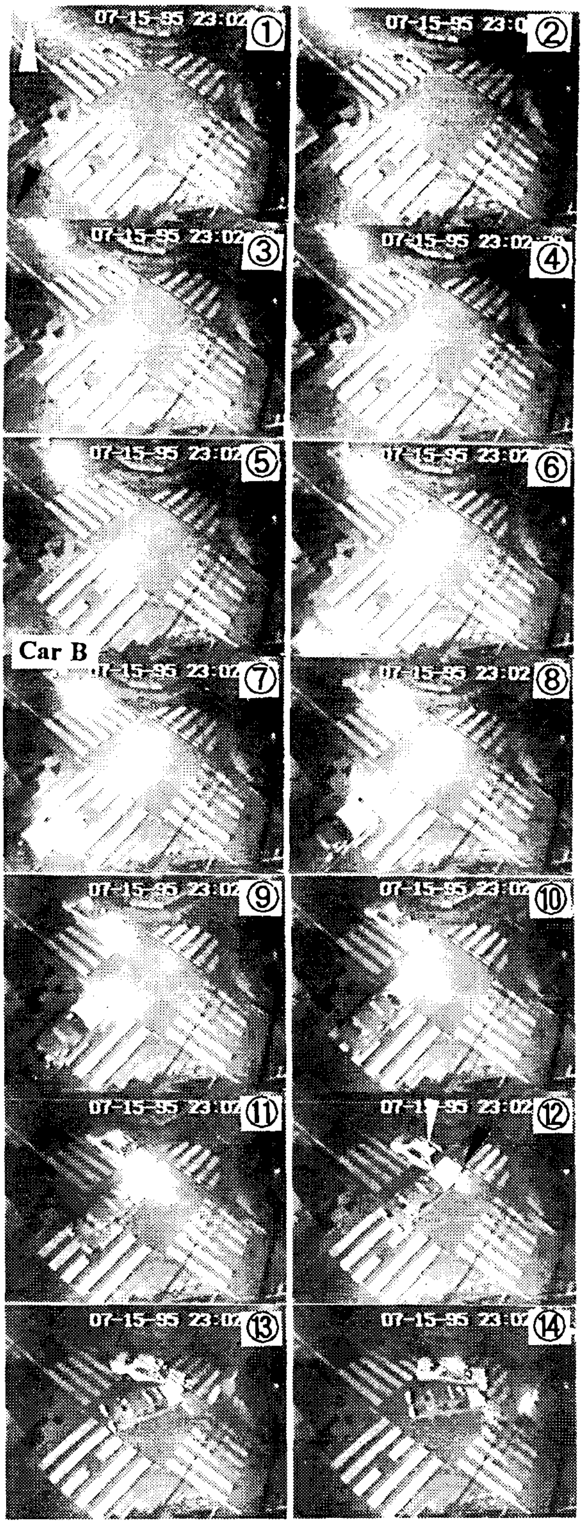

Fig. 17 Accident scene recorded by TAAMS.

One taxi "Car B" in the right-of-way was approaching to the intersection earlier than other taxi "Car A" can be seen in the some of the pictures beginning. Figure 18 shows a result of speed analysis from the TAAMS pictures. The Car A in the roadway with temporal stop mark, entered at a relative high speed of 45km/h constantly into the intersection, while speed of Car B in the right-of-way was 35km/h without deceleration.

In this situation, the driver of Car B judged to pass the intersection on safety. Two main reasons are inferred from this situation, i.e, one stems from his right-of-way, another rises from his cognition of gap distance. On the other hand, assuming that the driver of Car B recognized no approaching vehicle in midnight. As a result he drove the car at a speed of 45km/h without taking brake action. as shown in Figure 18. At least, the Car A should be slowdown before the intersection. If do that, this accident would be avoided.

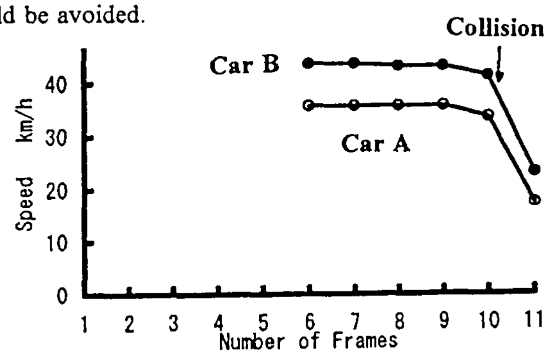

Fig.18 Speed vs. Frame Number.

For reference, a frequency characteristic pattern analyzed the sounds collected from this accident, is shown in Figure 20. Three times of collision occurred can be seen in the figure; first peak is due to main collision, next peak is second collision against sides of both cars each other, and last peak indicates impact against the fence of house.

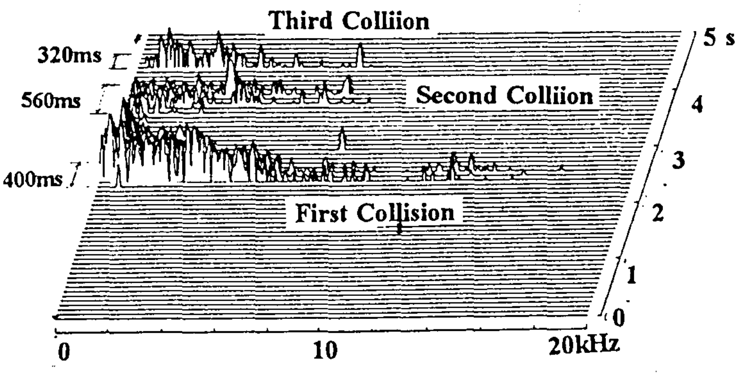

Fig.19 Frequency Characteristic Pattern.

Case No.9 - Fig.20 shows a near miss scene. A passenger car "Car A" was passed in the intersection after temporary stopped according to the law. Another passenger car (Car B) following approx. 3 meter behind Car A entered the intersection to turn right probably and nearly collided with a passenger car "Car C" approaching from right side on the crossing road.

Fig.21 illustrates the speed changes of vehicles The driver of Car B accelerated to enter the intersection, as if the safety was ensured by following the front Car A as shown in Fig.20. He/She applied brakes to make a halt the moment perceiving Car C. The driver of Car C found Car B approaching in front of his car and put on a sudden brakes just before the driver in Car B applied them.

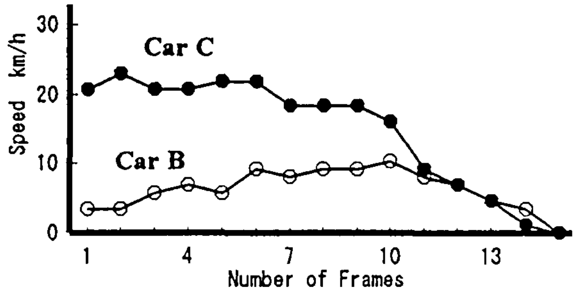

Fig.21 Vehicle Speed vs. Frame Number.

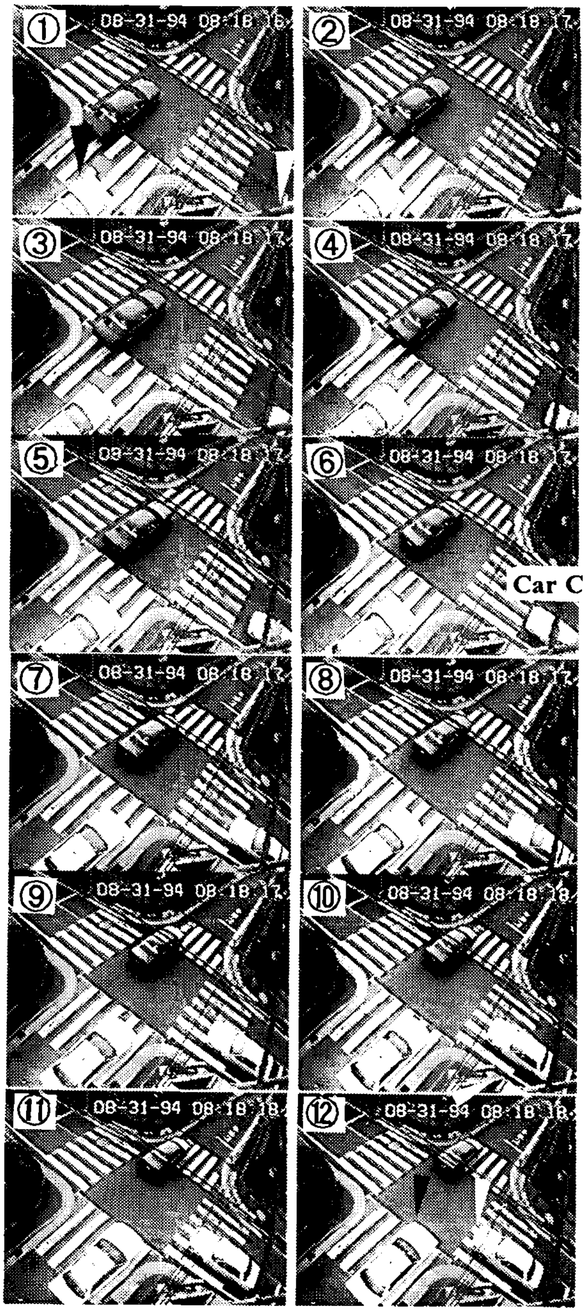

Fig.20 Near Miss Case recorded by TAAMS.

In these cases demonstrated previously, the main reason whether accident or near miss was depend on differences in driver vigilance levels associated with gap distance including approaching speed. From the engineering of view, it is due to brake capacity, i.e., choice of speed, on which can be stopped the car on safety. There is not remarkable difference of approaching speeds in three cases among Case No.7, Case No.8 and Case No.9 as shown in Figure 16, Figure 19 and Figure 22. The speed of approaching vehicles are approximately 30km/h, 35km/h and 20km/h, respectively, which are almost equal the regulation speed 30km/h. In other words, these cases indicate what the regulation speed required 30km/h in this intersection is reasonable and appropriate.

DISCUSSION

Although so many traffic accidents occurred everyday in the world, few studies are reported from the view of preventing recurrence, while countermeasures against aircraft accidents are prepared quite promptly and systematically. There are two issues on the traffic accidents preventions. One is due to the limitation of an analysis and reconstruction conducted by physical evidences obtained from accident scenes. Secondary, there is no distinction between police investigation and preventive measures, which should be distinguished from each other accordingly to the aims. Police report tends to attribute an accident to merely individual human error as a "negligence", in a legal sense.

From a different standpoint, almost all of the traffic accidents including near misses have not been

recorded by any means. It differs from aircraft accidents with flight recorder. Therefore, we have only discussed what happened based on the evidence left the scenes, have still no information how and/or why the accidents occurred. The drivers involved the cases will be only asked driver behavior before and after collision without informed a fact and process of the accidents because any authority did not know them any more in the detail.

Many factors are associated with every traffic accidents. However, it is implausible that such factors could be due to individual human error on professional negligence. In the 1970's, two major studies in UK and in US, were performed to identify factors associated with large sample of crushes[3]. Rumer[4] summarized the results from both studies. The factors were classified into three categories such as road environment, road user and vehicle. When only one factors is identified, it is overwhelmingly the road user (65% in the UK study, 57% in the US study). The British study finds that road user factors are present as sole or contributory factors in 95%, the US study 94%. These findings are very important to understand the role of human factors on traffic safety.

In recently, however, we need more precis and detail human factors on safety issue, for example, the process of misjudgment in left turn in intersections. How to make misjudgment for a driver in individual situation including road environment factors?

Two accidents demonstrated in this paper concerning with gap distance to cross the intersections. The examples indicate that most drivers judge gap distance without approaching vehicle speed in the real world. Some similar data of accidents, and also near misses are recorded by TAAMS. At this present, we suggest that relative many intersection accidents happen caused by misjudgment of gap distance. Therefore, mechanism of both recognition distance and gap distance should be examined for countermeasure of the accidents unsignalized intersections.

In addition, suppose a head to side collision in intersection resulting from improper overtaking at too high speed occurred in previous mentions. What information we need to improve to the safety traffic environments is why he/she determine the high speed under specific conditions at the time. Some examples of accident and near miss collected by TAAMS are demonstrated in this paper. As few cases recorded by TAAMS are reported to police, most of the accidents are unknown in any authority. Consequently, few drivers involved the cases were interviewed in depth. More cases in different typed intersection are requested to analyze, and it is necessary to find common factors, in particular, human behavior inducing human error under certain situations, resulting from analysis of the TAAMS's data and interview in depth based on the them.

CONCLUSION

The TAAMS developed is an equipment to record real-time information on traffic accident all through the sequence of the occurrence including the situation before as well as after the collision. The TAAMS dramatically expands the volume of data available, enabling detailed investigation and analysis of the traffic accidents that used to be impossible.

Three misjudgment groups on drivers are demonstrated as concrete examples of misjudgments of drivers under certain situations. The detailed pictures of traffic accidents are also available for interview with the persons involved, giving them not only incentives to avoid recurrence of accidents but also suggestion how to avoid accidents.

ACKNOWLEDGMENTS

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REFERENCE

1) M.Ueyama, M.Koura, A. Kast and H.Tikasue, "Study on Traffic Accident Mechanism with UDS and TAAMS", presented at JSAE Conference, September, 1995. 9839941, pp.37-40.

2) M.Ueyama and M.Koura, "The Study of Traffic Mechanism in Intersection by TAAMS". Presented at 25th Symposium on Safety Engineering, 1995, pp.297-300, in Japanese, 1995.

3) L.Evans, "Traffic Safety and the Driver" Van Nostrand Reinhold, 1991. pp.60-95.

4) K. Rumar, " Human Behavior and Traffic Safety", New York, Plenum Press, pp. 151-165.

VEHICLE DEFECTS IN CRASHES - INDEPTH VEHICLE FACTORS STUDY

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Paper Number: 96-S9-O-18

ABSTRACT

This paper presents the preliminary results and research methodology of an in-depth study examining vehicle factors in crashes in New South Wales, Australia. Previous research projects have reported that defects are a primary causal factor in approximately 4% of crashes and may contribute to 13% and 24% of all crashes.

The Crashed Vehicle Study will examine the presence of defects and their role in crash causation and severity. 5000 vehicles from all categories will be examined. A comprehensive on scene and follow-up examination is undertaken of all vehicles involved in the crash. Examinations are conducted to specified guidelines to provide a consistent and objective approach to data recording and analysis.

Vehicle inspectors record all major and minor vehicle faults, and wherever possible objectively measure these faults. Faults will be analysed in terms of vehicle category, rural verses. urban, and component areas (i.e. steering, brakes, vision, etc).

Results to date are discussed in terms of comparison to crash statistics and achievement rates.

BACKGROUND

The purpose of various roadworthiness programs is to audit the maintenance of vehicles to ensure that they have been maintained in a fit condition to use the road system. Roadworthiness of a vehicle has implications for both road safety and the environment.

In Australia a variety of different programs are implemented both at a National and State level. The programs vary greatly between States and between light and heavy vehicles. Annexure 1 details differences between States in Australia for light vehicles and heavy vehicles.

The types of programs conducted by the New South Wales (NSW) Roads and Traffic Authority (RTA) are:

- Authorised Inspection Schemes.
  Used for annual inspections on light vehicles. Inspections are performed by private workshops, usually petrol station mechanics, who are audited by the RTA.
- Heavy Vehicle Inspection Schemes.
  Inspection for heavy vehicles conducted by RTA Inspectors.
- New Vehicle Inspection Schemes.
  Conducted by private workshops who are audited by the RTA.
- Regional Targeted Enforcement Programs.
  Targeted random enforcement programs conducted by RTA Inspectors.

The above inspection schemes are estimated to cost the NSW community in the order of $130 million per year. This consists of RTA costs of $28 million (RTA), community costs $56 million and repair costs $49 million (if an average of $20 per vehicle was spent on repairs to pass inspection)

Compared to a State like South Australia, which has minimal inspection programs, it could be said NSW has very rigid inspection programs. The South Australian inspection program is virtually non existent for light vehicles. The concern for regulators is, it is not currently known if South Australian vehicles have more crashes caused or contributed to by defects than a State like New South Wales. It is known, when adjusted for age and category that, South Australian vehicles have the most defects, when inspected during transit through NSW. It is also a concern that NSW does not at present accurately know the contribution of defects to crashes, because police mechanical inspectors do not examine the majority of vehicles involved in crashes.

A current trend in Road Safety in Australia is towards national uniformity of road rules, vehicle regulations, etc. This includes vehicle roadworthiness. Work is currently being conducted to have uniform standards for maintenance of vehicles. Deregulation of the "industry" is also being trialed. This will change the governments' role from being a "regulator" to an "auditor/monitor".

PREVIOUS STUDIES

Two previous studies in Australia have provided some information on the contribution of vehicle/mechanical defects to crash causation. These are the in-depth studies conducted in Adelaide, South Australia, between 1975 to 1979 (McLean) and Sydney, New South Wales, studies conducted in the late 1970's. The Adelaide study found:

1. 1% of crashes with defects that were highly causative,
2. 5.4 % where defects were possibly causative,
3. Proportion of cars with one or more defects increased with age, and
4. Reporting of defects was poor by Police.

The Sydney studies found approximately 1% of light vehicle crashes were caused by vehicle defects and 10-50% of heavy vehicle crashes were significantly contributed to by defects. (Personal Communication)

International studies have reported that defects are a primary causal factor in approximately 4% of crashes and may contribute to 13% and 24% of all crashes (Paine).

Pilot Study

In 1992 the RTA initiated a review of the conduct and effectiveness of it's Vehicle Inspection Program. As part of this review, it became clear that a study investigating the presence and role of defects in vehicles involved in crashes would be needed. It had been almost 20 years since the last in-depth study which researched this point, had been conducted in NSW.

A pilot study was initially conducted to review Inspection Methodologies, Notification Systems and Inspector Training Requirements. During the pilot study 72 crashes were attended, and 110 vehicles inspected. The pilot scheme identified:

- Logistical Problems
- Form requirements and layout,
- Training,
- Notification issues, and
- The need to move away from the defect grading system currently in use.

The need to minimise variability of classification and grading of defects from different inspectors was essential.

THE STUDY METHODOLOGY

Ryan et al reviewed in-depth accident studies to determine what contributes to a successful in-depth crash investigation study. He made the following recommendations;

- Aims and objectives are clearly defined,
- Clearly defined sample and sampling method,
- Theoretical basis (explicit or implied) for identifying the data to be collected,
- Quality control at each phase,
- Use of standardised coding systems, and
- Analysis best done by those directly involved in the study and have appropriate qualifications and be motivated.

Throughout the preparation and conduct of this study the above recommendations have been adhered to.

Sample

The Crash Vehicle Study (CVS) is being conducted to assist in developing strategies and programs. As such it needed to be representative of all vehicles involved in crashes in NSW, and allow for comprehensive analysis of these vehicle categories.

A crash for the purpose of the study was defined as one in which Police are required to attend. The criteria for this in NSW is:

- A person is killed or injured
- Over $500 damage to property
- One of the parties failed to stop
- One or more of the drivers was reported to be under the influence of alcohol or other drug.
- One or more of the vehicles was required to be towed away.

A statistical analysis of the 1992 and 1993 records of the RTA's Crash Database was used to determine the vehicle type and regional quotas. NSW has over 50,000 crashes each year, in which a casualty occurs or a vehicle is towed away (RTA 92-94).

When developing this sample criteria, there were some vehicle categories in various regional areas, which could not have provided an adequate sample size to enable any significant analysis of results. A modification was required to the sample to allow for a weighted analysis. To determine the weighting's, crash statistics collected via the current Police reporting systems were used to establish the ratio estimation sample rate.

Table 1 indicates the sample size required to be representative of the crash statistics, for both vehicle types and location, and provide adequate numbers for analysis.

Table 1
Study Quotas

	Syd.	South	North	West	TOTAL
Buses, Coaches	75	30	30	15	150
Heavy Articulated	125	50	50	25	250
Heavy Rigid	175	70	70	35	350
Motorcycle	250	100	100	50	500
Light Commercial	625	250	250	125	1250
Light Vehicles	1250	500	500	250	2500
TOTAL	2500	1000	1000	500	5000

The sampling method is a targeted random sample. The less involved vehicle categories (bus, coaches, etc.) are required to receive high priority, as they are relatively rare events. Crashes are randomly selected by the inspectors attending the first crash they are notified of by the police after the inspectors come on duty. The inspector's are then classified as unavailable whilst inspecting a crash. At completion of a crash investigation, the inspectors are then available for the next crash.

Vehicle Inspectors.

The RTA has two type of inspectors, technical and non-technical. The major difference is that the technical inspectors are qualified mechanics.

The inspectors are trained to enforce vehicle condition regulations. This includes random on-road enforcement of regulations for public and commercial vehicles, auditing of private inspection stations, and occasionally of heavy vehicles involved in crashes. The on-road enforcement includes driving hours, weight of loads, dimensional compliance and mechanical roadworthiness.

To train the inspectors for the study they were put through a three day training course. The course involved:

- Hands on, objective inspections of crashed vehicles,
- Procedures for completing report forms,
- Crash investigation overview,
- Crash cause analysis
- Photography,
- Exercise programs and diet advice for good health for shiftworkers, and
- Introduction to trauma counselling.

Emphasis was placed on the need to change from an enforcement mode of thinking, to a more research scientific mode. The under lying theme of the course was the need for an objective and detailed inspection.

To date over 200 inspectors have been trained in 9 training courses. They come from all parts of NSW and are called into the study as required.

Notification

Police in NSW do not record where vehicles are being towed for repair. Hence, it is critical that inspectors attend the site before the vehicles are towed away. On site attendance provides the inspectors with the opportunity to immediately inspect vehicles that can be driven away, and to record details of any repair yard that vehicles will be towed to. This enables Post-Crash inspection of vehicle to be conducted without the pressures to move vehicles to re-open roads.

To achieve early notification of crashes, two primary modes of notification have been established. The first is the inspectors receive direct notification through the Police Radio Network. They are supplied with Police Radios and are called simultaneously with Police Units. An adaptation to this has been to constantly scan the Police Network with Radio Scanners and act on Police calls. This later system is primarily used in major metropolitan areas, when RTA inspectors are rostered on-duty.

The second notification system communicates via pagers. Police Radio Control Room, pages inspectors upon the occurrence of a crash. The inspector then contacts the control room and is advised of crash details and location. This system is used in country areas and when inspectors are "on-call", but off-duty.

Inspection Methodology

Throughout the vehicle inspection, emphasis is placed on objectivity of measurements. To assist, the inspectors are provided with a comprehensive tool kit, allowing removal of vehicle components and measuring of any movement. Annexure 2 itemises this kit.

Components inspected have been categorised into the following areas,

- Driving controls
- Seats, seat belts & airbags
- Lighting and wiring
- Windscreen & Windows
- Body Condition
- Towing devices, couplings and loading
- Engine, driveline, fuel systems & exhaust
- Steering, Suspension, wheels and tyres
- Brakes
- Modifications

The vehicle is inspected to assess its pre-crash condition. Failures of safety equipment during the crash phase are also recorded.

The inspector is provided with five options when observing a component:

N/A = Not Applicable

N= No fault

F = Fault.

U = Unable to inspect.

I = Indeterminable

The "unable to inspect" is used in cases where the crash damage makes it impossible to determine any pre-existing conditions. "Indeterminable" is used when a fault is found, but the inspector is unable to determine if it existed prior to the crash or because of the crash.

Inspectors are required to record ALL vehicle faults, as well as measure any movement in components, even if movement is within manufacturers tolerances.

The inspectors then describe the fault in detail. An example of the form and the inspection requirement is shown in Figure 1. Separate books are used for Light vehicles, Heavy vehicles, Buses/Coaches and Motorcyclists.

A1.1	**Steering Wheel**	**F/I/N/U**	
A1.2	Rot. Freeplay	F/I/N/U	47 mm
A1.3	S/Wheel Dia.	F/I/N/U	375 mm
A1.4	Spline Movement	F/I/N/U	2 mm
A1.5	Insecure	F/I/N/U	
A1.6	Rim broken	F/I/N/U	
A1.7	Spoke broken	F/I/N/U	
A1.8	S/Wheel bent	F/I/N/U	
A1.9	Sharp edges	F/I/N/U	
A1.10	End Float	F/I/N/U	

Fault Code - *A1.2 & A1.4*
Describe the Fault: *Rotational freeplay at the steering due to a combination of wear between the steering shaft spline and steering wheel splines (2mm) and rotational freeplay in steering box (45mm). Total freeplay at steering wheel 47mm*
How did you detect the fault: *Found through normal inspection procedures*
How would this fault be graded under the current guidelines. **A/B/C/D Not App Unknown**

Figure 1: Example of inspection form.

To determine contribution to crash cause, and/or severity of any vehicle component, the inspectors are asked to record their observations and reasons for selection. This is the most critical, but subjective

component of the study. The inspectors therefore need to record reasons why they consider any fault has contributed to the crash occurrence, or increased severity.

Simplified photogrammetrical techniques are used to record interior and exterior of vehicles (Duignan et al). The inspectors take a standard set of photographs for each vehicle, regardless of the amount of damage. In addition to the standard set of photographs shown in Figure 2, site and macro photographs of faults are also taken. Photographs are stored on Photo-CD's which allow more detailed examination through photograph magnification when required.

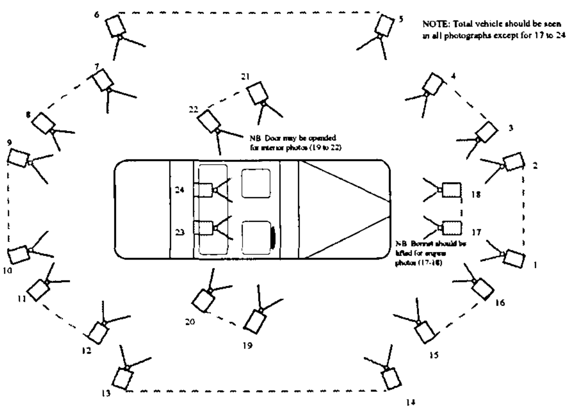

Figure 2: Standard photographs taken of a passenger vehicle.

Quality control has been built in at 4 stages of the project.

1. The means of data recording has been designed to guide the inspectors through every component of the vehicle. Every section must be completed.

2. Each form is reviewed by a central project inspector. The project inspector reviews the form for uniformity of inspections, data recording and conclusions. Discrepancies are discussed with the field inspector and corrected.

3. At data entry stage the forms are again reviewed from a non-technical perspective. The database has verification procedures incorporated to filter un-realistic data.

4. The project team accompany the inspectors to crashes at various stages of the project. This ensures consistent interpretation of the data, and identifies potential problems that may exist in data recording and coding.

Where possible standard coding systems have been utilised. Damage profiles are recorded using the SAE Collision Deformation Classification and the previously mentioned standard photographic procedures.

PRELIMINARY RESULTS

To date, 7.5% (224 crashes) of the sample quota has been investigated. These crashes involved 437 vehicles of which 90.2% (394) were inspected. The 43 vehicles were not inspected had either left the crash scene before the inspectors arrived, or refused permission to inspect.

Tables 2,3,and 4 shows the current achievement rates against crash statistics and quotas. Heavy trucks (articulated and rigid) are over-represented compared to the crash statistic. Passenger vehicles are similarly under-represented. This is acceptable when it is examined in terms of the sample quotas. These vehicles are relatively 'hard to get' and therefore require prioritisation in accordance with the weighted analysis the study sample has been designed for.

The study also has an over-representation of fatal crashes and an under-representation of non-injury crashes. This is due to Police not notifying inspectors of minor crashes that are cleared quickly.

The contribution of defects to crash cause and/or increased severity is not yet from a large enough sample to justify publication.

Table 2
Achievement rates
Vehicle Type

VEHICLE TYPE	STATISTICS (1994)	CRASH VEHICLE STUDY
Passenger Cars	82.1	64.5
Light Commercial	9.5	12.7
Heavy articulated	1.5	9.9
Heavy rigid	1.3	7.6
Bus or Coach	0.6	4.1
Motorcycle	2.5	1.3
Unknown	2.5	

Table 3
Achievement rates
Day of Week

DAY OF WEEK	STATISTICS (1994)	CRASH VEHICLE STUDY
Monday	12.6	14.3
Tuesday	14.7	19.7
Wednesday	13.8	20.2
Thursday	14.6	13.4
Friday	17.1	13.9
Saturday	15.8	10.5
Sunday	12.0	8.5

Table 4
Achievement rates
Crash Severity

DEGREE OF CRASH	STATISTICS (1994)	CRASH VEHICLE STUDY
Fatality	1.0	6.7
Serious injury	10.0	12.3
Other injury	28.5	34.3
No Injury	60.5	43.3
Unknown	n/a	2.9

CONCLUSIONS

The Crashed Vehicle Study is a critical component of the RTA's evaluation of vehicle defects and the role defects play in crash causation and injury severity. The study intends to:

- Provide information to assess effectiveness of current vehicle inspection programs,
- Provide information to develop guidelines on what should be inspected,
- Provide information to develop the strategic direction of Vehicle Inspection Programs, and
- Allow assessment of the role of uncertain vehicle features in crashes (eg. window tinting,, seatback strength).

Side benefits of conducting the study are:

- The development of formalised reporting and investigation systems, and
- Vehicle Inspectors trained and experienced in crash investigation.

ACKNOWLEDGMENTS

The authors which to acknowledge the input to the study by the RTA vehicle inspectors. It is their enthusiasm and constructive input that has assisted in making the study run smoothly and the data objective.

The Authors would also like to thank staff from Taverner Research Pty Ltd, who are assisting in project management, data entry and analysis.

REFERENCES

Duignan P, Griffiths M, Lie A. Photogrammetrical Methods in Crash Investigation, Experimental Safety Vehicles Conference, Melbourne 1996.

Mclean, A. Adelaide In-depth Accident Study, University of Adelaide, 1979.

Paine M, Contribution of Vehicle Defects to Crashes - Literature & Research Review. Report prepared for National Road Transport Commission, Australia, 1994.

Roads & Traffic Authority, Vehicle Regulation Strategic Review, Unpublished report, 1994.

Roads & Traffic Authority, Road Traffic Accidents in NSW - Statistical Statement, 1992, 1993, 1994

Ryan G A and Mclean AJ
A Reveiw of Indepth Crash Investigation; Report for Federal Office of Road Safety, Australia.

Annexure 1

Overview of light vehicle inspection requirements for different States in Australia

	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
Random Roadside	Taxis only	✓	✓	×	✓	✓	×	✓
Random with Notice	×	×	×	×	×	×	×	3-10 yrs
At Change of Ownership	✓	✓	✓	×	×	×	×	×
Annual	✓ > 3 yrs	×	×	×	Taxis only	×	✓ >3 yrs	✓ >10 yrs

Overview of heavy vehicle inspection requirements for different States in Australia

	NSW	VIC	QLD	SA	WA	TAS	NT	ACT
Random Roadside	✓	✓	✓	✓	✓	✓	✓	✓
Random with Notice	×	×	×	×	×	×	×	✓
At Change of Ownership	×	×	×	×	×	×	×	×
Annual	✓ buses (6 months)	Quality Scheme	✓ public (6 month)	× except special vehicle	× except special vehicle	× except special vehicle	✓ public (6 month)	✓ public (6 month)

Annexure 2

Crash Investigation Kit

TOOLS:

1 x tool box
1 X 3/4 in ULX bar & 1/2 adaptor
1 x 1/2 adjustable offset bar
1 x 1/2 driver ratchet
1 set open end/ring spanners
1 x 1/2 A/F socket 3/8 to 1-1/4
1 x 20 metric sockets 1 Omm to 32mm
3 x socket holder rack
1 x 8 in shifter
1 x 12 in shifter
1 set combination pliers
1 x diagonal wire cutter
2 x Phillip's screw drivers
3 x blade screw drivers
1 x medium ball pein hammer
1 set pin punches
2 x chisels (1 large, 1 small)
1 container of assorted split pins
2 x sample bottles for brake fluid
1 x syringe
1 x valve removing tool & spare valves
2 x china graph pencils
1 x compass
15 x loom ties
1 x spray bottle for LPG leak testing
1 x small podge bar
1 x 4way wheel brace
1 x large pinch bar

GENERAL EQUIPMENT
(Regionally Supplied):

1 x light meter (window tinting)
1 x light vehicle jack
1 x heavy vehicle jack
1 set light vehicle stands
1 x lay/creeper board

MEASURING EQUIPMENT:

1 x 8 metre tape measure
1 x 20 metre tape measure
1 x 150 mm (6in) steel rule
1 x 30 cm (12 in steel rule
1 x tread depth gauge
1 x rim width gauge
1 x 200 mm Vernier callipers
1 x brake pedal pressure meter (not in all tool kits)
1 x dial gauge and magnetic stand
1 x tri pod stand for dial gauge
1 x trailer king pin wear gauge
1 x trailer "ring fedder" type coupling wear gauge
1 x light vehicle tyre pressure gauge
1 x heavy vehicle tyre pressure gauge
1 x disc micrometer

MISCELLANEOUS:

Length of PVC tubing
Leather gloves
Stanley knife
Latex gloves
Disposable overalls
Safety glasses
Photogrammetry camera & equipment
Equipment canvas carry bag
Bottle of brake fluid
Pencil sharpener

METHODOLOGICAL FRAMEWORK FOR PRIMARY AUTOMOTIVE SAFETY : SYSTEM SAFETY APPROACH FOR THE DETERMINATION OF CRITICAL SCENARIOS

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ABSTRACT

The purpose of the research presented in this paper is to provide a methodological framework for primary automotive safety. The methodology proposed is based on a systemic approach of driving and follows the principles of System Safety Analysis. The paper first covers the general concepts involved in the approach. A Generic Driving Model is proposed and the notions of Operating Range and Accident Mechanism are explained. An Accident Typology and a Classification of Safety Systems are provided on the basis of these notions.

A method for the Determination of Critical Scenarios encountered in automotive driving is then proposed. This method first requires a qualitative modeling of the operation of the driver-vehicle system in a given driving phase. The different possible failures are then deduced from this model which leads to a Qualitative Failure Model. Finally, the malfunction probabilities must be quantified using In-Depth Accident Investigations and Driving Simulator Experiments. The Quantified Malfunction Model obtained can be used for Specification and Probabilistic Safety Assessment of crash avoidance systems.

INTRODUCTION

Several studies conducted on the limits of secondary safety have proved that approximately half of car occupants fatally injured in car accidents could be saved only by means of primary safety (Thomas 1990). In order to provide better safety, car manufacturers have developed driving assistance and crash avoidance systems. These systems were mainly designed on the basis of the driver needs that were established from general statistical studies (macro-accidentology). However, meeting those requirements is necessary but undoubtedly insufficient. The specification and safety assessment of crash avoidance systems requires a thorough analysis (micro-accidentology) of the malfunctions which occur in critical situations - accidents and near misses. The research presented in this paper is aimed at providing a methodological framework for the study of critical scenarios encountered in automotive driving. This research fits within the frame of *Specification* and *Probabilistic Safety Assessment* of crash avoidance systems. The paper first covers the System Safety Concepts on which the approach is based. A method for the Determination of Critical Scenarios is then proposed.

SYSTEM SAFETY CONCEPTS

<u>Driving Model</u> - Driving can be considered as the operation of a man-machine system in an environment (see figure 1). The operation of the driver-vehicle system in the road infrastructure and the traffic, going from one location to another, can be considered as a *mission*. This mission breaks down into different *driving phases* each one being defined by a unique general driving objective - 'intersection crossing', 'left turn at intersection', 'cornering', 'overtaking' for instance. Each phase can be divided into distinct *driving sub-phases* having its own unique elementary objective - for 'cornering', the sub-phases are the 'approach' for which the elementary objective is the adjustment of the speed, and the 'negotiation' of the bend, for which the elementary objective is to keep the vehicle in the curved lane.

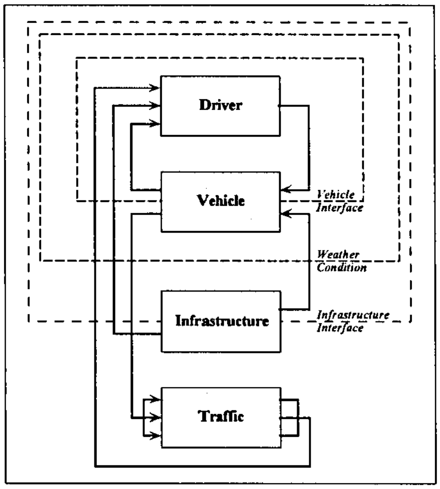

Figure 1. Interactions and Interfaces.

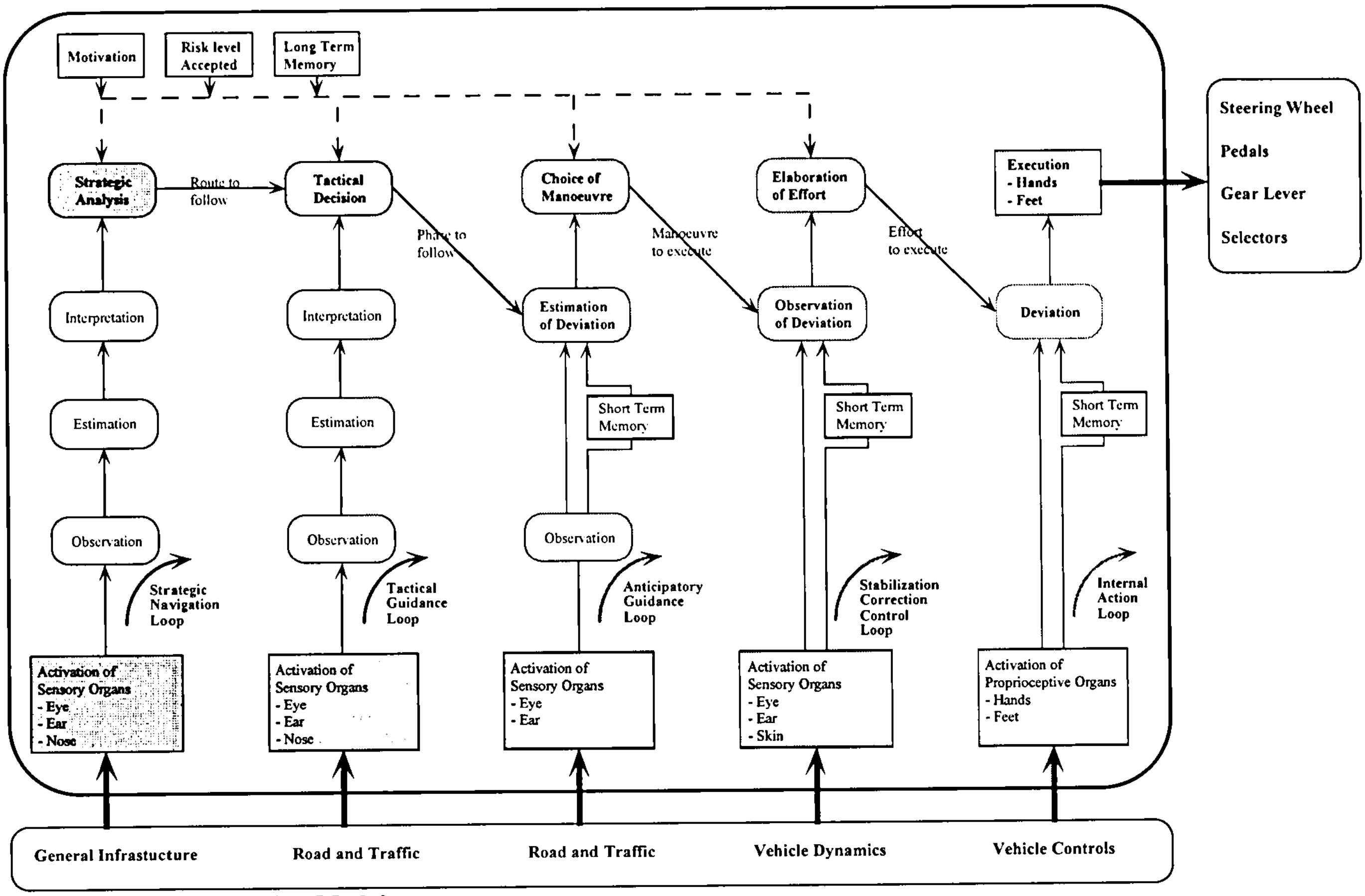

Figure 2. Generic Driving Model.

Since each phase has a different driving objective, driving tasks significantly depend on the current phase. In order to provide good coherence between analyses of driving conducted on phases, such analyses should rely upon a single general functional model of driving. This model should take account of the different task levels as those pointed out by Allen (1971) and Michon (1985) : *navigation* (strategical planning), *guidance* (tactical maneuvering) and *control* (operational control). These levels actually relate to the notion of long term, short term and immediate safety loops defined by Lievens (1976) in the scope of aeronautical system safety. Moreover, in order to support driving failure analysis, this model should also include the human processing functions similar to the mental activities identified by Rasmussen (1987). Since no such model was available, a *Generic Driving Model* was developed within the frame of the research presented herein. This model is proposed in figure 2. Meeting the previous requirements, it is thus a hierarchical control and cognitive process model of driver behavior. The functions involved in the different loops of this model are those activated by an experienced driver in an unfamiliar situation. Shortcuts may occur in familiar situations and additional functions may be necessary for inexperienced drivers, depending on the actual level of behavior activated (knowledge, rule or skill based).

The *strategic navigation loop* consists in planning the route that must be followed to complete the mission and is usually knowledge-based.

The *tactical guidance loop* consists in identifying or choosing the driving phase that must be followed (in accordance with the route planned) and is generally either knowledge-based or rule-based. Since its purpose is to fulfill the mission objective, it is a long term safety loop.

The *anticipatory guidance loop* consists in choosing the maneuver that must be executed within the driving phase (in accordance with the objective of the identified phase) and is generally rule-based. Since its purpose is to fulfill the phase objective, it is a short term safety loop.

The *stabilization control loop* consists in elaborating the effort that must be executed in order to achieve the maneuver. It is usually skill-based and is an immediate safety loop.

The *internal action loop* controls the effort applied to the vehicle controls.

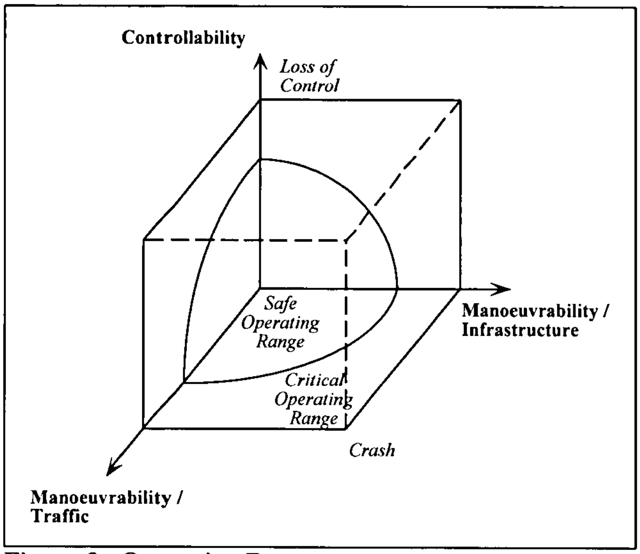

Figure 3. Operating Range.

<u>Operating Range</u> - In general, it is possible to define the *operating range* of the driver-vehicle system - this system being in a nominal state (see figure 3). Within this research, the operating range is defined according to two kinds of operating parameters : controllability parameters and maneuverability parameters. *Controllability* parameters are those involved in the control task (dynamic parameters as longitudinal and lateral acceleration for example). Their limit in the operating range relates to the dynamic stressing limits of the vehicle in relation to the driver's skills. The notion of *internal safety* has been introduced to designate the control of these parameters because it is independent of the traffic. Internal safety therefore consists in reducing the risk of loss of control. *Maneuverability* parameters are those involved in the guidance task (kinematic parameters as lateral position in the lane and distance from the preceding vehicle for instance). Their limit in the operating range relates to the trajectory of the vehicle in relation to its environment (infrastructure and traffic). The notion of *external safety* has been introduced to designate the control of these parameters because it is relative to the external environment. External safety therefore consists in reducing the risk of collision with obstacles (vehicles or fixed obstacles). Since the guidance task is relative to both the infrastructure and the traffic, maneuverability parameters are further divided into two classes : *infrastructure related maneuverability* parameters and *traffic related maneuverability* parameters.

The operating range defined on the basis of these two kinds of parameters divides into a *safe range* and a *critical range*. The controllability critical range corresponds to a higher risk of loss of control and the maneuverability critical range to a higher risk of collision. An excursion outside the controllability critical range will cause a loss of control which will increase the risk of collision thus the probability of exceeding the limits of the maneuverability safe range. Internal and external safety are therefore not completely independent.

<u>General Accident Mechanism</u> - The operation of a driver-vehicle systems in the infrastructure and traffic environment may result in an accident through a combination of factors, causes and events. As widely accepted, the breakdown of accidents into pre-crash, crash and post-crash phases leads respectively to the *primary*, *secondary* and *tertiary* safety notions, in terms of accident avoidance, mitigation of the injuries, and rescue. As this study deals only with primary safety, the pre-crash phase was further divided into *pre-conflict* and *conflict* sub-phases. The former refers to the situation of driver-vehicle systems before the appearance of visible elements of danger. The latter refers to the critical situation generated by visible elements of danger that drivers have to cope with in order to avoid the crash. The description of the pre-conflict sub-phase amounts to the description of the state of the system before the accident and will be essentially static. As regards the conflict sub-phase, since it is a dynamic phenomenon, its description must include the time-history of operating and interaction parameters.

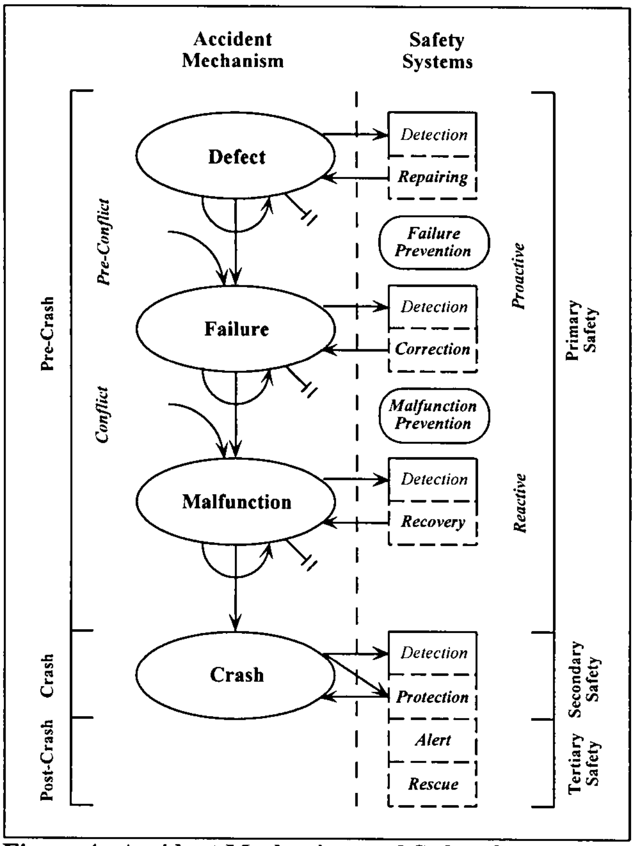

Figure 4. Accident Mechanism and Safety Systems.

Within this research, an accident is considered as a malfunction mechanism leading to the deviation of the operating point of driver-vehicle systems outside their operating range. This general mechanism is described in figure 4. It generally originates from one or more *defects* of the drivers (vision problem for example), vehicles (underinflation...) or road infrastructure (insufficient grip...). This defect may remain latent, may be repaired or may cause a *failure* (bad vision of the lane, tire blow out...) - vehicle and road environment failures may also be considered as disturbances. The failure may then lead to a *malfunction* (loss of control, bad lateral position in the lane...) or may be corrected. This malfunction is an excursion outside the safe range. Unless a recovery maneuver succeeds in returning the system to its safe range, this malfunction may result in a *crash* - an excursion outside the maneuverability operating range. In some cases, the first stages of this general mechanism are bypassed : many accidents are not caused by a defect but directly originate from a failure (failure to yield for instance).

Accident Typology - The general accident mechanism presented above provides a basis for two accident typologies referring to the conflict sub-phase. Both of them apply to each driver-vehicle system implied in the accident. The first relates to the kind of failure involved in the mechanism whereas the second relates to the type of malfunction induced by this failure.

The *failure based typology* differentiates accidents on three distinct criteria (which may combine) : pilotability, maneuverability and sensibility to disturbance (see figure 5). It is adapted from a classification used in the scope of aeronautics which is described in Wanner 1969, Wanner 1981 and Lievens 1976. *Pilotability* accident are those for which the maneuver carried out by the driver made the system leave its operating range, whereas another possible maneuver would have avoided such a deviation. This category especially groups accidents due to human error (failure to yield, overspeeding...). *Maneuverability* accidents are those in which no 'normal' maneuver could have kept the system in the operating range. This definition is actually different from the one proposed by Wanner and Lievens because it excludes elaborated emergency maneuvers which are in fact beyond the ability of common drivers. An accident with another vehicle which is visible too late belongs to this category. The *sensibility to disturbance* class is divided into two sub-classes. The first concerns cases for which a disturbance induced a *projection* of the system out of its operating range (tire blow out, lateral wind...). The second applies to cases for which the disturbance induced a *reduction* of the operating range (brake system failure, grip reduction...). In both of these sub-classes, the disturbance may be *internal* (vehicle failure) or *external* (environment failure).

The *malfunction based typology* proposed herein relates to the way the driver-vehicle system left its operating range. It relates to the extent to which the controllability safe range was exceeded. Accidents for which the failure initially resulted in a loss of control are called *control* accidents (involving internal safety). Accidents for which the failure generated a bad trajectory, with no loss of control, are called *guidance* accidents (involving external safety). As for maneuverability parameters, *infrastructure related guidance* accidents and *traffic related guidance* accidents are distinguished.

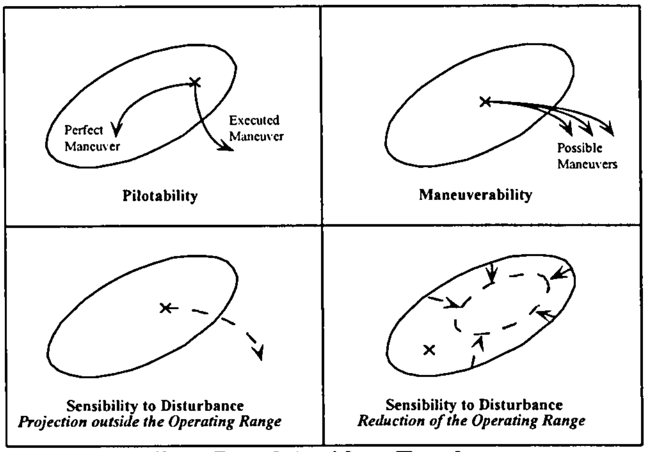

Figure 5. Failure Based Accident Typology.

Classification of Safety Systems - The common active and passive safety classification will not be used here because these notions have often been misinterpreted. This classification actually refers to the extent to which a certain measure requires the activity of the operator in order to be effective (Anderson 1995). Active safety, which refers to measures requiring the driver's intervention, has been incorrectly used instead of primary safety and passive safety, which concerns measures independent of the driver's activation, has been incorrectly used instead of secondary safety. Therefore, the primary, secondary and tertiary classification will be preferred herein.

The general accident mechanism described above provides a basis for the classification of primary safety systems. The classification proposed here refers to the step of the accident mechanism on which systems operate in order to stop this mechanism (see figure 4). The following systems are thus distinguished :

- *defect repairing* systems which detect defects in order to have them repaired (Underinflation Monitoring...),
- *failure prevention* systems which are constantly activated in order to prevent failures (Interactive Road Signaling, Vision Enhancement, Drowsiness Alarm...),
- *failure correction* systems which detect failures in order to have them corrected (Overspeed Alarm, Obstacle Detection, Grip Monitoring...),

- *malfunction prevention* systems which are constantly activated in order to prevent malfunctions (Autonomous Intelligent Cruise Control for instance, Lane Keeping...), making the driver-vehicle system respect safety margins, keeping it in the safe range and thus preventing it from approaching the limits of the operating range,
- *malfunction recovery* systems which detect malfunctions in order to improve a recovery maneuver (Anti-lock Braking System, Dynamic Vehicle Control), assisting the driver when the vehicle is in the critical range in order to return to the safe range and avoid reaching the limits of the operating range.

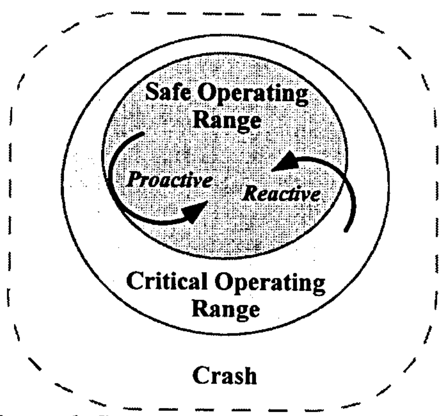

Figure 6. Proactive and Reactive Systems.

The malfunction plays a specific role in the accident mechanism : since it refers to the actual deviation of the driver-vehicle system outside the safe range, it can be considered as a risk exposure. Thus, on the basis of a typology defined by Catalano and Dooley (1980) in the scope of public health, a classification of primary safety systems focusing on their activity in relation to the malfunction is proposed here. This classification differentiates *proactive* systems which are designed to limit the exposure to risk from *reactive* systems aimed at improving the reactions when the risk exposure has taken place (figure 6). Thus, defect repairing, failure prevention, failure correction and malfunction prevention systems are proactive. Malfunction recovery systems are reactive.

DETERMINATION OF CRITICAL SCENARIOS

The specification and the safety assessment of crash avoidance systems require quantitative data about the pre-crash phase. Many statistical studies have been conducted on causes and factors involved in car accidents. However, these studies were mainly carried out on static parameters and provide little information on the conflict sub-phase. The research presented here focuses on the failures and malfunctions occurring in the conflict sub-phase. A method for the determination of the *critical scenarios* has been developed within this frame. It is based on a three-step analysis and must be conducted for each driving phase. It has already been applied to two different phases : 'intersection crossing' (involving mainly external safety) and 'cornering' (involving both internal and external safety). This method is proposed hereafter.

Nominal Scenario - The method first requires a qualitative modeling of the operation of the Driver-Vehicle system (with no crash avoidance devices) for the given driving phase with a pre-defined environment. This analysis must be conducted for each driver-vehicle system involved in the scenario. Different types of infrastructure and traffic configurations can be studied in the same scenario as long as the driving tasks are compatible. The determination of the *nominal scenario* consists of the identification of the driving tasks and the determination of the vehicle operating range. For each sub-phase, the *driving functions* required by the tasks are identified according to the Generic Driving Model. They are listed in a Phase Driving Model. Table 1 gives a simplified example for a driver with right of way in an 'intersection crossing' phase - another model has been developed for the non right of way driver. This functional model is still cognitive and qualitative. Although the driving activities are organized in loops, it is possible to represent driving functions in functional sequences. These sequences are based on the 'perception - estimation - interpretation - decision - action' scheme. In real driving situations, these sequences may be repeated several times with a different result each time. Since navigation is a mission level task, it is not taken into account in the analysis. Although this model is mostly oriented towards the guidance task (external safety), it also includes some elements of the control task (internal safety). Since the model must be as general as possible, driving functions relating to the recovery maneuvers must also be included.

Qualitative Failure Model - Within this second step, the method consists in identifying the different failures which may occur in the driving phase (still considering each driver-vehicle system involved). They are deduced from the Phase Driving Model by a qualitative a-priori analysis conducted on each driving function (driving failures) and on the possible vehicle response (vehicle failure modes). This results in a *Qualitative Failure Model.*

Table 1.
Simplified Phase Driving Model
'Intersection Crossing' Phase - 'Driver-Vehicle' with Right of Way

Intersection	Driver (with right of way)					*Vehicle*
Sub-Phase	**Perception**	**Estimation**	**Interpretation**	**Decision**	**Action**	***Response***
Approach *(Sequence)*	Intersection Signs		Right of way - Right of way - No right of way	Maneuver - Brake - Slow down - Continue - Speed up	Action - Braking - Throttle off - Continuation - Acceleration	*Response* *- Braking* *- Deceleration* *- Continuation* *- Acceleration*
Negotiation *(Loop)*	Other vehicle	Speed of other vehicle	Safety level - Safety state - Risk state - Danger state	Long. Maneuver. - Brake - Slow down - Continue - Speed up	Long. Action - Braking - Throttle off - Continuation - Acceleration	*Long. Response* *- Braking* *- Deceleration* *- Continuation* *- Acceleration*
				Trans. Maneuver. - Swerve	Trans. Action - Steering	*Trans. Response* *- Swerve*

Within this method, *driving failures* are defined as variations in the driving tasks leading to an excursion outside the safe range. This variation can be due to a driver internal failure (human error) or to a physical impossibility of achieving the task (in case of bad visibility for instance). The former refers to pilotability accidents and the latter to maneuverability accidents. As examined by Leplat and Rasmussen (1984), the study of human error requires the identification of human behavior variation in terms of internal behavior. Many comprehensive typologies of human errors have been developed in the scope of cognitive science (Leplat 1985, Rasmussen 1987, Reason 1990, Anderson 1995). However, the specification and safety assessment of crash avoidance systems requires a detailed analysis of the driving functions that a safety system could possibly handle. Therefore, within this objective, failures have to be described in relation to driving functions : driving failures will herein be considered in terms of variation between the internal functions required by the task (and defined in the Phase Driving Model) and the actual processing of the driver.

The method therefore consists in considering the failures that may occur in each function of the Phase Driving Model. Each single function must be studied separately and sequentially in terms of possible failure. Within the analysis, at least three types of failure are considered :
- non achievement of the function,
- late achievement of the function,
- incorrect or inadequate achievement of the function.

In other studies (Treat 1979, Malaterre 1985 and 1990), a similar failure analysis was carried out, but it was conducted at a more general level (for a general driving situation, with no specific phase given) and therefore addressed general function categories rather than elementary functions themselves.

The different mechanisms which may lead to the identified failures must also be taken into account. Many classifications also exist for these mechanisms. However, due to the difficulties of identifying the mechanisms involved in real accidents, only general kinds of mechanisms are taken into account within this research :
- unavailability of the information (visibility mask...),
- inactivation of the driver (inattention, distraction...),
- internal error (dealing with other driving task, panic...),
- risk taking.

As explained by Leplat and Rasmussen (1984), internal function failures and error mechanisms cannot be directly observed but must be inferred from characteristics of the task and the external manifestation of error. The guidance task being essentially rule-based on the basis of a short duration, it is quite impossible to determine whether a delayed action stems from a retarded estimation, interpretation, decision or from the retarded execution of the action itself. In this research, delays have thus been attributed either to the perception or to the interpretation function. As a consequence, categories for both types of failure and failure mechanism do not all apply to all driving functions ('unavailability of the information' class also only applies to perception and estimation functions).

As regards vehicle failures, it is well known that such failures are uncommon in accidents. Thus, the proposed method more generally focuses on a qualitative description of the possible *vehicle failure modes* (effects of defects and failures on the vehicle functions) in order to take account of any kind of sensibility to disturbance accidents. The vehicle failure modes are listed in terms of possible vehicle response to the driver's actions. The failure may originate from an internal disturbance (vehicle failure) as well as from an external disturbance (environment failure or defect).

Table 2.
Example of Pre-Crash Table
'Intersection Crossing' Phase

<>	Right of Way : Peugeot 405										Non Right of Way : Renault S5										
	Dist. out	Veh. Lengt	Lane Width	Mask	Eye-Front	Max. Decel	Right Pass	Left Passa	Opposite V		Dist. out	Veh. Lengt	Lane Width	Mask	Eye-Front	Max. Decel	Right Pass	Left Passa	Opposite V		
	0,7	4,4	2,5	15,0	2,5	-7,5	0,0	2,5	0		4,4	3,6	4,8	6,0	2,0	-7,5	0,0	0,0	0		
Step (s)	Vision	Veh. Width									Vision	Veh. Width							Direction		
0,05	10	1,7									0	1,6							Left		
Time																					Time
T(s)	A(m/s2)	V(km/h)	Long.(m)	Trans.(m)	Controlabi	Visibility	Perception	Interpretat	Action		A(m/s2)	V(km/h)	Long.(m)	Trans.(m)	Controlabi	Visibility	Perception	Interpretat	Action		T(s)
0,00		30,7	0,0	-0,2		*Automatic*						14,5	0,0	-0,8		*Automatic*					0,00
-0,05	-7,0	32,0	-0,4	-0,2	0	1	1	Danger			-0,8	14,6	-0,2	-0,8	1	1	0	Safety			-0,05
-0,10	-7,0	33,2	-0,9	-0,2	0	1	1	Danger			-0,8	14,8	-0,4	-0,8	1	1	0	Safety			-0,10
-0,15	-7,0	34,5	-1,4	-0,2	0	1	1	Danger			-0,8	14,9	-0,6	-0,8	1	1	0	Safety			-0,15
-0,20	-7,0	35,7	-1,8	-0,2	0	1	1	Danger			-0,8	15,1	-0,8	-0,8	1	1	0	Safety			-0,20
-0,25	-7,0	37,0	-2,4	-0,2	0	1	1	Danger			-0,8	15,2	-1,0	-0,8	1	1	0	Safety			-0,25
-0,30	-7,0	38,3	-2,9	-0,2	0	1	1	Danger			-0,8	15,4	-1,2	-0,8	1	1	0	Safety			-0,30
-0,35	-7,0	39,5	-3,4	-0,2	0	1	1	Danger			-0,8	15,5	-1,5	-0,8	1	1	0	Safety			-0,35
-0,40	-7,0	40,8	-4,0	-0,2	0	1	1	Danger			-0,8	15,7	-1,7	-0,8	1	1	0	Safety			-0,40
-0,45	-7,0	42,0	-4,5	-0,2	0	1	1	Danger			-0,8	15,8	-1,9	-0,8	1	1	0	Safety			-0,45
-0,50	-7,0	43,3	-5,1	-0,2	0	1	1	Danger			-0,8	15,9	-2,1	-0,8	1	1	0	Safety			-0,50
-0,55	-7,0	44,6	-5,7	-0,2	0	1	1	Danger			-0,8	16,1	-2,3	-0,8	1	1	0	Safety			-0,55
-0,60	-7,0	45,8	-6,4	-0,2	0	1	1	Danger			-0,8	16,2	-2,6	-0,8	1	1	0	Safety			-0,60
-0,65	-7,0	47,1	-7,0	-0,2	0	1	1	Danger			-0,8	16,4	-2,8	-0,8	1	1	0	Safety			-0,65
-0,70	-7,0	48,3	-7,7	-0,2	0	1	1	Danger			-0,8	16,5	-3,0	-0,8	1	1	0	Safety			-0,70
-0,75	-7,0	49,6	-8,4	-0,2	0	1	1	Danger			-0,8	16,7	-3,2	-0,8	1	1	0	Safety			-0,75
-0,80	-7,0	50,9	-9,1	-0,2	0	1	1	Danger			-0,8	16,8	-3,5	-0,8	1	1	0	Safety			-0,80
-0,85	-7,0	52,1	-9,8	-0,2	0	1	1	Danger			-0,8	16,9	-3,7	-0,8	1	1	0	Safety			-0,85
-0,90	-7,0	53,4	-10,5	-0,2	0	1	1	Danger			-0,8	17,1	-3,9	-0,8	1	1	0	Safety			-0,90
-0,95	-7,0	54,6	-11,3	-0,2	0	1	1	Danger			-0,8	17,2	-4,2	-0,8	1	1	0	Safety			-0,95
-1,00	-7,0	55,9	-12,0	-0,2	0	1	1	Danger			-0,8	17,4	-4,4	-0,8	1	1	0	Safety			-1,00
-1,05	-3,5	56,5	-12,8	-0,2	1	1	1	Danger			-0,8	17,5	-4,7	-0,8	1	1	0	Safety			-1,05
-1,10	-3,5	57,2	-13,6	-0,2	1	1	1	Danger			-0,8	17,7	-4,9	-0,8	1	1	0	Safety			-1,10
-1,15	-3,5	57,8	-14,4	-0,2	1	1	1	Danger			-0,8	17,8	-5,2	-0,8	1	1	0	Safety			-1,15
-1,20	-3,5	58,4	-15,2	-0,2	1	1	1	Danger			-0,8	18,0	-5,4	-0,8	1	1	0	Safety			-1,20
-1,25	-3,5	59,0	-16,0	-0,2	1	1	1	Danger			-0,8	18,1	-5,7	-0,8	1	1	0	Safety			-1,25
-1,30	-3,5	59,7	-16,8	-0,2	1	1	1	Danger			-0,8	18,2	-5,9	-0,8	1	1	0	Safety			-1,30
-1,35	-3,5	60,3	-17,7	-0,2	1	1	1	Danger			-0,8	18,4	-6,2	-0,8	1	1	0	Safety			-1,35
-1,40	-3,5	60,9	-18,5	-0,2	1	1	1	Danger			-0,8	18,5	-6,4	-0,8	1	1	0	Safety			-1,40
-1,45	-3,5	61,6	-19,4	-0,2	1	1	1	Danger			-0,8	18,7	-6,7	-0,8	1	1	0	Safety			-1,45
-1,50	-3,5	62,2	-20,2	-0,2	1	1	1	Danger			-0,8	18,8	-6,9	-0,8	1	1	0	Safety			-1,50
-1,55	0,0	62,2	-21,1	-0,2	1	1	1	Danger			-0,8	19,0	-7,2	-0,8	1	1	0	Safety			-1,55
-1,60	0,0	62,2	-22,0	-0,2	1	1	1	Danger			-0,8	19,1	-7,5	-0,8	1	1	0	Safety			-1,60
-1,65	0,0	62,2	-22,8	-0,2	1	1	1	Danger			-0,8	19,3	-7,7	-0,8	1	1	0	Safety			-1,65
-1,70	0,0	62,2	-23,7	-0,2	1	1	1	Danger			-0,8	19,4	-8,0	-0,8	1	1	0	Safety			-1,70
-1,75	0,0	62,2	-24,5	-0,2	1	1	1	Danger			-0,8	19,5	-8,3	-0,8	1	1	0	Safety			-1,75
-1,80	0,0	62,2	-25,4	-0,2	1	1	1	Danger			-0,8	19,7	-8,5	-0,8	1	1	0	Safety			-1,80
-1,85	0,0	62,2	-26,3	-0,2	1	1	1	Danger			-0,8	19,8	-8,8	-0,8	1	1	0	Safety			-1,85
-1,90	0,0	62,2	-27,1	-0,2	1	1	1	Danger			-0,8	20,0	-9,1	-0,8	1	1	0	Safety			-1,90
-1,95	0,0	62,2	-28,0	-0,2	1	1	1	Danger			-0,8	20,1	-9,4	-0,8	1	1	0	Safety			-1,95
-2,00	0,0	62,2	-28,9	-0,2	1	1	1	Danger			-0,8	20,3	-9,7	-0,8	1	1	0	Safety			-2,00
-2,05	0,0	62,2	-29,7	-0,2	1	1	1	Danger			-0,8	20,4	-9,9	-0,8	1	1	0	Safety			-2,05
-2,10	0,0	62,2	-30,6	-0,2	1	1	1	Danger			-0,8	20,5	-10,2	-0,8	1	1	0	Safety			-2,10
-2,15	0,0	62,2	-31,5	-0,2	1	1	1	Danger			-0,8	20,7	-10,5	-0,8	1	0	0	Safety			-2,15
-2,20	0,0	62,2	-32,3	-0,2	1	1	1	Danger			-0,8	20,8	-10,8	-0,8	1	0	0	Safety			-2,20
-2,25	0,0	62,2	-33,2	-0,2	1	0	0	Safety			1,5	20,6	-11,1	-0,8	1	0	0	Safety			-2,25
-2,30	0,0	62,2	-34,1	-0,2	1	0	0	Safety			1,5	20,3	-11,4	-0,8	1	0	0	Safety			-2,30
-2,35	0,0	62,2	-34,9	-0,2	1	0	0	Safety			1,5	20,0	-11,6	-0,8	1	0	0	Safety			-2,35
-2,40	0,0	62,2	-35,8	-0,2	1	0	0	Safety			1,5	19,8	-11,9	-0,8	1	0	0	Safety			-2,40
-2,45	0,0	62,2	-36,6	-0,2	1	0	0	Safety			1,5	19,5	-12,2	-0,8	1	0	0	Safety			-2,45
-2,50	0,0	62,2	-37,5	-0,2	1	0	0	Safety			1,5	19,2	-12,5	-0,8	1	0	0	Safety			-2,50
-2,55	0,0	62,2	-38,4	-0,2	1	0	0	Safety			1,5	18,9	-12,7	-0,8	1	0	0	Safety			-2,55
-2,60	0,0	62,2	-39,2	-0,2	1	0	0	Safety			1,5	18,7	-13,0	-0,8	1	0	0	Safety			-2,60
-2,65	0,0	62,2	-40,1	-0,2	1	0	0	Safety			1,5	18,4	-13,2	-0,8	1	0	0	Safety			-2,65
-2,70	0,0	62,2	-41,0	-0,2	1	0	0	Safety			1,5	18,1	-13,5	-0,8	1	0	0	Safety			-2,70
-2,75	0,0	62,2	-41,8	-0,2	1	0	0	Safety			1,5	17,9	-13,8	-0,8	1	0	0	Safety			-2,75
-2,80	0,0	62,2	-42,7	-0,2	1	0	0	Safety			1,5	17,6	-14,0	-0,8	1	0	0	Safety			-2,80
-2,85	0,0	62,2	-43,6	-0,2	1	0	0	Safety			1,5	17,3	-14,2	-0,8	1	0	0	Safety			-2,85
-2,90	0,0	62,2	-44,4	-0,2	1	0	0	Safety			1,5	17,1	-14,5	-0,8	1	0	0	Safety			-2,90
-2,95	0,0	62,2	-45,3	-0,2	1	0	0	Safety			1,5	16,8	-14,7	-0,8	1	0	0	Safety			-2,95
-3,00	0,0	62,2	-46,1	-0,2	1	0	0	Safety			1,5	16,5	-14,9	-0,8	1	0	0	Safety			-3,00

Quantified Malfunction Model - This last step consists in quantifying the previous model. However as explained above, the conflict sub-phase of an accident is essentially dynamic. Thus it seems necessary to go further than a simple statistical analysis of failures. A good description of the conflict sub-phase must include the whole malfunction mechanism and therefore failures in relation to the operation of the driver-vehicle systems involved. Driving failures and vehicle failure modes must be related to the physical operating parameters (at least vehicles' kinematics) and on the way the drivers handle the situation (output of driving functions). The development of the *Quantified Malfunction Model* consists of into two separate steps. First step consists in gathering malfunction data combining qualitative data concerning the driving functions (and failures) and quantitative operating parameters (and failure modes). The second step consists in analyzing those data in order to define of a limited number of generic *critical scenarios*.

As previously mentioned, it is very difficult to get information on the drivers' activities, and even more so to get such information in relation to time and space. However, In-Depth Accident Investigation (with a psychologist working on the scene of the accident and with full kinematic reconstruction of the pre-crash phase) and Driving Simulator Experiments can provide such data with a relatively satisfying degree of reliability. The former provides real condition data with a poor level of certainty

whereas the latter provides simulated situation data with a high level of certainty (especially for driver actions). Driving Simulator Experiments also provide data on successful recovery maneuvers (near misses) whereas In-Depth Accident Investigation cannot. Real Scale Experimentation (such as that described in Petit 1993) seems to combine advantages of the two approaches.

In order to combine qualitative driver data and quantitative vehicle data, 'state-event' tables were designed within the present research. A quantified table (called *pre-crash table*) provides the kinematic time-history in relation to parameters describing the output of certain driving functions. A qualitative table (called *driving functions and failures table*) contains all the data on driving function outputs and failures sequentially and is linked to the previous table.

DISCUSSION

The whole approach described above has been applied to 'intersection crossing' and 'cornering' phases. The method proposed has been successfully conducted and quantification of the model is being carried out. The limits of the method mostly arise from the limits of data collection sources used in this last step.

In-Depth Accident Investigation - Qualitative failure models have been developed and State-event tables are being used within In-Depth Accident Investigations in order to obtain a quantified malfunction model. An example of pre-crash table for the 'intersection crossing' phase is given in table 2. Kinematic parameters are obtained from a full reconstruction of the accident. Qualitative parameters describing driving function outputs are determined according to observable parameters (physical visibility for example) and changes in their value are related to physical parameters with certain delays (reaction-time estimated by a psychologist).

The determination of such tables is based on assumptions made by the accidentologists on certain parameters (deceleration, reaction time...). The most probable values are chosen and lead to a single table corresponding to the best hypothesis. A better solution would consist in expressing the assumptions in terms of probable intervals (instead of single values). Following this approach, further research is being carried out in order to provide automatically several different possible scenarios for a single accident with the Monte Carlo simulation Method. This will enable the taking into account of uncertainty intervals and therefore improve the reliability of accident reconstruction.

Driving Simulator Experiments - Concerning the 'intersection crossing' phase, a study was carried out on a static simulator developed by Renault (ESTER, described in Morel-Guillemaz 1995). In this experiment, 60 people drove about 15 minutes on a highway with right of way. At a given intersection, a moving vehicle was triggered with given kinematics in order to provoke a crash. Three configurations were determined on the basis of a statistical analysis of fatal accident reports and In-Depth Accident Investigations (vehicle with constant speed coming from the right, decelerating vehicle coming from the right, vehicle starting from the left). The experiment was followed by an interview of the driver carried out by psychologists of In-Depth Accident Investigation teams with the support of a video of the critical scene (including the visual display and the driver's face). The psychological data obtained was related to the time-history of operating parameters (vehicle kinematics) and driver's actions (on vehicle controls). This experiment therefore provided all the data on the driving malfunctions for both accidents and near misses.

As mentioned above, Driving Simulator Experiments are complementary to In-Depth Accident Investigations. However, although they are suitable for the study of maneuverability accidents, they are inadequate for the analysis of pilotability accidents. This stems from three main reasons. Firstly, the probability of driving failures is not compatible with the duration of any experiment. Secondly, the experimental aspect prevents the drivers from being in a natural psychological state of driving which is known to have much influence in pilotability accidents. Thirdly, since the driving tasks are slightly different from real driving, the error mechanisms may also be different. It is possible to artificially increase the probability of error (when compelling the driver to overspeed or when applying significant visibility masks), but the study must then be limited to the analysis of the malfunction initiated (excluding driving failure).

Another limit of studies conducted on static simulators is linked to the type of malfunctions observable. Because of the lack of dynamic feedback, the control task is very different from real driving. It is therefore not possible to study malfunctions related to control accidents.

CONCLUSION

The method proposed herein enables the determination of quantified critical scenarios encountered in automotive driving. The obtained reference critical scenarios provide a reference basis for the determination of safety system characteristics (reaction time, accuracy...). Moreover, when a given safety system is supposed to have influence on certain failures or malfunctions, a quantification of this influence in terms of probabilities (by expert judgment or specific studies) will enable to compute the new probability of the whole scenario. The main idea will therefore consist in focusing on local risks and enhancing safety by reducing those local risks. Thus, the analysis will

be aimed at specify and assess the safety of crash avoidance systems for the driving phases during which the system's activity is supposed to have an influence on driving. This approach should allow reliable Specification and Probabilistic Safety Assessment of crash avoidance systems.

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REFERENCES

Allen, Lunenfeld, Alexander ; *Driver Information Needs ;* Highway Research Record, No. 366, 1971

Anderson R., Menckel E. ; *On the prevention of accidents and injuries ; A comparative analysis of conceptual frameworks* ; Accid. Anal. & Prev., Vol. 27, No. 6, pp. 757-768, 1995

Catalano R., Dooley D. ; *Economic change in primary prevention* ; In Price R. H., Ketterer R. F., Bader B., Monahan J. ; Prevention in mental health ; Sage Publication, London, pp. 21-40, 1980

Leplat J. ; *Erreur humaine, fiabilité humaine dans le travail* ; Armand Colin, Paris, 1985

Leplat J., Rasmussen J. ; *Analysis of human errors in industrial incidents and accidents for improvement of work safety* ; Accid. Anal. & Prev., Vol. 16, No. 2, pp. 77-88, 1984

Lievens C. ; *Sécurité des Systèmes* ; Cepadues-Editions, Toulouse, 1976

Malaterre G. ; *L'analyse de la tâche appliquée à la situation d'accident* ; In Fleury D. ; Genèse des accidents et persepectives de recherche en sécurité : étude pilote de Salon-de-Provence ; Inrets, Arcueil, 1985

Malaterre G. ; *Error analysis and in-depth accident studies* ; Ergonomics, Vol. 33, No. 10/11, pp. 1403-1421, 1990

Michon J. ; *A critical view of driver behavior models : what do we know, what should we do ?* ; In Evans L., Scwing R. ; Human behavior and trafic safety ; Plenum Press, New York, 1985

Morel-Guillemaz J.; *E.S.T.E.R. - A driving simulation environment for automotive research and studies* ; SIA, Marne la Vallée, 1995

Petit C., Priez A., Brigout C., Tarrière C. et al ; *Driver's use of ABS in emergency : a physiological and behavioral trial* ; Isata, Aachen, 1993

Rasmussen J. ; *The definition of human error and a taxonomy for technical system design* ; In Rasmussen J., Ducan K., Leplat J. ; New technology and human error ; Wiley, Chichester, 1987

Reason J. ; *Human error* ; Cambridge University Press, Cambridge, 1990

Thomas C., Koltchakian S., Tarrière C. et al ; *Priorities in view to technical feasability limits to secondary automotive safety* ; FISITA,Torino ,1990

Treat J. ; A study of precrash factors involved in traffic accidents ; HSRI research review, Vol. 10/11, No. 6/1, 1980

Wanner J.-C. ; *Tentative d'application des critères de qualités de vol aux qualités de route des automobiles* ; Ingénieurs de l'Automobile, No. 10, 1969

Wanner J.-C. ; *Le facteur humain dans la conduite de grands systèmes* ; Le Progrès Technique, No. 21, 1981

WHIPLASH ASSOCIATED DISORDERS

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Abstract

This paper reports the results of several studies the aims of which were to determine the cost, prevalence, frequency of reporting and disability associated with whiplash associated disorders.

In 1982 the World Health Authority concluded that previous studies on the costs of road traffic accidents "had been based on cost of deaths and in-patient treatment, and had neglected to examine the cost of long term disability to the community" (WHO 1982). During the past 12 years we, with the Transport Research Laboratories and the Department of Transport, have tried to evaluate the cost of road traffic accidents, paying particular attention to whiplash associated disorders and looking at the cost of the residual disability.

Definition

Whiplash associated disorders (W.A.D) are non-specific soft tissue injuries of the cervical spine, once fractures, dislocations and subluxations have been excluded. Classically, a "whiplash" is an hyperextension injury following a rear impact. However, soft tissue injuries to the neck can also occur from frontal or side impacts. Whiplash associated disorders include soft tissue injuries to the cervical spine which previously have been described under terms such as neck sprain, neck strain, whiplash, soft tissue injury, acceleration-deceleration injuries etc.

Correlation Between Injury Severity And Long Term Disability

Our first study (Galasko et al, 1986) was designed to determine whether there was any correlation between injury severity and subsequent long term disability; whether long term disability was the consequence of particular injuries; and whether long term disabilities should be included in evaluating the costs of road traffic accidents. Fourteen hundred and twenty-two consecutive patients, who had been seen in an Accident & Emergency Department, following a road traffic accident were followed up for six months. The study was designed to assess whether there were any changes in their lifestyle or occupation, and the effect of the accident/injury on their sport, hobbies or activities of daily living. In this study "Long Term Disability" was defined as a disability persisting for more than six months, and of sufficient severity to interfere with their job (including housework).

Overall, 25.1% of patients had a residual disability at six months. Long term disability occurred more commonly in pedestrians (30.1%) and least commonly in pedal cyclists (15.9%). It occurred in 24.6% of vehicle occupants and 26.2% of motor cyclists. In each vehicle-user category patients with a long term disability were significantly older than those who were left without a residual disability at six months.

The more extensive the treatment required the higher the risk of long term disability. For example, 11.7% of the patients who had only been seen on a single Accident & Emergency Department visit had a residual disability compared with 32.8% who were seen in the Accident & Emergency Department for follow-up, 42.9% who were admitted to hospital, 45.2% who were referred to a fracture clinic, 50% who were referred to miscellaneous clinics (e.g. general surgery, plastic surgery, ENT, etc.) and 65.8% who were referred to an orthopaedic clinic.

The risk of disability was also associated with the severity of the injury assessed either by the Abbreviated Injury Score or Injury Severity score.

Of the patients who were admitted to hospital those who developed a long term disability remained in hospital for longer (24.21 ± 2.7 days compared with 9.26 ± 1.4 days for those who made a full recovery; $p < 0.001$).

The patients who were left with a long term disability also required more time off work (71.4 ± 5.0 days versus 15.1 ± 1.3; $p < 0.001$), more time off school/college (32.7 ± 8.5 days versus 11.3 ± 1.2 days; $p < 0.001$) and were unable to carry out other daily activities for a longer period (53.5 ± 7.7 days versus 10.1 ± 1.5 days; $p < 0.001$).

The commonest cause of long term disability in this study were whiplash-associated disorders and closed fractures of the long bones (upper limbs and lower limbs).

Our subsequent studies have concentrated on these two conditions, particularly whiplash-associated disorders. We have now studied over 15,000 patients injured in road traffic accidents, of whom approximately 6,000 have suffered a whiplash-associated disorder.

Prevalence Of Road Traffic accidents and whiplash associated disorders

The numbers of patients attending the Accident & Emergency Department at Hope Hospital were evaluated (Table 1).

Table 1

Prevalence Of Whiplash Associated Disorders (Hope Hospital)

Year	Number Of Patients Seen In A. & E. Dept. Having Been Injured In An R.T.A.	Number (%) with W.A.D.
Feb. '82 - Feb. '83	929	72 (7·7%)
Introduction of compulsory wearing of seat belts in U.K.		
Feb. '83 - Feb. '84	940	193 (20·5%)
1988	1189	372 (31·0%)
1990	1508	564 (37·4%)
1991	1964	709 (36·1%)
1994	1919	1032 (53·7%)

There was an annual increase in the number of patients attending, following a road traffic accident, from 1982/1983 (the year prior to the introduction of the compulsory wearing of seat belts in the United Kingdom) until 1991. Thereafter, there was a slight reduction. However,

throughout this period there has been a progressive increase in the number of patients attending with a whiplash associated disorder. There was virtually a three-fold increase in the year following the compulsory introduction of seat belt usage but since then the numbers injured have increased to an even greater extent. The increase between 1983/1984 and 1994 has been more than five-fold.

One possible explanation for the increased prevalence of patients is because patients attend the Accident & Emergency Department for insurance purposes, rather than for treatment. However, 99.64% of patients said that they had attended because of their symptoms. Only 0.36% had attended for insurance reasons.

The vast majority of patients claimed to have been wearing seat belts at the time of the accident (97.3% of drivers and 99.1% of front seat passengers) but a survey of usage in local roads (excluding motorways and dual carriageways) showed that 90% of drivers and 86% of front seat passengers were wearing seat belts.

Long Term Disability Following A Whiplash Associated Disorder

Patients attending three Accident & Emergency Departments were recruited into this study. One was in a major teaching hospital with an academic department of Accident & Emergency Medicine, one was in an inner city hospital and the third covered an area that was partly urban and partly rural. The patients were interviewed by a research nurse within days of the accident and, thereafter, at six monthly intervals for a total of 48 months. The incidence of whiplash associated disorder was virtually identical in the three Accident & Emergency Departments. The results are shown in Table 2 and Figure 1. There was a progressive reduction in the proportion of patients with a residual disability. This had reduced to 40% at twelve months, 24.2% at 24 months, 11.4% at thirty-six months and 8.2% at forty eight months.

Table 2

Long Term Disability Following A Whiplash-Associated Disorder (n = 413)

Time After R.T.A.	% Patients With Residual Disability
6 months	59·1
12 months	40·0
18 months	29·3
24 months	24·2
30 months	16·9
36 months	11·4
42 months	9·4
48 months	8·2

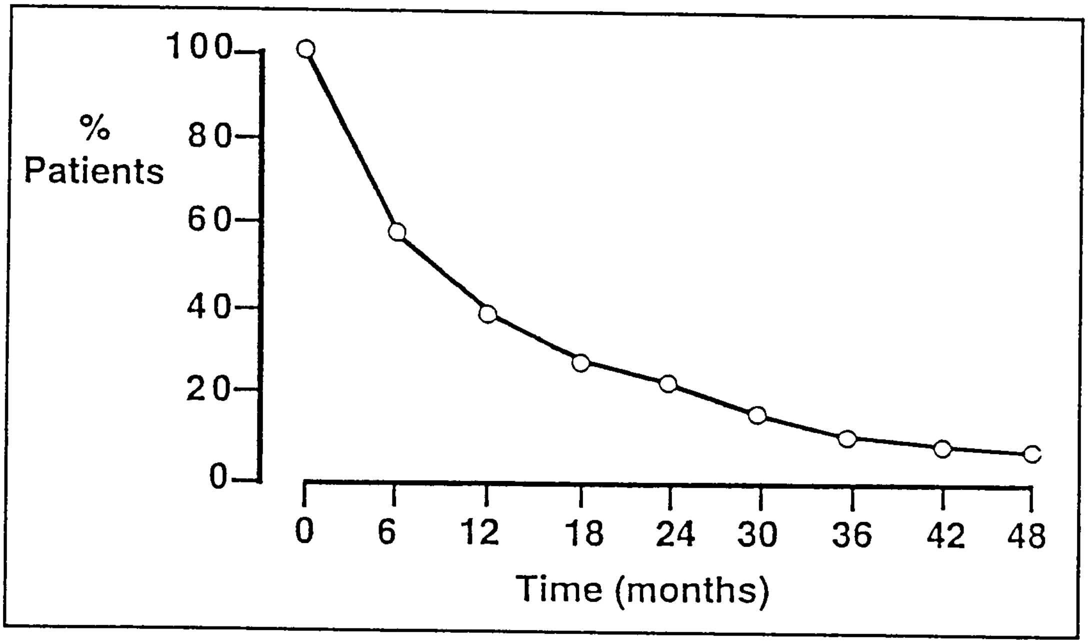

Figure 1. The percentage of patients with a residual disability following a whiplash associated disorder decreases with time following the causative road traffic accident. At 48 months 8.2% of patients still have a residual disability.

Severity Of Disability

We have developed a method of quantifying the disability. This is based on an assessment of the residual limitation of movement, such as lifting, bending, walking, sitting, reaching, etc; the residual limitation in physical activities such as washing, bathing, dressing, eliminations, eating etc.; and an assessment of any residual anxiety affecting daily activities, recreational activities, occupation, driving, etc. Each function was separately analysed and converted to a 0-3 scale for each of the three categories. Thus the maximum disability was 9 (Murray et al, 1994a).

There was a progressive reduction in disability during the four year period so that at 48 months the average disability score in the 8.2% of patients with a residual disability was just under 1 (Figure 2.) with a progressive reduction in all three components of the disability score.

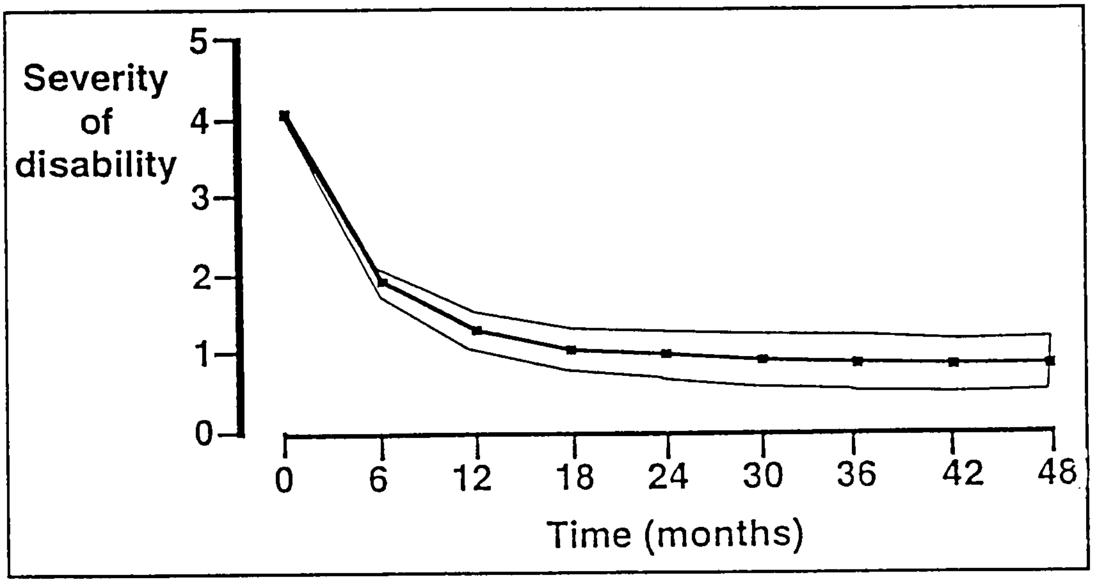

Figure 2. There is a progressive reduction in the severity of the disability with time following the road traffic accident in which the patient sustained a W.A.D. The maximum score is 9 (Murray et al 1994a).

Position Of Patient In Vehicle

Whiplash-associated disorders occurred most commonly following a rear impact. This was true both for car drivers and front seat passengers. (Rear seat passengers were not included in this study). In approximately one quarter of patients the injury was sustained from a frontal impact and in 16% of car drivers and 12% of front seat passengers the injury followed a side impact.

Costs Of Whiplash Associated Disorders

Many items contribute to the cost of road traffic accidents. These should include the cost of medical treatment, the cost of the Social Services provided, lost income to the family, a subjective element, the cost of lost output, the police costs in dealing with the accident and its aftermath and the cost of damage to property. These have been included in our studies and have either been taken from our own studies (health care costs, cost of Social Services provided and lost income to the family) or from costs provided by the Department of Transport (O'Reilly 1993, Hopkin & O'Reilly 1993).

There are two methods of measuring the subjective element. Previously, the Department of Transport has calculated a figure based on pain, grief and suffering. More recently they have based this figure on the value of avoidance (willingness to pay) (Jones-Lee et al 1993). We have calculated the costs separately for each method of costing the subjective element.

Not all costs have been included. For example, our costs did not include the cost of delays to road users following the congestion caused by a road traffic accident nor the cost of caring for someone whose injuries had resulted in an extended period of impairment, in terms of the anxiety, stress and loss of earnings for the carer.

Some of these costs are common to all countries, for example, medical costs, lost output

and the subjective element. Holland includes the cost of a house conversion resulting from the disability and the United States includes funeral costs for fatalities.

We have not included all elements of the health care costs. We have included the costs of the ambulance service (both the initial journey to hospital following the accident and any subsequent journeys to hospital for treatment), the Accident & Emergency Department costs, hospital in-patient costs, hospital out-patient costs, physiotherapy provided by the National Health Service, the costs of any District Nurse services provided and the costs of any orthoses provided (for example, collars). The costs of General Practice attendances were excluded because General Practitioners are paid on a per capita basis and not per treatment. The costs of any private medical care, private physiotherapy, private osteopathy, chiropody, etc. were excluded as were the costs of pharmaceuticals. The latter include the prescription costs as well as any pharmaceuticals bought over the counter.

The costs are, therefore, an underestimate of the true costs.

The average health care cost for a patient who sustained a whiplash associated disorder was £300 during the four years following the accident.

The cost for a closed fracture was £3,743. We have looked separately at the cost of treatment for tibial fractures. The mean cost was £4,671 with a range of £1,956 to £13,158.

The costs of other slight and serious injuries have been evaluated in a separate study (Murray et al, 1994b). Like the W.A.D. and fracture costs, the costs were calculated in terms of 1991 figures but were only calculated over an 18 month period. The Health and Social Security costs amounted to £3,186 per seriously injured patient and £238 per slightly injured patient.

The Social Services costs comprised Statutory Sick Pay (SSP, which is paid for sickness absences less than 28 weeks) and a range of additional benefits which tend to cover longer term illness and disability. During the four year duration of the study the types of benefits have changed. The average Social Services cost for a whiplash associated disorder, in terms of 1991 costs, was £355 and for a closed fracture was £1,186. The combined health care and Social Services costs are shown in Table 3. This is greater than the figures previously quoted by the Department of Transport, which were based on the 1990 value. The Department of Transport have subsequently increased their figures as a result of our studies.

Table 3

Health Care And Social Service Costs (Pounds Sterling)

Our Studies (1991 Value)	D.O.T. (1990 Value)
W.A.D. 655	Combined Slight 112
Other "Slight" 238	
Closed Fracture 4929	Combined Serious 2,499
Other "Serious" 3186	

The average days work lost following a whiplash associated disorder was 39 days for all patients with an average loss of income of £843. The average loss of income for a fracture was £1,472. The average time off work following a W.A.D. for those in work was 81 days. This compares with an absence of 86 days for females and 77 days for males in the Quebec Study (Suissa et al 1995).

The Department of Transport have re-calculated the costs of lost output. The estimate for lost output following a serious injury is £8,230 and for a slight injury is £1,031. The latter is based on an estimate that the lost output per "slight" casualty who had fully recovered from his/her injuries within one year was £333. and for a patient with a "slight" injury from which they fully recovered within one to three years was £7,312. The overall cost of £1,031 is weighted towards the more minor injuries. Our figures show that 40% of patients with a whiplash associated disorder have residual disabilities at 12 months and, therefore, the lost output for whiplash associated disorders, as opposed to all "slight" injury is £3,125.

In reaching our final calculations of the costs of road traffic accidents we have used the revised costs (1990 values) quoted by the Department of Transport for police costs, damage to property and the subjective element calculating separately the value for pain, grief and suffering and the value of avoidance. The latter is more expensive. For example, pain, grief and suffering for a slight injury was calculated at £330, whereas the value of avoidance was calculated at £4,405 (Hopkin and O'Reilly 1993).

The average cost of a whiplash associated disorder is shown in Table 4.

Table 4

Cost of A Whiplash-Associated Disorder (Pounds Sterling)

Costs	Basis Of Analysis			
	Value Of Avoidance W.A.D. Cost For Lost Output	**Value Of Avoidance Av. Of "Slight" For Lost Output**	**Pain, grief, suffering - W.A.D. cost for lostoutput**	**Pain, Etc. Av. "Slight" Cost For Lost Output**
Health Care	300	300	300	300
Social Services	355	355	355	355
Lost Income	843	843	843	843
Lost Output	3,124	1,031	3,124	1,031
Police	200	200	200	200
Damage To Property	1,081	1,081	1,081	1,081
Subjective Element	4,405	4,405	330	330
Total	**10,308**	**8,215**	**6,233**	**4,140**

Under-recording, Under-reporting And Mis-coding Of Road Traffic Accident Injuries

In the United Kingdom the number of accident injuries are calculated from Stats 19 which records fatality, serious and slight injuries. The figures are taken from police records. They are not taken from hospital records. We have matched the records of 2,670 patients seen in three Accident & Emergency Departments with the police records (Hopkin et al 1993a, Hopkin et al 1993b).

The study included 1,765 patients who had sustained a slight injury. For the purpose of this study, whiplash associated disorders were included under "slight" injuries because they are recorded as such in Stats 19. Seven hundred and ninety-nine patients did not report their injury to the police. Nine hundred and sixty six had reported their injury. Two hundred and thirty one of the 966 patients were not recorded in Stats 19, 17 were recorded as "serious" and only 718 were recorded as "slight". In addition there were 552 patients recorded in Stats 19 who had not reported to an Accident & Emergency Department. Overall, approximately 45% of patients with

whiplash associated disorders were unrecorded.

Calculated Incidence Of Road Traffic Accidents

Using the above information the annual incidence of road traffic accident injuries in the United Kingdom has been calculated at 460,560 of which 247,680 are W.A.D.'s (Table 5). Evans (1992) estimated that in the United States the annual incidence of new W.A.D.s was approximately 1 million.

Overall Costs Of Road Traffic Accidents

The United Kingdom costs for whiplash associated injury (in 1991 terms) ranged from £1,025m to £2,553m depending on whether the subjective element is costed in terms of pain, grief and suffering or in terms of value of avoidance and whether the lost output is calculated at the average costs for all "slight" injuries or specifically for whiplash associated disorders. This represents 18% of the total costs of road traffic accidents (Table 6). At the higher costs this represents approximately 0.4% of the Gross National Product for whiplash associated disorders.

Table 5

Calculated Annual Incidence of Road Traffic Accident Injuries in the U.K.

W.A.D.	247,680
Other "Slight"	139,651
Closed Fractures	39,500
Other "Serious"	33,729
Total	**460,560**

Table 6

Annual Costs Of Whiplash Associated Disorders In The U.K. (1991 Value - Pounds Sterling)

Subjective Element	Costs Of Lost Output	Total Cost
Value of avoidance	W.A.D. specific	2,555,086,000
Value of avoidance	Av. of all "slight"	2,034,691,000
Pain, grief, suffering	W.A.D. specific	1,543,790,000
Pain, grief, suffering	Av. of all "slight"	1,025,395,000

References

Galasko CSB, Murray PA, Hodson M, Tunbridge RJ, Everest JT. Long term disability following road traffic accidents. Transport Road Research Laboratory Research Report 59. Transport Research Laboratory, Crowthorne, United Kingdom. 1986.

Guria JC. Length of hospitalisation - an indicator of social costs of disabilities arising from traffic injuries.
Accident Analysis and Prevention, 22, 1990, 379-389.

Hopkin JM, Murray PA, Pitcher M, Galasko CSB. Police and hospital recording of non-fatal road accident casualties: A study in Greater Manchester, United Kingdom. Transport & Research Laboratory Project Report.PR/SRC/1/93Transport Research Laboratory, Crowthorne. 1993a

Hopkin JM, Murray PA, Pitcher M, Galasko CSB. Police and hospital recording of non-fatal road accident casualties: A study in Greater Manchester, United Kingdom. Transport & Research Laboratory Research Report 379. Transport Research Laboratory, Crowthorne. 1993b.

Hopkin JM, O'Reilly DM. Revaluation of the cost of road accident casualties: 1992 revision. Transport Research Laboratory Research Project 378, Transport Research Laboratory, Crowthorne, United Kingdom. 1993.

Jones-Lee NW, Loomes G, O'Reilly DM, Philips PR. The value of preventing non-fatal road injuries: findings of a willingness-to-pay national sample survey. Transport Research Laboratory Contractor Report 330, Transport Research Laboratory, Crowthorne, United Kingdom. 1993.

Murray PA, Pitcher M, Galasko CSB. The cost of long term disability from road traffic accidents. Four year study - final report. Transport Research Laboratory Project Report 45, Transport Research Laboratory, Crowthorne, United Kingdom. 1994a.

Murray PA, Pitcher M, Galasko CSB. The cost of some road traffic accident injuries within the DOT serious and slight range. Transport Research Laboratory Research Report 106, Transport Research Laboratory, Crowthorne, United Kingdom. 1994b.

O'Reilly. Costing new traffic accidents: the value of lost output. Transport Research Laboratory Working Paper WP/SRC.09 Transport Research Laboratory, Crowthorne, United Kingdom. 1993.

Suissa S, Harder S, Veilleux M. The Quebec Whiplash-Associated Disorders Cohort Study. Spine 20, No. 8 S, pp. 125-205, 1995.

World Health Organisation. The epidemiology of accident traumas and resulting disabilities. World Health Organization, Copenhagen, WHO Regional Office for Europe, 1982. (EURO Reports and Studies 57).

PHOTOGRAMMETRIC METHODS IN CRASH INVESTIGATION

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ABSTRACT

Photogrammetry uses a series of photographs to develop a three dimensional image. From these paired two dimensional images, systems have been developed to determine the third dimension.

Photogrammetry systems are used for a variety of purposes. These range from:

- Crash scenes
- Crime scenes
- Architecture and Buildings
- Roads
- Aerial photography

Traditionally photogrammetry of crime sites in Australia has been the domain of specialist photogrammetry units within the Police Service. Emphasis is placed on obtaining and recording site details. Items include:

- Vehicle rest positions
- Key markings and debris on roads
- Roadside furniture
- Road alignment

A new system developed in Sweden, jointly between Folksam Insurance and Chalmers University of Technology, allows photogrammetry to be conducted on vehicles to determine deformation. The system requires minimal training in both taking photographs and in their subsequent analysis.

This paper outlines the photographic procedures used and developed for an indepth crash study using such a system, to minimise on scene inspection time and maximise data collection. It outlines the advantages and disadvantages, as well as future enhancements of the system.

BACKGROUND

Crash investigations are an important part of the work conducted by road safety researchers and law enforcement officers. Crash Investigation provides essential information for the assigning of fault, determining causation and developing occupant kinematics, injury mechanisms and sources. One of the critical steps in many investigations is the determination of vehicle damage and deformation.

Vehicle inspections incorporate internal and external measurements and include photographs to fully document damage and evidence.

Interior photography should document:
- Intrusion
- Injury Sources
- Contact Points
- Component Failure
- Type and arrangement of restraint systems

Exterior photographs allow documentation of:
- Damage
- Impact points
- Deformation coding.

Exterior measurements are taken in some cases to document the crash profile of the car. This profile is then available for input into crash reconstruction programs, such as CRASH 3 and EDCRASH. The output from these programs determines the change in velocity during the crash, DELTA V. DELTA V is useful in providing an indication of the severity of the crash in conjunction with known crush stiffness characteristics of the vehicle.

Previous techniques in this area have primarily been by taking physical measurements of the crush profile. A common system takes measurements of the profile usually at six equally spaced points across the damaged proportion of the vehicle. (NHTSA)

The major disadvantages of this process is that after measurements have been taken and the vehicle scrapped or repaired, there is no opportunity to review the measurements or to measure any forgotten items.

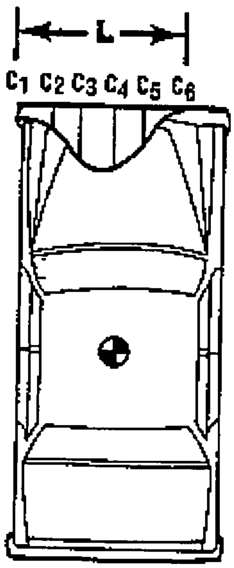

Figure 1: Crash Deformation Measurements
Source: National Accident Sampling Scheme.

PHOTOGRAMMETRY IN CRASH INVESTIGATION

Photogrammetry has been used as part of Crash Investigation by Police for many years. It is the domain of specialist units within the Police Service who photograph potential crime scenes, including crash scenes. The process involves the use of expensive cameras and analysis equipment. It has demanding calibration requirements and usually has a high level of accuracy. The photogrammetrists are highly skilled specialists in this area. The setup is time consuming and the photographs are transferred to photographic plates through a costly process. Crash scene photography is the major emphasis not the vehicle. Not many measurements of the vehicle are usually taken.

The use of photogrammetry for the measurement of vehicles and deformation has been examined by several papers in the past 10 years (Kullgren: Lie; Pepe; Woolley; Faig).

The most recent report was buy Lie et al. They reported on an analytical system performed in a mono-comparator style system (ie: without stereo viewing). Kullgren et al, reported the use of this system in investigating nearly 500 crashes over a two year period. This involved 15 different model cars and had a reported accuracy of approximately 15 mm.

THE STUDY

The Roads and Traffic Authority of New South Wales (RTA) Vehicle and Equipment Safety Section is undertaking an indepth vehicle factors crash study (Duignan). The study will investigate 5000 vehicles (approximately 3,000 crashes). The crashes are a targeted random selection and inspections are conducted by the RTA's vehicle regulation inspectors.

The inspectors are broadly categorised into technical and non-technical. The technical inspector generally has trade qualification as a mechanic. Most inspectors have no formal photographic training or experience in measurement of crash scenes and vehicles.

Two inspectors attend each crash. The investigations extend to removing components including tyres, brake drums, etc. They take approximately one to two hours. They thoroughly inspect the car recording window tint levels, modifications, rust, sketches of the damage, and occupant contact points.

As part of this investigation process, they are required to take detailed photographs of the crash site and the vehicle. The vehicle photography component utilises the photogrammetric system developed by Folksam and Chalmers University. The main reason for using this photogrammetry system is to allow post-inspection measuring of the vehicle and determination of the Collision Deformation Classification (CDC), without requiring specialist training of the vehicle inspectors.

THE SYSTEM

As mention previously the photogrammetry system used is an adaptation of the system outlined by Kullgren and Lie. The system uses standard 35 mm format cameras with fixed focuses 28 mm lenses. The cameras have been modified with the addition of a reseau plate containing reference points. They are then calibrated using a known field.

The Inspectors have been provided with zoom lenses and high powered flashes to assist with other on-scene photography and macro photography of specific vehicle components.

THE PHOTOGRAPHIC PROCEDURE

The inspectors take a mandatory series of 12 pairs of photographs of the vehicle from set locations (see Figure 2). The photoplan has been designed to ensure all aspects of the vehicle are documented even if un-damaged.

As detailed by Kullgren et al and Lie et al, the photographer and the position of the vehicle only needs to be roughly within the guidelines. Investigators are asked to ensure the vehicle fills the viewfinder, so as to maximise definition in analysis and subsequent enlargements. The cameras are hand-held but a monopod is supplied to encourage standardisation of height and assist higher clarity of photographs in darker environments with slow shutter speeds. Before taking the photographs the inspectors place a series of targets on the vehicle which become connecting points to link the photographs together. The positioning of the connecting points scale ruler is shown in figure 3.

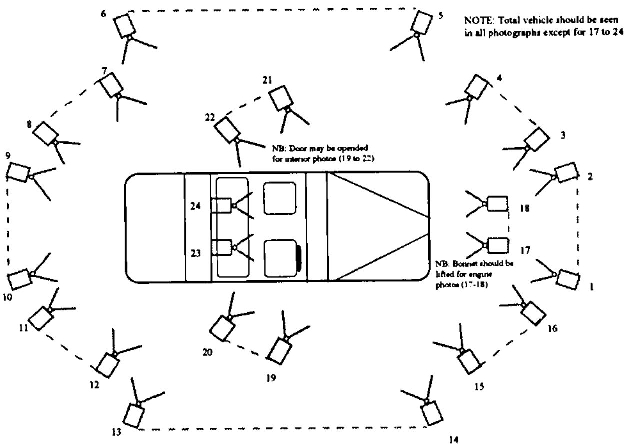

Figure 2: Photoplan (Lie).

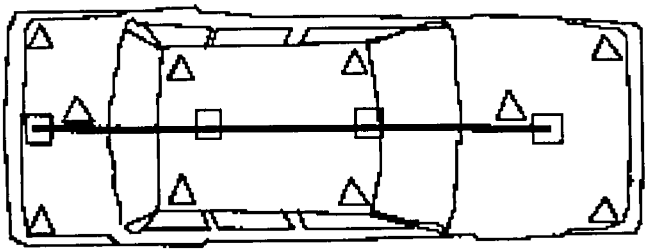

Figure 3: Positioning of scale rule and connecting points.

After the photos have been taken the inspectors supply their inspection documentation and undeveloped film to a central location for processing. The development of the film is conducted by a film processing and digitising laboratory. The processed product comprises negatives, prints and digitised photographs using a Kodak Photo-CD formats. It is recorded in 5 different resolutions ranking from 198 x 128 to 3,000 x 2,000 pixals. Once in a digital format the photographs are ready for analysis.

The analysis includes photogrammetry and a review of contact points. The review also assists in the quality control of the study through confirmation of inspectors observations. This is achieved through a zoom capabilities of the photo-CD viewing software. An example of the zoom capability is shown in figures 4 and 5. The lower resolution images are also added to the crash database for quick reference.

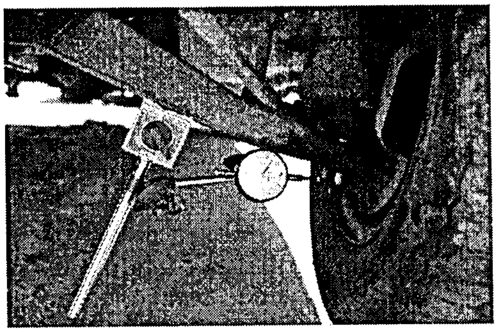

Figure 4: Standard Vehicle Photograph

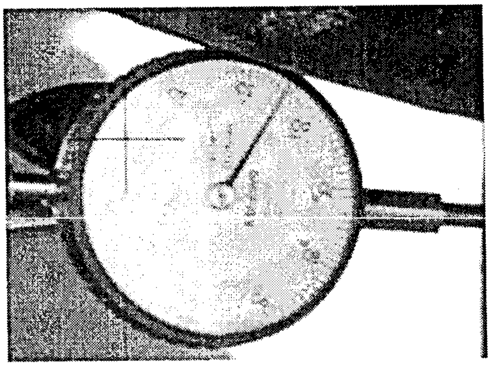

Figure 5: Zoom of dial gauge to confirm measurements.

The photogrammetry measurement system consists of an Apple Macintosh computer with CD ROM player and an IBM compatible PC. The photogrammetry

measurement procedures are similar to that used by Lie et al. As Australia has a substantial number of different vehicle models as part of its fleet, modifications were required to the system. The system was changed to allow greater flexibility in conducting the photogrammetrical analysis without the use of a reference vehicle. This incorporated a need to provide scaling and orientation capabilities. Figure 6 provides a plan view of the output from the photogrammetrical system. The output includes control, undamged and damaged points. This vehicle was damaged on the front right corner.

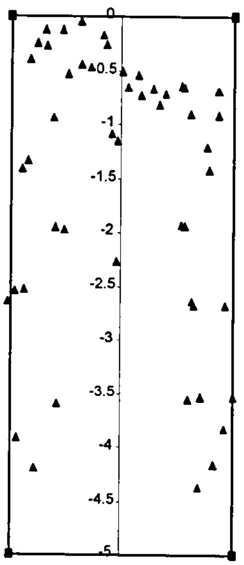

Figure 6: Output from the photogrammetry analysis.

DISCUSSION

This study appears to have been the most extensive use of such a simplified photogrammetric system to date. Our evaluations have highlighted the advantages and disadvantages.

Advantages

The advantages of using the photogrammetry system and a photo-CD storage of crash photographs are:

1. No detailed experience of photogrammetry is required, although it does help. This extends to use of cameras has the cameras used are similar to any standard 35 mm cameras.

2. Photo-CD as a storage medium reduces storage space (if compared to photo albums) and also simplifies reprints when attached to a colour printer.

3. Time for filing is greatly reduced as each Photo-CD has a unique identification number and ideally suited to a computer database.

4. Selected photographs can be attached to the crash database to allow a quick reference.

4. Ability to take accurate measurements at any time post crash.

5. Ability to review any data that has been calculated if discrepancies are argued.

6. The photo-CD process allows the ability to zoom in to observe specific detail areas, such as possible contact points, on the image. It assists in the quality control process of the study.

Disadvantages

1. When using the system without a reference vehicle, there is additional analysis time required.

2. Accuracy is approximately 15 to 30 mm.

3. It is not always possible to get a full set of photographs of the vehicles due to the storage location.

CONCLUSION

The photogrammetry system has been used to photograph the damage of over 500 vehicles to date. The system is an integral part of the quality audit process and the analysis of vehicle damage, contact points and injury mechanisms.

Times for the setup and field photography are approximately 20 - 30 minutes. This time compares very favourably to the time required to manually measure the deformation profile with measuring rods, particularly when it is considered that the whole vehicle interior and exterior profile is recorded in this time.

Costs are increased by the additional analysis time and the film processing costs (approximately $A 1.00 per photograph). These extra costs have been easily outweighed by improved storage, retrieval, and most importantly improved post analysis capability.

The photogrammetry system has had high acceptance by the field inspectors because of its ease of use and time saving factors.

Future developments that will enable greater flexibility and analysis include:

- a link to a CAD program to enable 3-dimensional views to be developed.
- link to vehicle information/dimensional databases to eliminate the need for the photographing of reference vehicles.
- development of artificial intelligent software that will determine the Crash Deformation Classification from the photogrammetrical output.

- use of digital cameras.

- Obtaining still photographs for analysis through digitised video footage.

REFERENCES

Duignan P, Williams S, Griffiths M
Vehicle Defects in Crashes - Indepth Vehicle Factors Study, Experimental Safety Vehicles, Melbourne 1996

Faig W, Wilson F, King D, Shif T
Photogrammetric solution for vehicle damage investigation. Canada 1992

Kullgren A, Lie A, Tingvall C.
Photogrammetry for documentation of Vehicle Deformations - A tool in a system for advanced data collection. Accident Analysis & Prevention Vol 26 No. 1 pp99-106 1994

Lie A Tingvall C, Johansson S, Johansson S-O, Metimur AB, Gothenburg
Photogrammetric Measurements of Damaged Vehicles in Road Traffic Accidents.
Experimental Safety Vehicles Munich 1994

National Highway & Traffic Safety Administration
National Accident Sampling Scheme.

Pepe, M.D, Sobek J.S. , Huett, G.J.
Three dimensional computerised photogrammetry and its application to accident reconstruction SAE paper 890739.

Woolley R, White K, Asay A , Bready J
Determination of vehicle crush from two photographs and the use of 3D displacement vectors in accident reconstruction.

AN UPGRADED SYSTEM FOR CRASH TEST DATA ACQUISITION SYSTEM EVALUATION

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ABSTRACT

Since 1987 the National Highway Traffic Safety Administration has been providing to each of its crash and sled test contractors a signal waveform generator (SWG) which supplies precision test waveforms to evaluate the facility's crash or sled test data acquisition system performance for compliance to SAE J211 [1] requirements. As more experience was gained with the SWG, requests from crash test sites world wide to borrow an SWG increased until they exceeded the numbers of SWGs in existence. The SWG was custom designed and built in the early 80's because the required technology was not commercially available. Although the basic electronic design is good, its mechanical construction left the SWG vulnerable to shipment from one site to another and reliability on site was poor. Since the required technology is now available, the National Highway Traffic Safety Administration has developed a system that uses commercially available hardware to the extent possible and can be used by any crash or sled test site in the world to evaluate its own system.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) regularly conducts vehicle and component crash tests to study and rate the crashworthiness of motor vehicles, and to enforce compliance to Federal Motor Vehicle Safety Standards in the United States. A multitude of sled and component tests are also conducted to support anthropomorphic test device development and basic biomechanics research. In practice, several test facilities perform the testing under contract for the NHTSA. The accuracy and correctness of the collected data is critical for both the valid comparison of data from the different facilities and for performing analyses utilizing the data. Moreover, these data serve as a basis for NHTSA published reports, and the corresponding analyses support existing and new safety standards.

Since 1987, NHTSA has been providing to each contractor test facility a custom built SWG for evaluating the facility's crash test data acquisition system (DAS) [2]. The SWG supplies precise waveform sequences with known characteristics to be injected at the crash sensor interfaces. Currently, for the evaluation testing, the waveform data is recorded and digitized employing the facility's regular practices, then the collected data is sent to NHTSA where it is processed utilizing specialized signal processing software. Time and amplitude performance measures, based on the recommended instrumentation practices of the Society of Automotive Engineers, SAE J211, and of the international standard ISO 6487, are computed and analyzed for each data channel. Sufficient details are provided in the analysis to indicate which channels have failed to meet NHTSA's performance requirements and to aid in the diagnosis and troubleshooting of problem areas.

To date, performance evaluation of data acquisition is performed every six months at facilities actively conducting tests for NHTSA under the New Car Assessment Program (NCAP) and the vehicle to barrier compliance testing, FMVSS 208. This evaluation testing is also performed at the active biomechanics sled testing facilities on an as needed basis. DAS evaluation testing has also been performed at the Federal Outdoor Impact Laboratory of the Federal Highway Administration (FHWA), at the Mike Monrooney crash facility of the Federal Aviation Administration, and at the CRASH-LAB facility of the Road Traffic Authority, Australia. Recently, several requests for the SWG hardware to perform the DAS evaluation have been received from the automotive testing industry, from road side testing facilities in the United States, and from the European roadside testing community. In particular, the FHWA is putting forth a prerequisite that its contractor test facilities must pass NHTSA's SWG performance evaluation as part of its certification requirement for testing. Also, the European Committee on Normalization, TCC 226-Road Equipment, WG1-Road Restraint System has plans to adopt the SWG performance evaluation as part of its test facilities calibration requirements. The committee members view calibration of the instrumentation as a prerequisite to accreditation of their test facilities.

The current SWG hardware was custom designed and built by MGA Research Corporation in the early 1980's as the required technology was not commercially available [2].The basic solid state electronic design of

the ten units built is good, although the mechanical construction left the units vulnerable to shipment from site to site, and considerably affected reliability on site. The waveform cards needed to be continually reinserted and the edge connectors cleaned. Some units overheated and other had significant noise at the lower level signal outputs. Therefore ongoing repair and maintenance was needed, and a hardware recertification process was put in place to ensure the required performance accuracy of each of the SWG units.

Contrary to when the SWG was originally developed, the technology for such a waveform generator is now available. State of the art arbitrary waveform generators with a multitude of features can now be acquired commercially. Moreover, there is a need to provide a variety of voltage level outputs from the SWG hardware, currently limited to two output levels, in order to match the different crash transducer outputs. As such, with the demand on the SWG units far exceeding the numbers available and the extensive maintenance required for the existing units, NHTSA opted to upgrade this hardware to a system that utilizes, to the extent possible, commercial components. The goal is to obtain a low cost upgraded SWG system which requires low maintenance and upkeep, and is geared towards the crash test facilities performing self evaluation of their data acquisition. This will make the SWG system available to any test site and will enable the sites to evaluate their own DAS with minimal NHTSA involvement.

This paper describes the approach followed to implement a commercial SWG using a PC based arbitrary waveform generator (ARB) and an output distribution box. The selection process for the most cost effective ARB is described. The requirements for a SWG output distribution box are established and the specifications for this box are provided. The precision waveforms developed for evaluating ARB performance and the methods for controlling the ARB and acquiring test data are described. The concept evaluation testing of the upgraded SWG prototype is described and the results of the test are provided.

HARDWARE UPGRADE APPROACH

The upgraded SWG replaces the custom made "blue box" SWG with a commercially available ARB and a facility fabricated output distribution box. The ARB is an option card that plugs into any IBM compatible PC/XT/AT/386/486. The output distribution box distributes the analog waveform signals from the two output channels of the ARB to many output channels for DAS testing at voltage and impedance levels typical of sensor outputs.

The selection of the Keithly Metrabyte PCIP-AWFG/2 for the recommended ARB option card is described below. The output distribution box is described and specifications for it are provided, below.

The use of the upgraded SWG in DAS evaluation testing is shown symbolically in Figure 1. The waveform data is supplied to the PC on a floppy disk, where it is loaded into ARB on-board memory. Under external control the ARB produces the waveform and time reference data that is modified and distributed to the DAS sensor interface inputs by the output distribution box. The test data recorded by the DAS is indicated symbolically by a floppy disk in Figure 1. Then using the SWG signal processing software, also symbolized by a floppy disk, the test data is processed in a facility PC and the resulting processed data files can be printed for DAS evaluation.

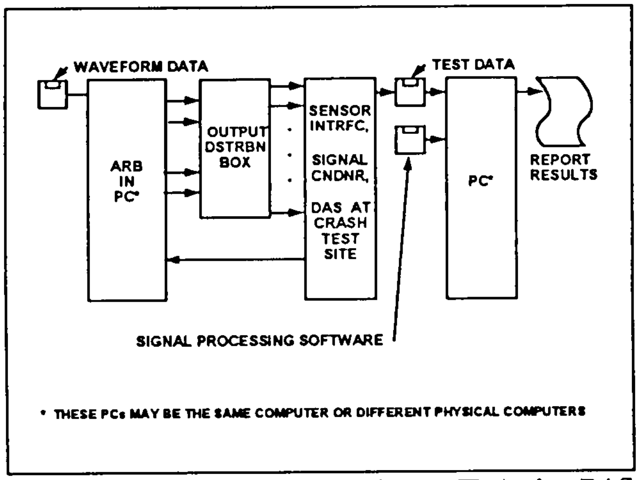

Figure 1. SWG Upgrade Data Flow in DAS Evaluation Testing.

COMMERCIAL EQUIPMENT EVALUATION

As a first step in developing a new SWG, a specification was prepared which defined the performance and features desired in a new SWG. Then fifteen manufacturers of arbitrary waveform generators were contacted to request technical descriptions of their ARB products. The material received was reviewed and modifications to the SWG specifications were made so as to not exclude some of the products described because of a specification requirement that was not considered essential to SWG performance. The revised SWG specifications were sent to the fifteen manufacturers with a request that each one recommend which of their products would most closely meet the new SWG specifications and what they would be willing to do to modify their equipment to meet the specifications that their standard equipment did not satisfy.

A review of the ARB information received showed that several of the requirements of the SWG specifications could be met by only one or two of the available ARB units. First, only two products could provide two independent waveforms, each on eight separate outputs. Second only one ARB product of those that would satisfy most other SWG requirements had a time base accuracy of 10 PPM. From this it was obvious that to make use of most of the ARB equipment available commercially, a separate output distribution box would be required to provide eight or more analog waveform outputs of each waveform group at the required voltage and impedance levels. Several manufacturers did allow that for extra money they would be willing to install a more accurate time reference.

To determine which of the commercial ARBs would satisfy the SWG requirements in the context of using a separate output distribution box, a set of specifications containing only requirements essential to SWG performance was prepared (See Appendix A) and the commercial ARBs were evaluated on the basis of these specifications. Incidentally, the maximum ARB output update interval was specified to be 31.25 µs to minimize on-board memory requirements (so the maximum number of commercial ARB models could be considered in this evaluation) while still keeping the ARB update frequency greater than twice the highest likely test facility data sampling frequency. The pertinent information from the technical data sheets of each manufacturer is summarized in Appendix B. The entries in the top part of the table have the potential to satisfy the requirements for an SWG with only minor modification. They are listed in the order of increasing price. Price estimates are for the equipment needed to replace one SWG. Price quotes are 1991 prices. Price estimates do not include the cost of an output distribution box. Entries at the bottom part of the table are the equipment that failed to satisfy at least one essential requirement of the SWG specification. The equipment characteristic that failed to meet SWG requirements is shown bold faced. The ARB units from PC Tools, Burr-Brown, Wavetek, and Philips had insufficient on-board memory to perform the required waveform storage. The Rapid Systems unit lacked the ability to synchronize its digital outputs with the analog outputs. The Markenrich and Philips units had insufficient digital-to-analog converter (DAC) resolution. The Hewlett-Packard unit did not provide synchronized digital outputs.

Since it met all but one of the essential requirements for an SWG ARB, was the least expensive of the ARB products that did meet these requirements, and the manufacturer was willing to provide a more accurate time base, the Keithly Metrabyte PCIP-AWFG/2 with a 25 PPM time base was selected as the candidate ARB to use for the SWG upgrade. A 25 PPM time base is used in the present SWG and has proved to be satisfactory. The PCIP-AWFG/2 is pictured in Figure 2.

Having made this selection, one question remained. Would this ARB actually meet the manufacturer's performance specifications? The best way to answer that question was to test the product.

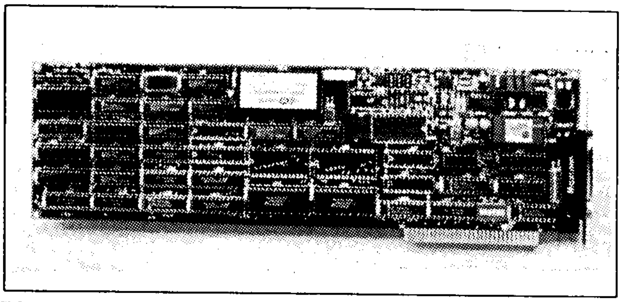

Figure 2. Keithley Metrabyte PCIP-AWFG/2

CANDIDATE ARB TEST PREPARATION

Prior to testing the candidate ARB in the context of an upgraded SWG, several tasks had to be accomplished. A waveform data file for use in the ARB had to be developed. Software to control data acquisition and operation of the test had to be developed. Hardware to provide the functions of an output distribution box had to be designed and fabricated.

Waveform Data File Development

To minimize the software development required for processing the test waveforms, the waveforms to be used for the test of the SWG upgrade prototype were designed to be as similar to the waveforms used in the present SWG as possible. These waveforms were described in detail in an earlier paper [2]. One characteristic of the Keithly-Metrabyte PCIP-AWFG/2 that affects waveform development is it's minimum output update interval resolution of 200 ns. The present SWG update interval is 30.50 µs, which cannot be duplicated by the PCIP-AWFG/2. Thus the SWG signal processing software had to be modified to provide for a different update interval. Although many shorter sample intervals could have been used in the PCIP-AWFG/2, use of the interval closest to the maximum specified, 31.20 µs, would permit the acquisition of the greatest quantity of calibration data. Another characteristic of the PCIP-AWFG/2 that affects waveform data file development is that the digital output data is combined with the analog data for each channel. In each data word in the ARB input file, the most

significant 12 bits are converted to analog data and the least significant four bits are the digital data.

The SWG waveform sequences are nominally configured to consist of four 125 ms waveform segments preceded by a 30 ms period consisting of a 10 ms pre-time-zero pulse followed by 20 ms of null output. The 31.2 μs sampling interval precludes achieving these period durations exactly. For example, 125 ÷ 0.0312 = 4006.410256. Therefore let each waveform segment be of 4006 sample interval duration. Then each waveform segment duration is 4006 × 0.0312 = 124.9872 ms. This is close enough to 125 ms for practical purposes. The time-zero (T0) time reference waveform is a 50 percent duty cycle square wave, spending 2003 sample intervals (62.4936 ms) at each level. The "10 ms" pre-time-zero pulse is 320 sample intervals = 9.984 ms duration. The entire period before time-zero is 960 sample intervals = 29.952 ms duration.

Plots of the three waveform files generated for this task are shown in Figure 3. The magnitude of the group 1 and group 2 waveforms is expressed as a decimal equivalent to the binary number that will be applied to the input of the DAC in the ARB.

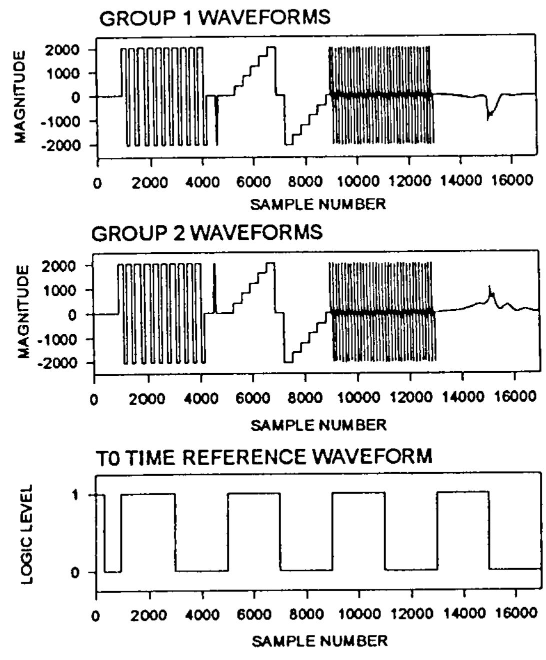

Figure 3. SWG Waveforms.

Rectangle Waveform - The rectangle waveform consists of 10 cycles of a square wave alternating between positive full scale and negative full scale. The nominal cycle time is 10 ms. Nominally six ms are spent at the positive full scale level and four ms are spent at the negative full scale level. However, ten ms is not evenly divisible by 0.0312 ms. The closest integer number of update intervals of 0.0312 ms duration that approximate a 10 ms interval is 320. This results in a 9.984 ms cycle time. Of this cycle period 192 sample intervals or 5.9904 ms are spent at the positive full scale level and 128 sample intervals or 3.9936 ms are spent at the negative full scale level. The resulting rectangle waveform is 99.84 ms long. This does not cause a problem because the waveform signal processing software developed for this test reflects the correct waveform duration. The waveform generated for this task is scaled to have its peaks (its full scale level) at the nearest level to the maximum positive output from the DAC that is divisible by five so that the five levels of the STAIR waveform will be precise and equal increments of the full scale level. The rectangle waveform is preceded by 960 sample intervals of zero level to allow time for the pre-time-zero pulse.

Half-Sine Pulse - The half-sine pulse waveform is 2.985 ms duration at its base and has its peak at the nominal center of the 25 ms interval following the rectangle waveform. For the X-axis (group 1) waveform the peak extends to negative full scale level. The Z-axis (group 2) waveform peak is at positive full scale level. For these datasets, the half-sine pulse starts 357 sample intervals (11.1384 ms) after the end of the rectangle waveform.

Stair Waveform - The stair waveform consists of five equal magnitude steps from zero level to positive full scale level, followed by a single step back to zero level, followed by a single step to negative full scale level, followed by five equal magnitude steps back to zero level. The time spent at each level is 320 sample intervals (9.984 ms).

Sum-Of-Sines Waveform - The sum-of-sines waveform consists of the sum of 14 equal amplitude sine waves whose frequencies are successive integer harmonics of the fundamental (lowest) frequency (273.4375 Hz) of the composite signal. The peak level of the composite signal is scaled to be ± the waveform full scale level. Because this waveform is the summation of equal amplitude successive integer harmonics, only the highest and lowest frequencies are visible in the composite waveform.

Crash Pulse - The crash pulse used in the present SWG is derived from actual crash test data recorded at a sample interval of 75μs. To convert these data to the 31.2μs update interval to be used by the ARB requires interpolation. The interpolation method used here was described by Crochiere and Rabiner [3] and used digital computer programs available from the IEEE [4]. The resulting interpolated data file differed from the original

by 0.3 percent in peak x-axis acceleration and 0.5 percent in peak z-axis acceleration. The head injury criterion (HIC) value computed from the interpolated data differed from the HIC value computed from the original data by -0.05 percent. The HIC value used in the waveform signal processing software was changed to agree with the HIC value computed from the interpolated data file.

Data Acquisition Control

The ARB has both an external gate input and an external clock input that can be used to control ARB output. When the ARB external gate input is at a transistor-transistor-logic (TTL) high level, the ARB produces output updates. When the external gate input drops to a TTL low, ARB output stops. The data acquisition system used for this test, the data acquisition processor (DAP), has the capability to produce both analog and digital outputs. For this test the DAP was programmed to produce a TTL high on a digital output for the length of time a sequence of ARB outputs was desired. This digital output was connected to the ARB external gate input.

The test consisted of three sequences of data acquisition. During the first sequence, the ARB was programmed to provide constant calibration level signals from its two analog output channels for 7800 update intervals each at 31.2 μs per interval. This signal was sampled and averaged for 243.36 ms by collecting and averaging 8112 samples from each analog channel sampled at 30 μs intervals. During the second sequence, the ARB was programmed to provide a zero output level from both analog channels for 7800 update intervals. Again these signals were collected and averaged for 243.36 ms. The averaged zero and calibration level signals provided the data necessary to scale the waveform data acquired in the third data acquisition sequence. During the third sequence, the ARB was programmed to produce a single sweep of the waveform data that was stored in its random access memory (RAM). The "data ready" (or external clock) output from the ARB was connected to the external clock input of the DAP so that each time a new output was available at the ARB output terminals, the DAP did one sampling sweep of the data available at each terminal.

Test Output Box

For the purposes of testing and evaluating the SWG upgrade concept all of the features of the full output distribution box are not required. Only one output of each waveform is required. The digital signals can be connected directly from the ARB to the DAP. Consequently the test output box (TOB) used to test and evaluate the SWG upgrade concept need provide only two analog channels for testing the circuitry that provides the required output voltage ranges and impedance levels under real world conditions. A summary of TOB specifications is shown in Table 1.

Table 1.
Test Output Box Specification Summary

Inputs: 2 analog, single ended, ±5 V
Outputs: 2 analog, differential, full scale voltage selectable from ±500 mV, ±200 mV, ±100 mV, ±50 mV, ±20 mV, ±10 mV, ±5 mV, output impedance ≈ 350 Ω
Calibration output voltage: within ±2% of nominal full scale level
Accuracy: ±0.20% of full scale calibration voltage
Output noise: rms level < 0.05% of full scale level
Step response settling time to 0.01% of final value < 16 μs

The circuitry for either channel of the TOB consists of the input from the ARB being split between the inputs of two amplifiers, one a unity gain buffer and the other a unity gain inverter. The output of each amplifier is connected to one end of a resistive voltage divider wired onto a disk of a rotary switch. The rotor pickoff from each disk of the switch is connected to one end of a 357 ohm resistor which provides the output resistance for the TOB. The output leads are connected to each end of the 357 ohm resistor. A schematic for one channel of the TOB is shown in Figure 4. Actually all four rotary switch disks for both channels are mounted on the same switch shaft.

FEASIBILITY TEST & EVALUATION

The hardware tested is the combination of the ARB and the TOB, together called the ARB/TOB. The test consists of measuring timing and amplitude accuracy and amplitude frequency response.

Timing Accuracy

Five factors contribute to ARB/TOB timing accuracy. The first is the actual frequency of the ARB crystal clock oscillator. The second is the timing accuracy of the time reference signals from the ARB. The third is the precision with which the ARB time reference pulses coincide with the ARB/TOB waveform data. The fourth is the precision with which the group 1

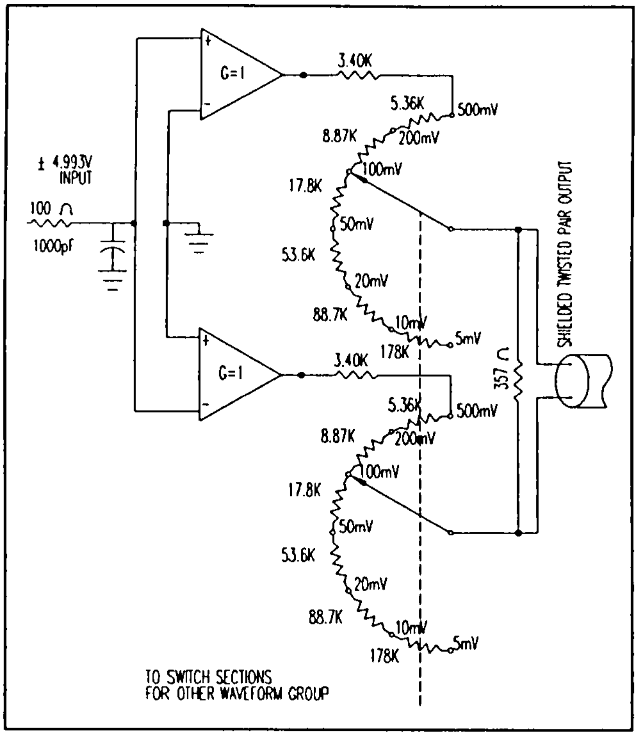

Figure 4. Schematic for One Channel of TOB.

and group 2 waveforms are synchronized with each other. The fifth is the timing accuracy of the individual waveforms.

Clock Frequency - The frequency of the ARB crystal clock oscillator, which determines the timing of all ARB/TOB outputs, was measured using a Hewlett-Packard 5386A-004 precision frequency counter.

Time Reference Signals - The primary time reference signal from the ARB is the T0 output. The accuracy of the time reference signal determines the accuracy with which the ARB/SWG can test the timing accuracy of a crash test DAS. The time between the rising edges of the first and fourth T0 pulses after the pre-time-zero pulse is used to determine sample timing accuracy of the DAS under test. The leading edges of the first and second T0 pulses after the pre-T0 pulse are the time references that mark the start of the rectangle/half-sine and stair waveform segments.

The actual time of occurrence of the T0 transitions within the 31.2 μs ARB DAC output update interval was measured using the DAP. The start of the DAP sampling sweep was synchronized to the ARB DAC strobe pulse. Consequently, all time measurements over intervals greater than 31.2 μs are relative to the ARB crystal clock oscillator frequency. Sample timing within one 31.2 μs interval was controlled by the DAP crystal clock oscillator.

Coincidence of Waveform Edges - The coincidence of the initial rising edges of the time reference pulse and the rectangle waveform was measured to determine the timing accuracy of the waveform data relative to the time reference. This was measured using a Hewlett-Packard 54600A dual trace digital storage oscilloscope. This is a critical measurement because the time reference pulses are used by the processing software to determine the starting time of each waveform and thereby the timing accuracy of the DAS under test.

Waveform Group Synchronization - The half-sine pulses in each waveform group are used to measure any time differences between the two waveform groups.

Waveform Timing - The software used to process ARB/TOB waveform data performs a test to determine the times at which recorded changes in level of the rectangle and stair waveforms occur. If the ARB/TOB waveform level changes at times that are different from those that the software uses as a reference, a time difference error is calculated.

Amplitude Accuracy

The accuracy of the waveform amplitudes was determined by two methods. The SWG signal processing software (SPSW), as modified to make it compatible with the waveform files that are generated by the ARB, was used to analyze the waveform data recorded by the DAP. The amplitude accuracy measures determined are ARB/TOB full scale amplitude accuracy using the positive calibration signal and the zero calibration signal from the ARB/TOB as references, amplitude linearity, and zero offset.

Calibration Level - The positive and negative calibration voltages at all seven output level settings from both output channels were measured with a Fluke 8050A digital multimeter to confirm that each channel output is providing the correct calibration voltage level (and thus, transmitting correct DAC outputs). "Zero" output levels were also measured to establish "zero" offsets.

Waveform Amplitudes - The ARB SPSW compares the average values of the constant portions of the rectangle and stair waveforms with the theoretical values for these waveforms at those levels. The peak values for the half-sine waveforms are detected by the SPSW.

Frequency Response

The frequency response of the ARB/TOB is determined by processing the unfiltered sum-of-sines waveform output from the ARB/TOB.

Waveform Data Acquisition

The test setup used to acquire waveform data is shown in Figure 5. The signal source is the ARB, a

PCIP-AWFG/2. The analog waveform signals are fed to the TOB which converts them to voltage and impedance levels expected from crash test sensors. These sensor level signals are then fed to the test instrumentation module (TIM) which contains instrumentation amplifiers. The amplified signals are fed to the DAP which acquires the data. The DAP is a Microstar DAP2400/5 data acquisition processor. In a sense this setup is analogous to crash test data acquisition in that the ARB/TOB provides the sensor signals. The TIM provides the amplification of the on-site signal conditioners and the DAP is a digital data acquisition system.

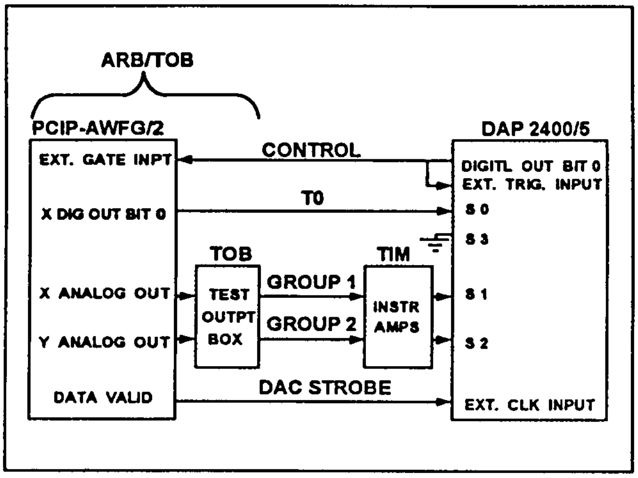

Figure 5. ARB/TOB Waveform Data Acquisition Test Setup.

Test Instrumentation Module (TIM) - The TOB was described above. The TIM consists of two variable gain instrumentation amplifiers. A schematic for one channel of the TIM (one amplifier) is shown in Figure 6.

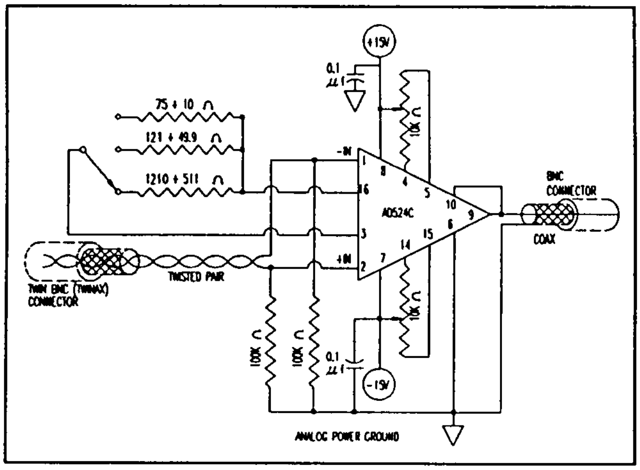

Figure 6. Schematic for One Channel of TIM.

Test Results

The performance requirements and the test results for the ARB/TOB test and evaluation are summarized in Table 2 which shows that the ARB/TOB met or exceeded all performance requirements.

Table 2.
Test Results

	Required Performance	**Test Results**
Timing Accuracy:		
Clock Frequency	5 MHz ±45 Hz	4,999,981 Hz
Time Reference Signals	exact match with input dataset	exact match with input dataset
Waveform Edge Coincidence	±1 μs	start within 1 μs interval
Waveform Group Synchronization	± 500 ns	exact, no time difference
Waveform timing	exact match with input dataset	exact match with input dataset
Amplitude Accuracy:		
Calibration Levels	± 2% of nominal level	± 1% of nominal level
Waveform Amplitudes	± 0.25% of full scale calibration level	errors < 0.25% of full scale at all output levels
Noise	rms level < 0.07% of full scale at all output levels	rms level < 0.07% of full scale at all output levels
Frequency Response:		
Amplitude Response	0 ± 0.05 dB, 0 to 4 kHz	0 ± 0.02 dB, 273 to 3828 Hz

OUTPUT DISTRIBUTION BOX

As mentioned earlier, the output distribution box (ODB) distributes the two analog signals from the ARB to many output channels at voltage and impedance levels typical of sensor outputs. In addition the ODB carries digital data to and from the ARB. The ODB is shown schematically in Figure 7. The 75 ohm resistors in the ARB input leads are recommended by Keithly Metrabyte

for impedance matching purposes. If external signals are fed to the ODB by coaxial cable, the shunt resistors should be switched into the circuit. Since the ODB will be specified, designed, and fabricated (or at least specified and purchased) by each using facility, it is desirable to separate the specifications required for satisfactory performance from recommendations for design of the ODB. The recommendations represent optional specifications that can be used or modified by the using facility. The requirements are presented in Table 3. The optional recommendations are provided in Table 4.

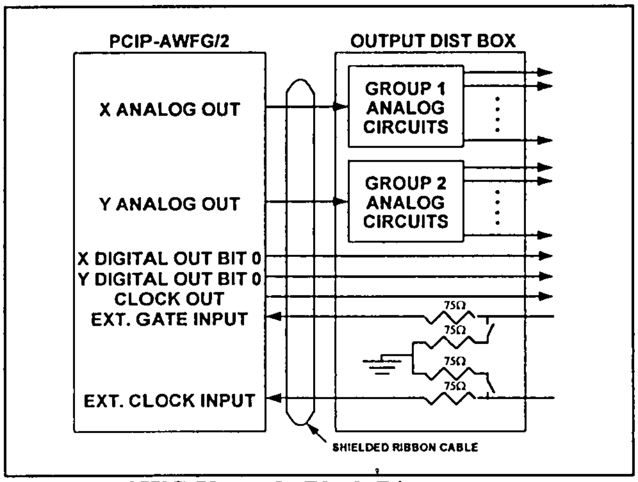

Figure 7. SWG Upgrade Block Diagram.

The circuit design approach used for the ODB can be like that used for the TOB (Figure 4.). This design approach superimposes amplifier noise on the highest signal level part of the circuit, resulting in the highest signal-to-noise ratio. If seven different output levels are to be selected using currently available rotary switches, at most two channels can be carried on one switch. Thus, if a large number of output channels are required, the limit of two channels per switch requires that a large number of rotary switches be accommodated. If a smaller number of output levels can be tolerated or if an electronic switching arrangement can be designed, then the space penalty will not be as great. Another design approach, shown in Figure 8, uses fewer amplifiers and fewer rotary switches. However, in this scheme the amplifiers are used at signal levels that can be quite small. Consequently a very low noise amplifier (output noise voltage density < 25 nV/√Hz, 10 Hz to 1 MHz) is required to maintain the output noise below the specified level.

Table 3.
ODB Requirements

Number of analog (waveform) inputs	2
Number of digital signal paths from the ARB	3
Number of digital signal paths to the ARB	2
Required amplitude accuracy	0.20% of full scale voltage (referred to calibration voltage) at all output levels
Nonlinearity error	0.03% max.
Full scale calibration accuracy	Within 2% of nominal voltage level
Settling time for step response from minus to plus or plus to minus full scale voltage	≤ 15 μs to 0.01% of step magnitude
Amplitude frequency response	0 ± 0.05 dB, 0 to 4 kHz
Output noise	Rms noise level ≤ 0.05% of full scale voltage at all output levels
Input filter (analog inputs)	Single pole RC, R=100 Ω, C = 1000 pF
Input connector	25-pin (female) "D"

Table 4.
Recommendations for ODB

Number of analog outputs	Optional
Differential analog output voltage levels	±5, ±10, ±20, ±50, ±100, ±200, and ±500 mV
Output impedance	≈ 350 Ω
Output connector(s)	User option but connecting to shielded twisted pair cable

BETA TEST OF SWG UPGRADE

Beta testing of the SWG upgrade will be performed at the NHTSA Vehicle Research and Test Center, the FHWA Federal Outdoor Impact Laboratory, and the current three NHTSA crash test contractor's sites. The purpose of the test will be to familiarize test site personnel with the operation of the SWG hardware and software, to evaluate the performance of the SWG upgrade in a real world impact test site environment, and to use the SWG upgrade to evaluate the instrumentation and data acquisition system at each test site.

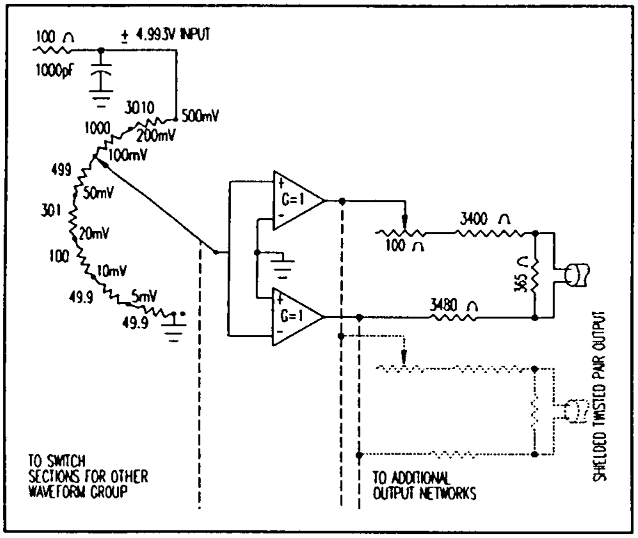

Figure 8. Optional Design Approach for ODB.

NHTSA will furnish to each test site one ARB with output cable. Each test site will be required to design and fabricate or have made for it an output distribution box that matches facility requirements while following the recommendations provided by NHTSA.

The test site will perform certification testing of the SWG upgrade according to NHTSA furnished requirements. If the onsite SWG upgrade passes the certification test, the SWG upgrade will be used to perform a DAS evaluation test of the test site's instrumentation and data acquisition system.

CONCLUSION

An upgrade to the current SWG system for evaluation testing of crash test acquisition systems performance has been developed. All results to date indicate that the new hardware will be a satisfactory replacement for the (blue box) SWG. In addition, the upgraded system offers several advantages.

It is based on a low cost commercially available, state of the art, PC option card and a simple electronic distribution box which is easy to assemble. Several design approaches for the distribution box have been outlined in this paper. As such, the overall system has minimal upkeep and maintenance requirements. It also ensures availability of the system to any crash or sled test facility in the world. The new system also provides a variety of voltage level outputs in order to better match the different crash transducer outputs.

A report will be made available by NHTSA to contain as minimum, operating instructions for the SWG upgrade, specifications for the ARB, and specifications and recommendations for the output distribution box. NHTSA will also provide PC compatible software for processing waveform data collected from the upgraded SWG so crash test facilities can evaluate their own instrumentation and data acquisition equipment.

REFERENCES

1. Society of Automotive Engineers, Inc., "Instrumentation for Impact Tests", SAE Recommended Practice, SAE J211 OCT88, 1994 SAE Handbook, Vol. 3, 1994, pp. 34.270 - 34.276.

2. Radwan, Randa and Nickles, John, "Performance Evaluation of Crash Test Data Acquisition Systems", Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles, November 1991, pp. 1157 - 1171.

3. Crochiere, R. E. and Rabiner, L. R., "Optimum FIR Digital Filter Implementations for Decimation, Interpolation, and Narrow-Band Filtering", IEEE Transactions on Acoustics, Speech, and Signal Processing, Vol. ASSP-23, No. 5, October 1975, pp. 444 - 456.

4. Crochiere, R. E., "A General Program to Perform Sampling Rate Conversion of Data by Rational Ratios", Section 8.2, pp. 1 - 7, McClellan, J. M., Parks, T. W., and Rabiner, L. R., "FIR Linear Phase Filter Design Program", Section 5.1, pp. 1 - 13, Programs for Digital Signal Processing, IEEE Press, 1979.

APPENDIX A. MINIMUM ESSENTIAL REQUIREMENTS FOR ARB

1 - Provide two independent waveform sequence outputs, two independent timing sequence outputs, and one DAC strobe output, all synchronized to within ±1 ms.

2 - Provide sufficient on-board RAM (for option card configuration) or non-volatile storage (for stand-alone configuration) for two waveform sequences and two time reference sequences all of 530 ms duration.

3 - The digital-to-analog converter shall have at least 12 bit resolution.

4. DAC update interval shall be less than or equal to 31.25 μs with a minimum resolution of less than or equal to 200 ns.

5 - If ±10 PPM time reference accuracy is not standard, a higher time reference accuracy crystal than the standard crystal supplied must be available.

6 - Amplitude accuracy required: ±0.25 percent of full scale calibration level (provided in the calibration mode)..

7 - Calibration levels shall be provided by the two waveform outputs. Calibration voltage level shall be within ±2 percent of the nominal output voltage level

8 - Dynamic response: The settling time for a step from - to + full scale (or + to - full scale) shall be less than 10 ms to within 0.1% of final value. The frequency response shall be 0 ±0.02dB from 0 to 10 kHz.

9 - The maximum rms level of output noise shall be less than 0.05 percent of full scale.

10 - ARB shall have remote operation capability.

11 - ARB shall have self-test capability.

APPENDIX B. ARB COMPARISON PART 1

Make	Model	# Analog Channels	# Digital Channels	RAM/ Channel	NV Mem/ Channel	DAC Amp Res	DAC Smp Res	Config- uration
Keithly Metrabyte	PCIP- AFWG/2	2	8	32K	0	12 bits	200 ns	PCC *
RC Electronics	RC-202 RC-204 RC-216	4 1	8 4 0	0 0 64K	0 0 0	 16 bits	 1 μs	PCC PCC PCC
Integrated Technologies Solutions	IPDS- 3000	3 (16 out chan)	12	0	32K	12 bits	167 ns	SA *
Krohn-Hite	5920	1	1	0	16K	12 bits	100 ns	SA
Analogic	2020-25	1	1	64K	0	12 bits	40 ns	SA
Yokogawa	AG1200 705142	2	2	32K	720K 3.5" FDD	12 bits	100 ns	SA
LeCroy	9112	2	2	32K	175K	12 bits	20 ns	SA
Tektronix	VXI 73A-243 VX1401 system	2 (16 out chan)	2	16K	0	12 bits	40 ns	VXI system
PC Tools	Analog 12/2	2	8	0	0	12 bits	7.7 μs	PCC
Burr-Brown	PCI- 20006M-2 20007M-1	2	4	0	0	16 bits	125 ns	PCC
Markenrich	WAAG II	1	0	32K	0	8 bits	50 ns	PCC
Rapid Systems	R4000	1	0	16K	0	12 bits	200 ns	PCC
Wavetek	680-01	1	2	12K	0	12 bits	50 ns	SA
Philips	5138-023	1	0	1K	0	10 bits		SA
Hewlett- Packard	8770A	1	0	256K	0	12 bits	8 ns	SA

* PCC = Personal Computer Option Card, SA = Stand Alone Unit

ARB COMPARISON PART 2

Make	Model	Time Base Accuracy	Amplitude Accuracy	Amplitude Rise Time	Settling Time	Noise	Interface	BIF *	Cost $
Keithly Metrabyte	PCIP-AFWG/2	100 PPM **		150 ns	600 ns	-70 dB S/N	PC bus	N	1229
RC Electronics	RC-202 RC-204 RC-216	***	±0.01%			0.01% rms	PC bus	Y	4880
Integrated Technologies Solutions	IPDS-3000	50 PPM ***			50 ns		none	N	6000-8000
Krohn-Hite	5920	100 PPM ***	±0.1%	100 ns			IEEE-488	Y	7990
Analogic	2020-25	50 PPM	1%+10 mV	10 ns	60 ns	0.5 mV rms	IEEE-488	Y	13990
Yokogawa	AG1200 705142	50 PPM	±0.5% +15 mV	70 ns		1 mV rms	GPIB	Y	15950
LeCroy	9112	5 PPM	1 %	8 ns	20 ns	0.1% FS+ 2 mV	GPIB	Y	16050
Tektronix	VXI 73A-243 VX1401 system	250 PPM	±0.4%		125 ns		VME bus	Y	30000
PC Tools	Analog 12/2				10 μs		PC bus	N	395
Burr-Brown	PCI-20006M-2 20007M-2	150 PPM	±0.12%		8 μs		PC bus	N	1185
Markenrich	WAAG II		1 %				PC bus	N	2790
Rapid Systems	R4000		0.1%	50 ns	50 ns		PC bus	Y	4490
Wavetek	680-01	5 PPM	1% + 5 mV				GPIB	Y	6790
Philips	5138-023	2 PPM	1%				GPIB	Y	7980
Hewlett-Packard	8770A	$5X10^{-10}$	0.024%				HPIB	Y	50000

* BIF = Built In Function Generator
** 25 PPM time base available at extra cost
*** 10 PPM time base available at extra cost

RAIL-HIGHWAY CROSSING SAFETY: FATAL CRASH AND DEMOGRAPHIC DESCRIPTORS

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Paper Number 96-S9-W-28

ABSTRACT

This report was prepared as part of the June 1994 Departmental Rail-Highway Crossing Safety Action Plan. Initiative V.B, Data and Research -- Demographics, called for a study describing the circumstances under which fatal rail crossing crashes occur and characteristics of the drivers involved in such crashes. This report compares fatal motor vehicle rail crossing crashes with fatal crashes occurring at intersections and all fatal crashes. Data from the National Highway Traffic Safety Administration's (NHTSA's) Fatal Accident Reporting System, supplemented with information from Claritas, a commercially available geodemographic database, were used to provide the descriptive statistics.

INTRODUCTION

In June 1994, the U.S. Department of Transportation published the Rail-Highway Crossing Safety Action Plan, encompassing support proposals from the Federal Highway Administration, Federal Railroad Administration (FRA), Federal Transit Administration, and the National Highway Traffic Safety Administration (NHTSA). The action plan presents a multi-faceted, multi-modal approach for improving safety at our nation's highway-rail crossings and for the prevention of trespassing on the rights-of-way of our nation's railroads. One of the six major initiatives identified in the plan was initiative V -- Data and Research.

The current report represents the culmination of crash and demographic data analysis, described in the action plan as initiative V.B -- Demographics. This report presents an analysis of fatal motor vehicle rail crossing crashes, describing the circumstances of occurrence and characteristics of drivers involved. Data from NHTSA's Fatal Accident Reporting System (FARS) and Claritas, a commercially available geodemographic database, were used to provide the descriptive statistics. The ultimate goal of this report is to provide a description of fatal crashes and involved drivers to effectively focus countermeasure efforts on appropriate target populations.

In 1992, there were 388 fatal traffic-related rail crossing crashes and 489 associated fatalities. Both the National Highway Traffic Safety Administration and the Federal Railroad Administration maintain statistics on rail crossing crashes. However, NHTSA collects information only on traffic-related crashes, and thus, the fatality totals reported by FRA are generally greater than those reported by NHTSA.

CRASH DATA

The National Highway Traffic Safety Administration's Fatal Accident Reporting System (FARS), which became operational in 1975, contains a census of fatal traffic crashes within the 50 states, the District of Columbia, and Puerto Rico (although Puerto Rico is not included in national totals). To be included in FARS, a crash must involve a motor vehicle on a public trafficway and must result in the death of an occupant of a vehicle or a nonmotorist within 30 days of the crash.

In this report, data from FARS calendar years 1975-1992 were used. Most figures in the report show, in addition to fatal rail crossing crashes, fatal intersection and all fatal crashes for comparison purposes. Intersection crashes were used as a comparison because rail crossings are a special type of intersection and a comparison of rail crossing to other intersection fatal crashes could be enlightening. In this report, fatal intersection crashes do not include fatal rail crossing crashes; thus, these two groups do not overlap. The all fatal crashes comparison group represents all crashes in FARS.

ANALYSIS

Fatal Crashes

Figure 1 displays the number of fatal rail crossing crashes and the number of fatalities in rail crossing crashes over the past 18 years. In 1992, 388 fatal traffic-related rail crossing crashes resulting in 489 fatalities were reported to the FARS database.

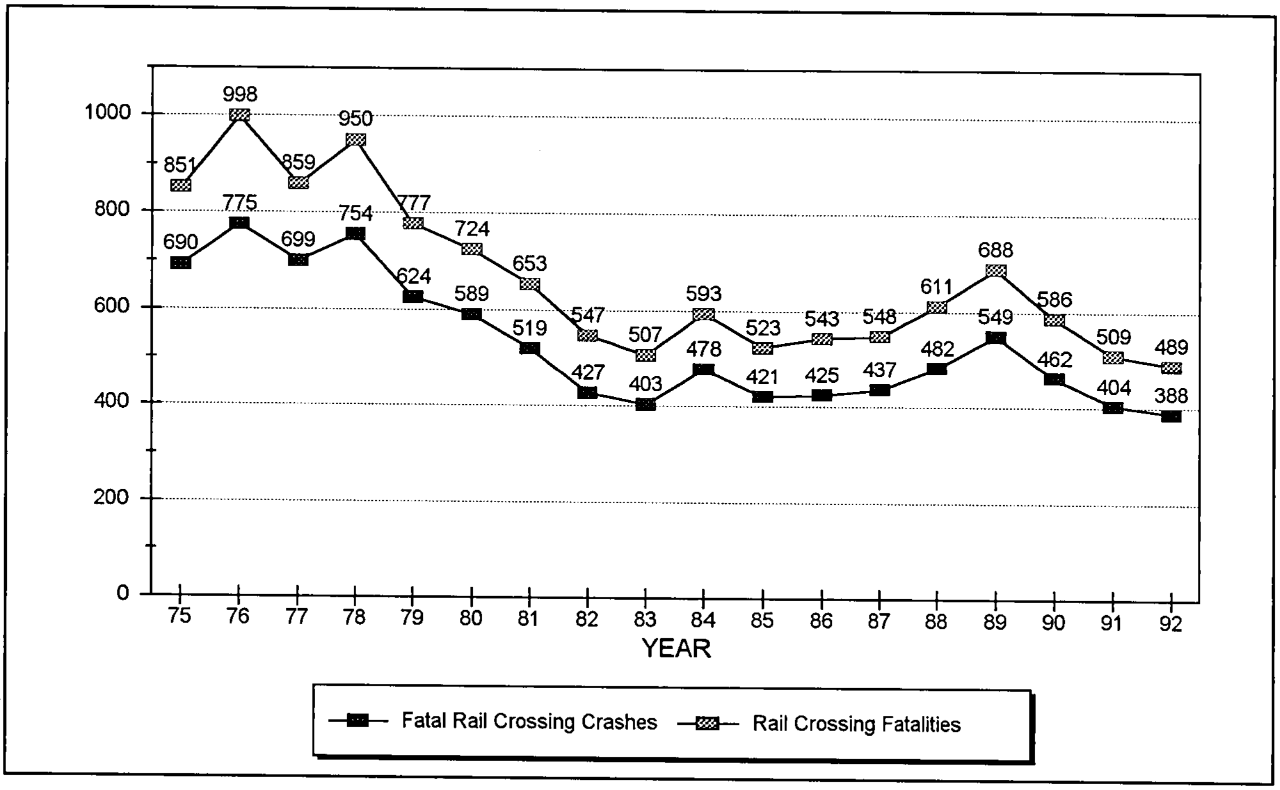

Figure 1. Rail crossing crashes and fatalities by year. Source: FARS 1975-1992.

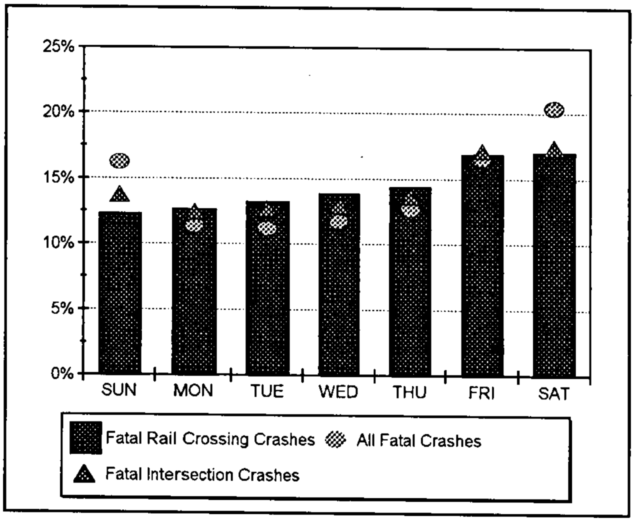

Figure 2. Percentage of crashes by day of week. Source: FARS 1975-1992.

Figure 2 shows the percentage of fatal crashes by day of the week. Fatal rail crossing crashes occur least frequently on Sundays, and increase daily through the week, reaching a peak on Fridays and Saturdays. In contrast, the pattern for all fatal crashes shows a greater percentage during Friday, Saturday and Sunday, and a lesser portion occurring during Monday through Thursday.

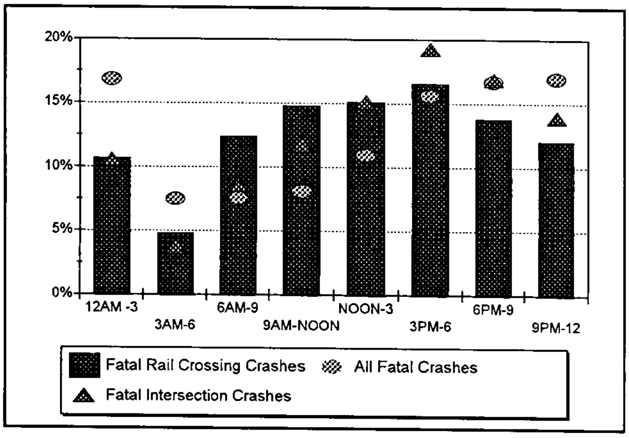

Figure 3. Percentage of crashes by time of day. Source: FARS 1975-1992.

Figure 3 shows the percentage of fatal crashes by time of day. With the exception of the 3 a.m. to 6 a.m. time frame (in which there are very few such crashes), fatal rail crossing crashes occur fairly regularly throughout the day. This is in contrast to all fatal crashes, which are much more frequent between the hours of 3 p.m. to 3 a.m.

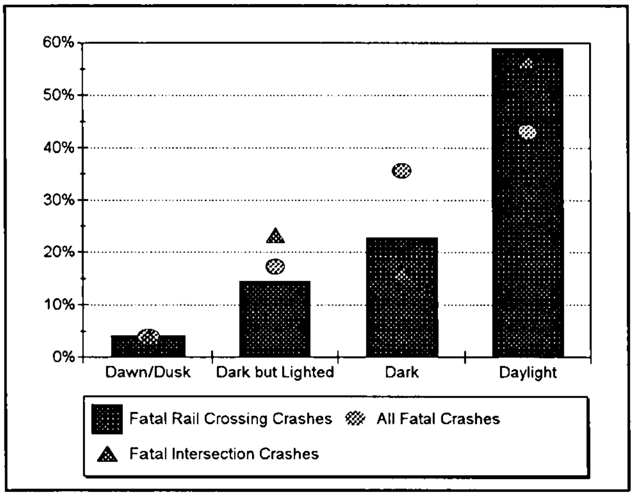

Figure 4. Percentage of crashes by light condition. Source: FARS 1975-1992.

Figure 4 shows the percentage of fatal crashes by light condition. Almost 60 percent of fatal rail crossing crashes occur during daylight conditions, compared to less than 45 percent of all fatal crashes (a greater percentage of which occur during dark conditions). The difference between fatal intersection and fatal rail crossing crashes during dark and dark but lighted conditions may be due to the possibility that more traffic intersections are lighted than are rail crossing intersections.

Traffic Control Devices

Figure 5 shows the percentage of fatal rail crossing crashes in FARS 1992 and the percentage of rail crossings present in the United States in 1992 by traffic control device. These estimates serve to contrast the presence of devices and occurrence of fatal rail crossing crashes. These estimates do not reflect measures of exposure, such as the number of trains and motor vehicles passing at each traffic control device. These data are available within the Federal Railroad Administration databases, and could provide fruitful information for further investigation.

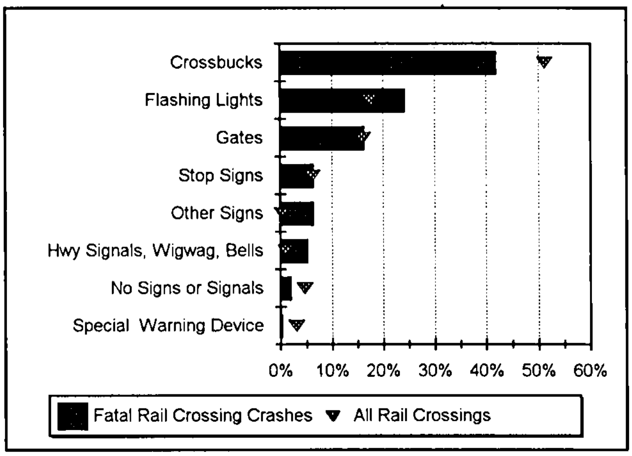

Figure 5. Percentage of fatal rail crossing crashes and rail crossings by traffic control device. Source: FARS 1992, Federal Railroad Administration "Highway-Rail Crossing Accident/Incident and Inventory Bulletin" No. 15 Calendar Year 1992.

Fatal rail crossing crashes at crossings with crossbucks as the traffic control device comprised 42 percent of all fatal rail crossing crashes in 1992, the most frequent traffic control device present. At the same time, 52 percent of all crossings had crossbucks as the traffic control device. This apparent "underrepresentation" of crossbuck locations could also be associated with lower exposure in terms of potential motor vehicle-train collision opportunities.

Crossings with flashing lights as the traffic control device comprised 24 percent of all fatal rail crossing crashes in 1992, the second most frequent traffic control device present. At the same time, 17 percent of all crossings had flashing lights as the traffic control device. Again, motor vehicle-train exposure could be a factor in relating fatal crash occurrence to the presence of this and other types of traffic control devices.

Crossings with gates and stop signs (the third and fourth most frequent traffic control device present, respectively) experienced the same percentages of all fatal rail crossing crashes as their representation at rail crossing locations.

Roadway Characteristics

The variables, posted speed limit and land use (urban or rural), describe the types of roads where rail crossing crashes occur.

Figure 6 displays the percentage of fatal crashes by posted speed limit. Over the period 1975-1992, over 30 percent of fatal rail crossing crashes occurred on roads posted 55 mph. The second most frequent occurrence of fatal rail crossing crashes was on roads with posted speed limits of 25-

30 mph (over 25 percent).

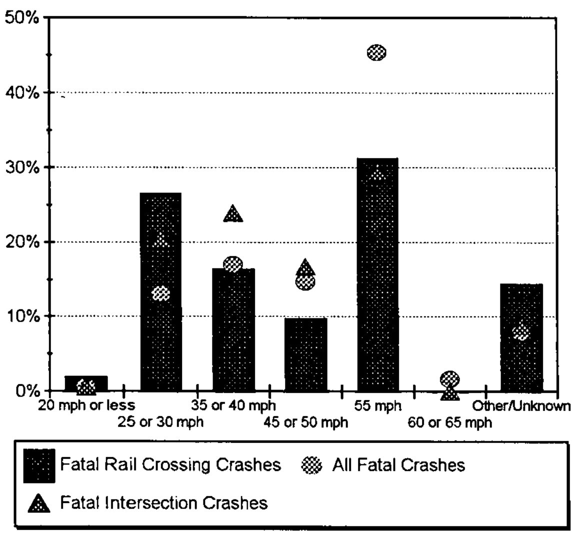

Figure 6. Percentage of crashes by posted speed limit. Source: FARS 1975-1992.

The land use (urban or rural) distribution for fatal crashes is displayed in figure 7. Over 60 percent of fatal rail crossing crashes occurred in rural areas, a greater percentage than either all fatal crashes or other fatal intersection crashes.

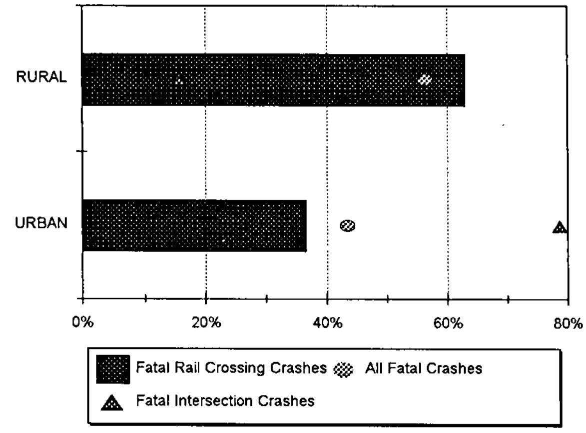

Figure 7. Percentage of crashes by land use. Source: FARS 1975-1992.

State Statistics

In 1992, over 50 percent of the fatal rail crossing crashes occurred in eight states: Texas, Ohio, Indiana, Michigan, Louisiana, Illinois, Oklahoma and California. The next 8 states (Kansas, North Carolina, Georgia, Mississippi, Arkansas, Alabama, Florida, and Missouri) add an additional 25 percent, yielding an estimate that in 1992, over 75 percent of the fatal rail crossing crashes occurred in 16 states. Due to the small number of fatal crashes in some states (the top 16 states for 1992 ranges from a high of 36 to a low of 9), state-level estimates are subject to relatively high year-to-year variability.

Involvement by Vehicle Type

Figure 8 shows the percentage of vehicles by type of vehicle. The most frequently involved motor vehicles in fatal rail crossing crashes were passenger cars (63 percent), followed by light truck and vans (25 percent).

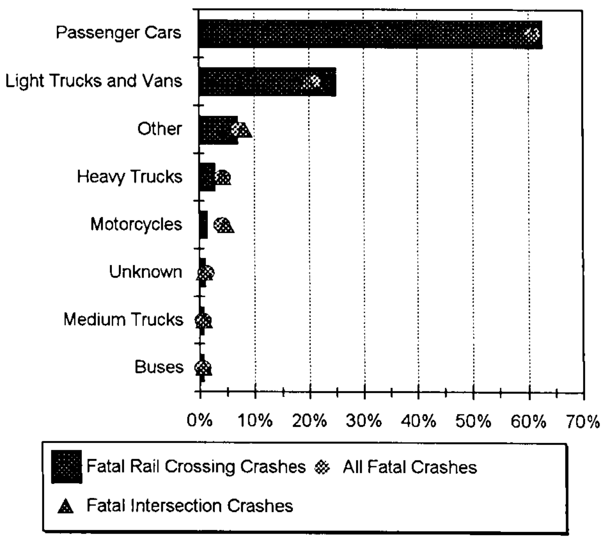

Figure 8. Percentage of vehicles involved in fatal crashes by vehicle type. Source: FARS 1975-1992.

As expected, most vehicles involved in fatal rail crossing crashes were severely deformed and were initially impacted in the side. Ninety-two percent of vehicles involved in fatal rail crossing crashes were severely deformed and eighty percent of rail crossing vehicles were initially impacted in the side.

Drivers Involved

The percentage of drivers involved in fatal crashes by age category is shown in figure 9. Drivers 25-34 years old

comprised the greatest percentage (24 percent) of fatal involvements, followed by drivers 16-20 years old (at 17 percent). The 16-20 year old group is particularly high when considering that this age group includes only five years, while the 25-34 year olds include a ten-year span.

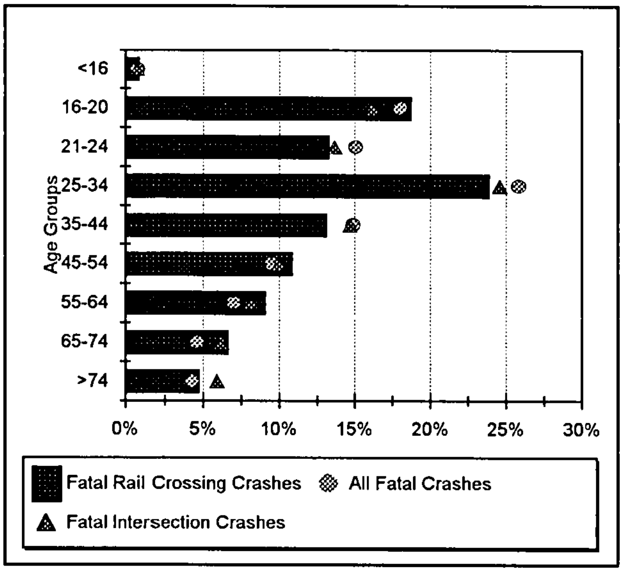

Figure 9. Percentage of drivers involved in fatal crashes by driver age. Source: FARS 1975-1992.

Figure 10 shows the percentage of drivers involved in fatal crashes by driver sex. Male drivers comprised approximately the same percentage involvement in fatal rail crossing crashes (77 percent) as in all fatal crashes and fatal intersection crashes.

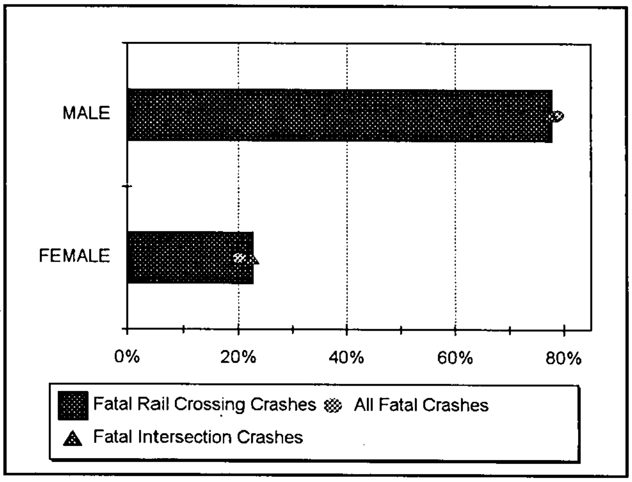

Figure 10. Percentage of drivers involved in fatal crashes by driver sex. Source: FARS 1975-1992.

Table 1 shows the distribution of alcohol involvement for drivers involved in fatal rail crossing crashes, all fatal crashes and fatal intersection crashes. These distributions represent a combination of known blood alcohol concentration (BAC) test results, and estimated probabilities for drivers with unknown BAC test results using NHTSA's alcohol imputation method.

Table 1.
Percentage Drivers Involved in Fatal Crashes by BAC
Source: FARS BAC Databases 1987-1992

	BAC .00	BAC .01-.09	BAC .10+
All	66.1%	7.8%	26.1%
Intersection	80.6%	6.6%	12.8%
Rail Crossing	66.7%	8.9%	24.4%

Drivers in fatal rail crossing crashes exhibited rates of alcohol involvement (a BAC of 0.10 percent or greater) approximately twice as great (24.4 percent) as drivers in other intersection crashes (12.8 percent). The rate of alcohol involvement for drivers in fatal rail crossing crashes is close to that for drivers in all fatal crashes, which is a combination of single-vehicle crashes (in which drivers exhibit much greater levels of alcohol involvement) and multi-vehicle crashes (in which drivers exhibit levels of alcohol involvement similar to those in fatal intersection crashes). Thus, drivers in fatal rail crossing crashes do not appear to exhibit the extremely high levels of alcohol involvement associated with single-vehicle fatal crashes (in which approximately 45 percent of the drivers exhibit BAC's of 0.10 percent or greater).

Claritas

NHTSA subscribes to a commercially available market research tool, Claritas, which utilizes geodemographics to characterize different population segments. Geodemographics links demographic and lifestyle data with different geographic units. All population segments are classified by zip code. Claritas is a useful tool to gain information about households of drivers involved in certain types of crashes. By using the driver's zip code, Claritas can help determine who the target population(s) are: where they live, what they read, which television programs they watch, and what their consumer habits are like. Driver zip codes from FARS are available for merging with the information from Claritas, to conduct the analysis of demographics.

Claritas classifies each of the more than 3,500 zip codes in the United States into one of 62 cluster groups. Each cluster group represents a unique set of demographic, socio-economic, and lifestyle characteristics. The 62 cluster groups

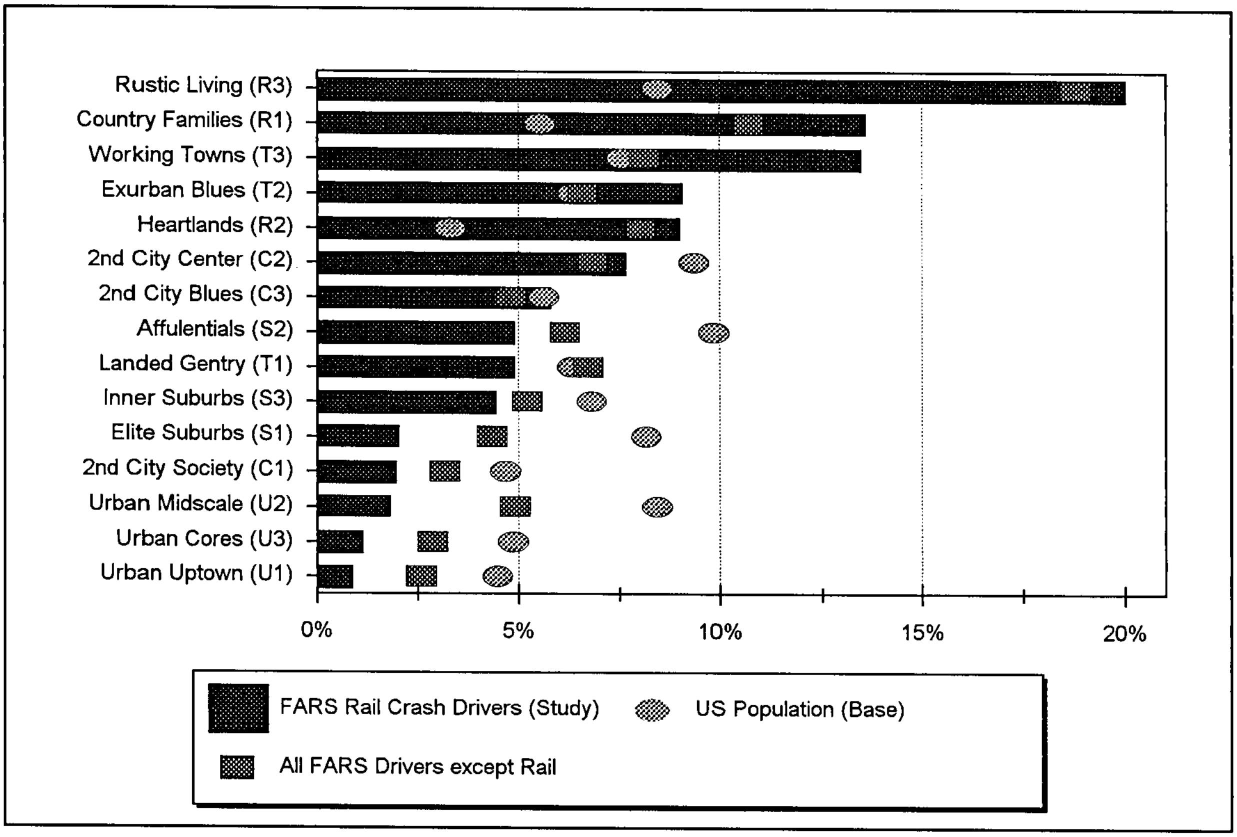

Figure 11. Percentage of claritas population by social group.

all fall into one of 15 Social Groups with 3-5 clusters each. The 15 Social Groups are organized by urbanization (neighborhood density) and socio-economic status (income, occupation, home value, etc). Each of the 15 Social Groups fall into one of five broad geographic types: Suburban Populations (S), Urban Populations (U), Second City Populations (C), Town Populations (T), Rural Populations (R).

Driver zip code is only available in FARS from 1987 to 1992. These driver zip codes were analyzed with the Claritas database. The drivers involved in fatal rail crossing crashes in 1987 to 1992 are the study population. United States residents age 15 years or greater are the base population. There were 2,678 drivers in the study population and 201,104,559 people in the base population. Comparisons with all drivers involved in fatal crashes, excluding rail crossing crashes, from 1987 to 1992 were computed as well. There were 383,172 drivers in this category.

Figure 11 presents the percentage distribution of social groups for three populations: drivers involved in fatal rail crossing crashes, drivers involved in all other fatal crashes, and the U.S. population. The graph appears to exhibit three distinct groupings:

(1) The five Claritas-defined social groups most involved in fatal rail crossing crashes comprise approximately 65 percent of the drivers involved. Three of the five social groups represent rural populations, while the remaining two represent town populations. The locations of these populations are likely to result in the greatest exposure to rail crossing opportunities, contributing greatly to their population-based overrepresentation.

(2) The five Claritas-defined social groups least involved in fatal rail crossing crashes comprise approximately 8 percent of the drivers involved in these crashes. Three of these social groups represent urban populations, which may have the least exposure to rail crossing opportunities, while the remaining two represent the most affluent city or suburban populations. This lower exposure to rail crossing opportunities is likely a major contributor to their population-based underrepresentation.

(3) The middle five social groups (2nd city center through inner suburbs) comprise approximately 27 percent of the drivers involved in fatal rail crossing crashes. This

grouping consists of several populations that are over involved relative to other fatal crash-involved drivers or the U.S. population, but their involvement pattern does not fit either the greatest or least involved groups. This group consists of the most affluent town population, and the moderate and less affluent suburban and second city populations.

Claritas contains descriptions for each of the 15 groups on a number of characteristics describing household attributes and media and life style preferences. From the information provided for each of the individual 15 social groups and the percentage distribution in the three populations under study (U.S. population, drivers in fatal rail crossing crashes, and drivers in all other fatal crashes), it was possible to construct a single number for each attribute, that represents the weighted averages of these characteristics within each study population. Table 2 presents demographic statistics for the three populations under study.

Table 2.
Characteristics of Drivers Involved in Fatal Crashes

		Percentage of US Population	Percentage of Fatal Rail Collision Driver Population	Percentage All Other Fatal Driver Population
Education	4+ Years College	**20.6%**	15.7%	17.7%
	1-3 Years College	**24.9%**	23.4%	23.9%
	High School Graduate	**29.9%**	33.1%	31.8%
	Less than High School	**24.6%**	27.8%	26.6%
Household Income	Less than $15,000	**24.3%**	27.8%	26.2%
	$15,000 - $34,999	**33.4%**	36.1%	34.9%
	$35,000 - $74,999	**32.8%**	29.9%	31.3%
	$75,000 +	**9.5%**	6.1%	7.7%
	Median HH Income	**$31,900**	$27,667	$29,649
Family Type	Married Couples	**55.2%**	58.6%	57.9%
	Married w/Children	**26.7%**	28.6%	28.2%
	Single Parents	**9.3%**	8.9%	8.9%
	Single Female HH Head	**11.6%**	10.7%	10.8%
Occupation	Professional/ Manager	**25.8%**	21.8%	23.4%
	Other White-Collar	**31.4%**	28.7%	29.6%
	Blue-Collar	**26.6%**	32.8%	31.2%
	Service	**13.7%**	14.0%	13.7%
	Farm/Ranch/Mining	**2.5%**	4.3%	3.9%
Race/Ethnic Origin	White	**80.1%**	85.0%	83.3%
	Black	**10.6%**	8.5%	9.1%
	Asian (API)	**2.1%**	1.0%	1.5%
	Hispanic	**6.5%**	4.5%	5.3%
	Foreign Born	**7.7%**	4.2%	5.6%
Household Size	1 Person	**24.6%**	23.2%	23.4%
	4+ Persons	**26.0%**	26.5%	26.6%
	HH w/ Children	**36.0%**	37.5%	37.1%

A review of Table 2 shows that a larger percentage of drivers involved in fatal rail crossing crashes have no college experience (60.9 percent) compared to both fatal crash-involved drivers (58.5 percent) and the U.S. population as a whole (54.5 percent), with the greatest differences observed for the 4+ years of college category (15.7 percent for fatal rail crossing-involved drivers, 17.7 percent for other fatal crash-involved drivers, and 20.6 percent for the U.S. population).

The median household income for fatal rail crossing-involved drivers also is lower ($27,667) than both other fatal crash-involved drivers ($29,649) and the U.S. population ($31,900), with a greater percentage of households earning under $34,000.

There are only minor differences in the family type (single vs. married, with or without children) among the three populations.

One of the largest differences among the three populations is in the area of occupation, with fatal rail crossing-involved drivers coming from households in which 32.8 percent report blue-collar occupations, close to the 31.2 percent for other fatal crash-involved drivers, and much greater than the 26.6 percent reported for the U.S. population. While the service sector appears equally represented across the three populations, there are fewer professional/manager and other white-collar occupations for both fatal crash-involved groups and more reporting of farm/ranch/miner occupants than in the U.S. population.

In terms of race/ethnic origin, fatal rail crossing-involved drivers come from areas with a greater percentage of white households (85.0 percent), slightly higher than for other fatal crash-involved drivers (83.3 percent), and higher than the U.S. population (80.1 percent). This is also likely a function of geographic location (the higher propensity for involvement by rural and town populations).

There are essentially no differences among the three populations with regard to household size.

Table 3 shows the magazines read in the fatal rail crossing-involved driver population. This table was prepared by listing the top ten magazines for each of the 15 social groups and weighting their appearance on the list by the percentage of driver involvements in fatal rail crossing crashes.

Table 3.
Top Magazines for Fatal Rail Crossing Driver Social Groups

	Percentage Fatal Rail Crossing Drivers
Field & Stream	65%
Outdoor Life	65%
Sports Afield	64%
Hunting	56%
Country Living	52%
Guns & Ammo	49%

For example, *Field and Stream* and *Outdoor Life* were listed in the top magazines read by households that comprise 65 percent of fatal rail crossing-involved drivers. This was followed by two other outdoor-oriented magazines (*Sports Afield* and *Hunting*). These magazines could be an important delivery mechanism for reaching and educating the population of drivers most likely to encounter and become involved in rail crossing crashes. Informational messages on the potential dangers related to rail crossing maneuvers could be effective if focused on these populations.

This is an abridged version of this report. To obtain a copy of the full report contact the National Technical Information Service at 5285 Port Royal Road, Springfield, VA 22161 and ask for report number DOT HS 808 196, Rail-Highway Crossing Safety: Fatal Crash and Demographic Descriptors.

OVERVIEW OF THE NATIONAL OCCUPANT PROTECTION USE SURVEY

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United States
Paper Number 96-S9-W-29

ABSTRACT

The National Occupant Protection Use Survey (NOPUS) was designed to gather information on the use of safety belts, motorcycle helmets, and child restraints. NOPUS is composed of three observational studies: the moving traffic study, which provides information on overall shoulder belt use and motorcycle helmet use; the controlled intersection study, which provides more detailed information about shoulder belt use by type of vehicle, characteristics of the belt users and child restraint use; and the shopping center study, which provides information on rear-seat belt use and shoulder belt misuse. An overview of the NOPUS survey design, implementation and significant results from all three of the studies are presented in this paper.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation (DOT) is responsible for reducing deaths, injuries and economic losses resulting from motor vehicle crashes. One of the most successful means to achieve fewer injuries and deaths is for motor vehicle occupants to use safety belts and child safety seats, and for motorcycle riders to use helmets. NHTSA has played a major role in promoting the use of occupant restraint systems by people traveling on the nation's roads. To improve the measurement of safety belt use, NHTSA has provided assistance to individual states in the design and implementation of probability-based observational surveys, and has developed minimum guidelines for these surveys. These state surveys provide an essential source of information for monitoring progress in restraint system use in the states. At the national level, however, no detailed data were available to assist NHTSA in assessing and monitoring safety belt use and the use rates of child safety seats and motorcycle helmets.

To fulfill its mandate and assess and monitor occupant safety and restraint use nationwide, NHTSA contracted with The Washington Consulting Group (WCG) to design and conduct the NOPUS. The sample design of NOPUS is statistically-based and allows the computation of sampling errors directly from the survey data. In addition, to minimize bias, rural as well as urban roads, controlled intersections as well as interstate ramps and intersections where vehicles do not come to a complete stop were included in the survey. The results of this national survey are of significant interest not only to NHTSA, but also to the United States Congress, state governments, and other highway safety support groups.

STUDY OVERVIEW

The goal of NOPUS was to estimate the shoulder belt use rate for occupants of passenger vehicles that are generally covered by the state safety belt use laws -- automobiles and light trucks (vans, pickups and utility vehicles). Separate front-seat shoulder belt use estimates were desired for the following:

- Type of vehicle: automobile and light truck.
- Type of road: Interstate, U.S./State route, and other road.
- Type of area: urban, suburban and rural.
- Front seat occupant type: driver and passenger.
- Age of occupant: infant (less than 1 year), toddler (1 to 4 years), youth (5 to 15 years), young adult (16 to 24 years), and adult (25 years and older).
- Occupant sex: male and female.
- Occupant race: white, black, other.

In addition to these front-seat shoulder belt use estimates, estimates were desired for:

- Motorcycle helmet use.
- Child restraint use.

- Rear-seat occupant safety belt use.
- Shoulder belt misuse.

NOPUS was designed as a multi-stage probability sample to ensure that the results would represent occupant protection use nationwide. Fifty primary sampling units (PSUs) consisting of counties or groups of counties were selected based on vehicle miles traveled (VMT) in the PSU. Within sample counties, roadways were selected from two categories, major roads and local roads. Finally, specific intersections were chosen. All 50 states and the District of Columbia were part of the universe of interest. The sample of roadway intersections included sites on some of the country's busiest interstates and state highways as well as some less frequently traveled residential streets and rural roads.

NOPUS is composed of three separate restraint studies: the *Moving Traffic Study* which provides information on overall shoulder belt use, the *Controlled Intersection Study* which provides more detailed information about shoulder belt use by type of vehicle, characteristics of the belt users and child restraint use, and the *Shopping Center Study* which provides information on rear-seat belt use and shoulder belt misuse.

The basic data collection methodology for NOPUS was counting persons using and not using safety belts and helmets at predesignated sites. These sites include controlled intersections (where traffic is stopped by a traffic light or a stop sign) as well as intersections where vehicles do not come to a complete stop. Information on race, age, and sex of front-seat occupants, child restraint use, and vehicle license plate was recorded only for vehicles stopped at a red light or stop sign. Observations were conducted on weekends as well as weekdays.

The results from the national survey have some scope limitations. The observations were conducted during daylight hours, from 7:00 a.m. to 6:00 p.m., when light was adequate for observation. Safety belt use was observed in passenger vehicles only -- automobiles and light trucks. Excluded were commercial vehicles, buses, taxis, and emergency vehicles. In the *Moving Traffic Study* and *Controlled Intersection Study,* belt use was recorded only for front-seat outboard positions because it was impractical to observe belt use in the middle of the front seat and back seat. For safety reasons, observations on interstates and other controlled-access freeways were done on exit ramps.

DATA COLLECTION METHODOLOGY

As discussed below, the data collection approach was somewhat different for each of the three studies. The methodology was driven by the requirements of the data items being collected.

Moving Traffic Study

The data collection approach for the *Moving Traffic Study* involved two observers working simultaneously for 30 minutes at each site. Observer 1 collected the passenger car and light truck driver data, while Observer 2 collected the passenger car and light truck data for the right front passenger. Each observer used four metal counters to collect these data. Pairs of counters were taped together; one used for recording shoulder belt use (yes-no) for passenger cars and the other for light trucks. Motorcycle helmet use for driver and passenger was recorded by Observer 2. At the end of each 30-minute observation period, the counts were transferred from the counters and the tally sheets to the Moving Traffic Recording Form.

For purposes of the survey, passenger cars include 2- and 4-door sedans, hatchbacks, station wagons, and convertibles, but exclude taxis and emergency vehicles, such as police cars and ambulances. "Light" trucks are all trucks with a gross vehicle weight rating under 10,000 pounds (4500 kg) including minivans, standard vans, sport utility vehicles (such as jeeps) and pickup trucks, but exclude light trucks for commercial and emergency uses, such as ambulance vans and small fire vehicles.

Controlled Intersection Study

For the *Controlled Intersection Study*, belt use was observed for front-seat occupants only. If there were more than one front-seat passenger, only the outboard passenger was observed. However, for child restraint use data, children in the front and second seat were observed, but the third row seats in minivans and station wagons were excluded. The observation approach for this study consisted of recording information for 40 minutes while

the vehicles were stopped, either at a red light or stop sign. Data collection forms with check-boxes were used to record the various data items -- shoulder belt and child seat use, race, sex and age group. One observer collected the information for the first eligible vehicle, then moved to the next eligible vehicle behind the one that the other data collector was observing, The observers continued alternating in this fashion until the light turned green. At stop signs, information was record for eligible vehicles that stopped at the stop sign. The helmet use data were recorded following the same procedure.

Shopping Center Study

The *Shopping Center Study* was conducted at 143 shopping centers (2 or 3 per PSU) to address lap belt use, rear-seat belt use and shoulder belt misuse in passenger cars only. The exact shopping center locations were selected by the data collectors and the description of the observation location was documented on the Shopping Center Recording Form. The observation approach for this study consisted of using two observers at each shopping center for a one-hour observation period. Observer 1 collected the driver and left side rear-seat outboard passenger data. Observer 2 collected the front-seat outboard passenger, right side rear-seat outboard passenger and vehicle data.

SAMPLE DESIGN

Sample Design Overview

The sample design for the NOPUS is a multi-stage sample involving clustering and stratification. The first stage of the sample selection was drawing a stratified sample of 50 primary sampling units (PSU) consisting of a single county or group of counties. The sampling strata were based on Census region, metropolitan statistical area (MSA) or non-MSA status, and the state's use rate -- high, medium, and low: In the MSA strata, PSUs consisted of entire MSAs or MSA parts. In the non-MSA strata, PSUs consisted of single counties or grouped counties to achieve PSUs with a minimum measure of size.

Prior to sampling, roads were classified into two primary strata: (1) major roads, which included interstates, US roads and state routes, and (2) local roads, which included county roads and other roads. About 50 percent of the sample was allocated to major roads and the other 50 percent to local roads. Major roads were sampled from computerized road inventories supplied by the state Department of Transportation offices in the 25 states represented by the sample PSUs. For sampling purposes, local roads were clustered within Census tracts in the selected PSUs to avoid listing all the local roads in the states. The sampling of local roads was restricted to the selected Census tracts. The characteristics of the sampled PSUs and road sites are summarized in Table 1 below.

Table 1.
Sampled PSUs, Census Tracts and Road Sites by Region

	Total	North-east	Mid-west	South	West
PSUs	50	8	13	19	10
Census Tracts	500	95	123	168	115
Major Roads	1995	329	484	752	430
Local Roads	2012	292	535	762	423

Sample of Primary Sampling Units

In order to select the PSU sample, it was necessary to develop a sampling frame with county-level data for the entire U.S. These data were used to define PSUs, stratify the PSU sample and develop a measure of size (vehicle miles of travel) for sample selection.

Some states were unable to provide VMT by county. To develop a measure of size for counties in these states, a regression model was developed with county VMT as the dependent variable and the following independent variables: county population, number of non-fatal injury crashes in the county, and county MSA status.

After imputing missing county VMT for states that did not have that data available, the county level VMT was adjusted to correspond to the total 1992 state VMT shown in the DOT publication *Highway Statistics, 1992*. This "benchmarked" VMT was used in computing the measure of size for PSU selection.

The sample design called for PSUs to be defined as counties or groups of counties. In general, counties within MSAs were grouped to form single PSUs. However, MSAs that crossed states (e.g., the Washington D.C. metropolitan area) were split by state into separate PSUs. MSAs that accounted for an inordinately large proportion of the VMT and land area in a state, such as the Atlanta MSA, were split into several PSUs. Small counties in terms of VMT and land area were collapsed with an adjacent county into single PSUs in order to achieve a minimum level of VMT. When counties were grouped into PSUs, VMT was aggregated to the PSU level to define the PSU measure of size.

The following stratification scheme was used:

- Census geographic region - *Northeast* (ME, VT, NH, MA, RI, CT, NY, PA, NJ), *Midwest* (MI, OH, IN, IL, WI, MN, IA, MO, KS, NE, SK, ND), *South* (WV, MD, DE, VA, KY, TN, NC, SC, GA, FL, AL, MS, AR, LA, OK, TX), and *West* (AK, WA, OR, CA, NV, ID, UT, AZ, NM, CO, WY, MT, HI);
- Level of urbanization - MSA counties, non-MSA counties; and,
- Estimate of safety belt use based on the "best" estimate available from individual states - *high*: over 70%, *medium*: 55 to 69%, and, *low*: under 55%.

The first two levels of the stratification scheme (census region and MSA status) defined 8 primary strata. Fifty secondary strata of approximately equal measure of size were then defined within the 8 primary strata. The secondary strata were allocated to the primary strata in proportion to the percentage of total VMT in each primary strata. Implicit stratification by state belt use category and PSU VMT was implemented by ordering the PSU frame by these characteristics within the primary strata. Finally, one PSU was selected from each of the 50 secondary strata with probability proportional to measure of size (PPS).

Within-PSU Sampling

The sample of approximately 2,000 major roads, which included interstates, U.S. roads, and state routes, was selected across the entire PSU. The sample of approximately 2,000 local roads, however, was further clustered within 500 census tracts selected within sample PSUs.

Sample of Major Road Sites - Since major roads were selected across the entire PSU (no clustering within census tracts) the sampling frame was developed from machine-readable state-maintained road inventories for the counties represented in the sample. These databases included all the information necessary for defining and sampling road segments, such as segment beginning and ending points, VMT and segment length.

For purposes of sample selection, the sampling frame for major roads consisted of records that each represented one road segment. A road segment was defined as a portion of road between two boundaries such as major roads or county/city limits (except for Interstates where the end points were two exits), and corresponded to a road portion within which the average daily traffic volume (ADT) was approximately the same.

The sampling interval for the major road sample was computed as the total weighted VMT (the PSU weight times the segment VMT) divided by the number of major roads to be sampled. Segments were selected with a standard PPS selection methodology with the frame sorted by PSU, county, road identifier and VMT.

Sample of Local Road Sites -Tracts served as the second-stage units for the local roads subdomain. The tract sampling frame included the state, county and tract identifiers and population count for the 15,300 tracts and BNAs (Block Numbering Areas) in the selected PSUs.

Following the same rationale as described in the selection of PSUs, the selection of census tracts was based on probability proportional to a measure of size. Population was the measure of size used because VMT is not available at the tract level. In earlier state surveys, tract population was found to be highly correlated with VMT. An overall sampling interval was then developed as the sum of the weighted population for the tracts in the frame divided by 500, the number of tracts selected.

The sampling of local roads was carried out within sample census tracts. Hence, the sampling frame for local roads was constructed by listing all local roads (excluding major roads) in sample census tracts using 1990 census maps. The listed roads were randomly

numbered from 1 to the number of roads in the tract. Within each tract, the sampling rate was established so as to obtain a total sample of approximately 2,000 local roads.

WEIGHTING

Weighting in these surveys had two objectives:

- To reflect the varying probabilities of selection
- To adjust for sample losses due to nonresponse.

First, variation in the probabilities of selection was introduced by the sampling process to select the observation sites--PSU, tract, and road intersection sampling. The base weight, which is the reciprocal of the probability of selection, reflects these sampling stages. Hence, the base weight, BWT, is given by:

$$BWT = \frac{1}{(P_{PSU} \times P_{TRACT} \times P_{SITE})} \qquad (1.)$$

where,

P_{PSU} = Probability of selection of the PSU;

P_{TRACT} = Probability of selection of the tract (for local road sites) conditional on the PSU; and,

P_{SITE} = Probability of selection of the site conditional on the tract and PSU.

Variation in the overall probability of selection was also introduced by subsampling one lane out of all the lanes in the assigned traffic direction, and at interstate sites, observation conducted at exit ramps instead of on the interstate. Also, during the processing stage for each study, an adjustment was applied to account for observations that were not conducted for the full amount of time.

In general, to account for nonresponse the base weight was inflated to account for eligible sites not visited after repeated follow up efforts. Nonresponse adjustment is usually carried out within adjustment cells similar in characteristics relevant to the survey. The implicit assumption in nonresponse adjustment through weighting is that within an adjustment cell, sites not visited are similar with respect to the characteristics being measured by the survey to those visited. To develop the nonresponse adjustment factors, sites were grouped by PSU and road type (major roads and local roads).

ESTIMATION

In addition to the weight adjustments described above, the weighted use rates must reflect the conceptual framework that the sample of sites consists of a "snap shot" of an "instant" of belt use in the target geographic area. Since belt use is observed for a fixed period of time at each site, the segment length and travel time on the segment must be reflected in the contribution of each site to the total estimate. The travel time represented by a particular roadway segment is estimated as: travel time = (road segment length)/(vehicle speed). The speed estimate was based on the observer's perception of how fast the vehicles are traveling during the observation period.

Moving Traffic Estimation

The adjustment made to the base weight for the Moving Traffic estimates is comprised of the following factors:

- a factor that reflects the fact that not all sites originally sampled were observed;
- a factor that inflates counts recorded at sites on controlled access roads, such as interstates, where data were collected at the exit ramp, to account for the full volume of traffic on the segment for the observation time;
- a factor to weight up the number of lanes observed to the number of lanes in the observed traffic direction; and,
- a factor that corrects for observations conducted for less than the scheduled 30 minutes.

The fully adjusted final weight, MWT_{ic}, that was applied to the Moving Traffic counts is as follows:

$$MWT_{ic} = BWT_i \times IAF_i \times LAF_i \times NRFM_c \times SOF_i, \quad (2.)$$

where,

BWT_i = Base weight associated with ith site;
IAF_i = Interstate adjustment factor;
LAF_i = Lanes adjustment factor;
$NRFM_c$ = Nonresponse adjustment factor; and
SOF_i = Short observation factor.

Incorporating the travel time component, the weighted safety belt use rate is given by:

$$Use\ rate = \frac{\sum((MWT) \times (Time) \times (\#belted))}{\sum((MWT) \times (Time) \times (All))} \quad (3.)$$

Controlled Intersection Estimation

The adjustment made to the base weight for the Controlled Intersection estimates is comprised of the following factors:

- a factor that reflects the fact that not all sites originally sampled were observed;
- a factor that reflects the fact that not all sites originally sampled were controlled intersections;
- a factor to account for missing observations at controlled intersection sites;
- a factor to weight up the number of lanes observed to the number of lanes in the observed traffic direction; and
- a factor that corrects for observations conducted for less than the scheduled 40 minutes.

The nonresponse adjustment for the controlled intersection estimate was applied in three parts. The first step was to create an adjustment to account for the fact that not all the sites originally sampled were controlled intersections (traffic stopped at a traffic light or stop sign). The formula for this adjustment is similar in form to that of the NRFM. This adjustment, NRFC1, is the ratio of the sum of the weights for all visited sites from the *Moving Traffic Study* to the sum of the weights for all visited sites from the *Moving Traffic Study* that are controlled intersections.

The second adjustment, NRFC2, consisted of the ratio of all eligible controlled intersections from the *Moving Traffic Study* to all controlled intersections actually visited in the *Controlled Intersection Study.*

The third adjustment was to multiply the base weight (BWT) by the nonresponse adjustment factor (NRFM) from the *Moving Traffic Study* to account for sites not completed in that study (it is not known whether these sites are controlled or not). The final weight formula, fully adjusted, that was applied to the Controlled Intersection counts is as follows:

$$CWT_{ic} = BWTC_i \times LAF_i \times NRFC1_c \times NRFC2_c \times SOF_i \quad (4.)$$

where,

$BWTC_i$ = Base weight, ith site, X NRFM;
LAF_i = Lanes adjustment factor;
$NRFC1_c$ = Controlled intersection existence factor;
$NRFC2_c$ = Missing controlled intersection factor; and,
SOF_i = Short observation factor.

Eligible vehicles in the *Controlled Intersection Study* were only those that were stopped at a traffic light or stop sign. Therefore, the traffic volume observed during the *Moving Traffic Study* for a given site was used to weight, by vehicle type, the results of the *Controlled Intersection Study* to account for the traffic, stopped and moving, during the observation period. For a specific site, the traffic count is the total number of vehicles observed during the *Moving Traffic Study*, with an adjustment for the interstate count, if applicable, and the short observation factor from the *Moving Traffic Study.*

In the estimation equation incorporating the weighting by traffic volume, the numerator consists of the ratio of belted occupants to all occupants multiplied by the traffic count, multiplied by the fully adjusted weight, multiplied by the travel time adjustment, and summed over all sites. The denominator of the estimation equation is the traffic count multiplied by the fully adjusted weight, multiplied by travel time adjustment, summed over all sites.

Thus, the adjusted estimator is given by:

$$\text{Use rate} = \frac{\sum_i ((CWT)_i \times (Time)_i \times NUMV_i(\frac{belted_i}{all_i}))}{\sum_i ((CWT)_i \times (Time)_i \times NUMV_i} \quad (5.)$$

where the sum is over all sites where observations were conducted and $NUMV_i$ is the vehicle-specific traffic count (or, in the case of all-vehicle estimates, the sum of the traffic counts for a given ratio).

HIGHLIGHTS OF STUDY FINDINGS

Moving Traffic Findings

Data for the *Moving Traffic Study* were collected during the months of October and November, 1994. A total of 167,000 passengers cars, almost 84,000 light trucks, and 997 motorcycles were observed.

Estimates of shoulder belt use statistically weighted according to the sample design, are as follows, with two standard errors in parentheses:

Table 2.
Percent Shoulder Belt Use by Person Type and Vehicle Type

Estimate	Percent
Overall	58.0 (3.8)
Passenger Cars:	62.8 (3.8)
Drivers	64.2 (3.6)
Passengers	59.1 (4.4)
Light Trucks:	50.2 (3.6)
Drivers	50.7 (3.8)
Passengers	49.1 (3.6)

Regional estimates of shoulder belt use ranged from 55.1 percent in the Northeast to 63.3 percent in the West.

Just under 1,000 motorcycles were observed during this study. Overall helmet use was 63%, but it varied by time of day and day of week. Rush hour helmet use was 91.2% compared to 60.6% at non-rush hour times. Weekday use (85.9%) was much higher than weekend use (55.2%).

Controlled Intersection Findings

The *Controlled Intersection Study* data were collected for 72,000 drivers and 12,000 passengers in 50,000 passenger cars and 22,000 light trucks. As expected, restraint use varied according to age, gender, race and also by the type of area where the data were collected. Highlights of the specific breakdown of demographic attributes is as follows:

- *Restraint use by Age:* Infants(less than 1 year) had the highest rate of restraint use at 88 percent while there was a significantly lower rate for toddlers (1-4 years) at 61 percent. Young adults (16-24 years) had the lowest restraint use rate at only 53 percent.
- *Shoulder Belt Use by Gender:* Female occupants had a use rate ten percentage points higher than male occupants, 64 percent compared to 54 percent.
- *Shoulder Belt Use by Race:* Belt use by occupant race varied as follows: white- 60 percent, black- 53 percent, other- 55 percent. However, none of these differences are statistically significant.
- *Shoulder Belt Use by Area Type:* Suburban areas had the highest rate of restraint use with 63 percent. City areas had a slightly lower rate at 58 percent, followed by rural areas restraint use of 53 percent.

The following tables break down the overall restraint use rates by age, area type, race and gender for both passengers and drivers. All estimates have been statistically weighted according to the sample design. Two standard errors are given in parentheses with each estimate.

Table 3.
Percent Shoulder Belt Use by Age Group

Estimate	Overall	Youth (5 to 15 Years)	Young Adult (16 to 24 Years)	Adult (Over 24 Years)
Shoulder Belt Use	58.0 (4.2)	57.7 (7.2)	52.6 (5.6)	59.1 (4.4)
Passenger Cars :	62.7 (3.8)	59.0 (7.5)	55.8 (5.8)	63.9 (4.1)
Drivers	63.2 (3.9)	n/a	57.1 (6.1)	64.1 (4.1)
Passengers	61.3 (3.9)	58.8 (7.6)	50.4 (7.0)	64.0 (4.4)
Light Trucks:	50.0 (5.1)	54.8 (7.6)	45.7 (7.4)	51.0 (5.4)
Drivers	49.6 (5.3)	n/a	47.5 (7.3)	50.5 (5.6)
Passengers	52.2 (6.1)	57.1 (8.9)	41.7 (12.9)	53.1 (6.2)

Table 4.
Percent Shoulder Belt Use by Area Type

Estimate	Overall	City	Suburb	Rural
Shoulder Belt Use	58.0 (4.2)	57.7 (4.2)	62.9 (3.2)	52.8 (7.1)
Passenger Cars:	62.7 (3.8)	60.4 (7.9)	67.0 (2.5)	59.5 (6.6)
Drivers	63.2 (3.9)	60.6 (8.2)	67.3 (2.6)	60.6 (6.5)
Passengers	61.3 (3.9)	59.5 (6.9)	65.5 (4.3)	57.7 (6.6)
Light Trucks:	50.0 (5.1)	51.9 (9.6)	55.3 (5.5)	44.0 (7.4)
Drivers	49.6 (5.3)	52.1 (10.0)	54.6 (6.3)	43.3 (7.6)
Passengers	52.2 (6.1)	52.8 (11.2)	56.7 (8.0)	47.3 (8.3)

Table 5.
Percent Shoulder Belt Use by Race

Estimate	White	Black	Other Race
Shoulder Belt Use	59.6 (4.1)	53.0 (6.9)	54.6 (9.7)
Passenger Cars:	64.8 (3.8)	54.9 (6.7)	58.9 (10.2)
Drivers	64.9 (4.1)	56.3 (7.0)	60.0 (10.2)
Passengers	63.7 (3.7)	48.6 (7.7)	48.7 (11.5)
Light Trucks:	50.9 (4.8)	45.8 (10.6)	44.8 (12.2)
Drivers	50.6 (5.4)	45.9 (10.7)	46.6 (11.7)
Passengers	52.7 (5.3)	41.3 (18.4)	39.6 (19.7)

Table 6.
Percent Shoulder Belt Use by Sex

Estimate	Female	Male
Shoulder Belt Use	64.4 (4.4)	54.4 (4.2)
Passenger Cars:	66.5 (4.2)	59.1 (3.8)
Drivers	66.8 (4.0)	60.4 (3.9)
Passengers	65.4 (4.5)	50.8 (5.3)
Light Trucks:	60.5 (5.5)	46.3 (5.4)
Drivers	61.9 (6.0)	46.7 (5.6)
Passengers	58.1 (7.1)	42.3 (7.0)

During the controlled intersection collection, a total of only 1,600 infants and toddlers were observed. For infants and toddlers separately, reliable estimates can be made only for overall restraint use. For infants, the observed restraint type was always child safety seats. However, among restrained toddlers, 62% were observed in safety seats and the other 38% were observed using safety belts. Reliable estimates by individual restraint type could not be made due to the limited sample size. Some of the estimates in the following table are subject to large sampling errors and should be interpreted with caution.

Table 7.
Percent Restraint Use by Children Under 5 Years

Estimate	Percent	
Overall	66.1	(8.2)
Infants (less than 1 year)	87.7	(4.1)
Toddlers (1 to 4 years)	60.7	(10.3)
Passenger Car	68.4	(8.7)
Light Truck	60.6	(19.3)
Front Seat	61.1	(12.0)
Back Seat	70.0	(8.2)
Rush Hour	55.7	(13.2)
Non-Rush Hour	68.9	(7.4)
Weekday	66.1	(9.8)
Weekend	66.2	(11.1)
City	69.1	(18.0)
Suburb	68.1	(9.8)
Rural	59.8	(13.1)

Shopping Center Findings

The *Shopping Center Study* was conducted at 143 shopping centers to address lap belt use and shoulder belt use/misuse in passenger cars only. The restraint use was observed for the driver, left-side passengers (front and back), and the right side rear-seat passengers. Since the sample shopping centers were purposively selected, the estimates generated from this study are unweighted and no standard errors could be estimated. Selected findings from the *Shopping Center Study* are shown below.

Table 8.
Shopping Center Study Findings

Estimate	Percent
Occupants Using Both Belts	55.2
Occupants Using Lap Belt	58.2
Occupants Using Shoulder Belt	56.7
Occupants Not Using Shoulder Belt at All	35.4
Occupants Misusing Shoulder Belt	8.0
Occupants Misusing Shoulder Belt (Under) *if Misused*	10.0
Occupants Misusing Shoulder Belt (Behind) *if Misused*	40.2
Occupants Misusing Shoulder Belt (Loose) *if Misused*	49.8

Future Findings

More detailed estimates of shoulder belt use from the *Controlled Intersection Study* data will be available in the near future. Results anticipated include shoulder belt use by type of restraint (automatic, manual, with and without airbag) and type of vehicle (utility, minivan, standard van, pickup, fullsize automobile, compact automobile).

ACKNOWLEDGMENTS

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REFERENCES

National Highway Traffic Safety Administration, "Guidelines for State Observational Surveys of Safety Belt and Motorcycle Helmet Use". Federal Register, Vol. 57, No. 125, June 29, 1992.

Shelton, Terry, "National Occupant Protection Use Survey: Controlled Intersection Study". Research Note, National Highway Traffic Safety Administration, May 1, 1995.

Shelton, Terry, "National Occupant Protection Use Survey: Moving Traffic Study". Research Note, National Highway Traffic Safety Administration, May 18, 1995.

Shelton, Terry, "Observed Safety Belt Use in 1994". Research Note, National Highway Traffic Safety Administration, February 15, 1995.

The Washington Consulting Group, "National Occupant Protection Use Survey, Final Report under Contract DTNH22-93-D-070096". National Highway Traffic Safety Administration, July, 1995.

BASIC ANALYSIS OF THE MECHANICS OF HEAD-ON CAR COLLISIONS

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ABSTRACT

When a car collides head-on with another car or some other yielding or unyielding object the subsequent motion of the car can be predicted by using the laws of physics. This is first done in the paper in a gross way by means of a simple graphical method. The analysis is then refined to take into account the non-uniformity of crushing strength found in real cars. The motion of the occupants using a simple model completes the picture. It is shown that for older cars, which have no air bags and elementary seat-belt systems, strike with the steering wheel or dashboard is almost inevitable at the speeds considered in the paper. The advice to drivers is to drive at a less-than-average speed and to occupants to set the seat back as far as possible.

INTRODUCTION

When a vehicle collides with either a stationary unyielding object (a tree, a bridge pylon, etc.) or with a yielding object (another vehicle, a crash barrier, etc.) which may be moving, the laws of momentum and energy conservation apply. The change of momentum of the vehicle is measured either by its mass x its change of velocity or by the average force x duration of impact. Since both the force (or action) and the duration of the contact are the same for the impacting vehicle and the impacted object it follows that the momentum (= F x t) given up by the former is the same as that absorbed by the latter. Hence momentum is preserved. The difference between the total energy of the vehicle(s) before and after impact is dissipated as heat, sound and permanent structural deformation (crushing) of the vehicle(s). Assuming that the heat and sound energy dissipated are small this difference of energy is equal to the average force x crush length. In the case of a two-vehicle collision the crush length should be taken as the sum of the crush lengths of the two vehicles.

As far as the occupants of a vehicle are concerned a primary element in rating the severity of a collision is the deceleration of the <u>vehicle</u>. It is self-evident that for a given set of parameters (mass of vehicle(s), velocities, etc.) the smaller is the crush strength the greater is the crush length and hence the lower is the deceleration. In other (American?) words the softer is the ride-down. The analysis of this aspect of vehicle collisions is presented briefly in Section 2. A fuller development is available in Murray(1994).

However, the important criterion for safety is the level of injury sustained by the occupant(s) and this will depend upon a number of parameters. The distribution and characteristics of internal padding have important influences as will frontal and side air bags and seatbelt pre-tensioners. These elements are relatively recent introductions and they are not extant in most of the vehicles being driven on the roads today. It is well-known that in a frontal collision at 40 kph or above, the wearing of an older style seatbelt will not prevent the wearer from hitting the steering wheel (in the case of the driver) or dashboard (in the case of the front seat passenger). In such a collision the occupant is effectively a loose object in the vehicle. The velocity with which he or she hits the steering wheel or dashboard relates closely to the level of injury sustained. The relative velocity between the upper torso and, say, the steering wheel is determined on the one hand by how quickly the vehicle itself is decelerated (as considered above and in the next section) and on the other hand how the occupant's torso moves (considered in a later section).

It is desirable that the torso should have a soft landing on the steering wheel and this is best achieved if the relative velocity between steering wheel and torso is as small as possible. Some vehicles are soft up-front because of the extensive use of weak bumpers and soft front panels while others,such as trucks and larger cars, are more rigid. These interactions form the basis of an interesting study whose aim is to arrive at some simple recommendations concerning safety for the occupants of older vehicles. These recommendations are possibly of greatest relevance to younger drivers because they seem to drive more recklessly and faster than more experienced drivers. Furthermore, it is often the case that younger drivers purchase an older car as their first vehicle and

they should be made aware of the best driving strategy to adopt.

In developing this study a simple graphical approach has been adopted deliberately as a better way of explaining the influence of the various individual parameters on injury level. The graphical approach enables quick estimates to be made and it allows problems to be accessed from different directions (e.g., from a design perspective or for the purposes of analysis of a pre-existing situation).The alternative is, of course to use an existing computer package but this does not have the flexibility of the approach adopted here.

ANALYSIS OF IN-LINE VEHICLE COLLISIONS

When two vehicles collide in-line the event can be considered in three ways (Murray 1996) as shown in Fig.1. The vehicles will either lock together (Fig.1(a)) or can be treated as a mass system and a spring with a coefficient of restitution (Fig.1(b)) or as a mass/spring/damper system (Fig.1(c)). The latter two methods allow for some rebound but, for our present purposes, the first of the three approaches is the simplest and in most cases has sufficient accuracy.

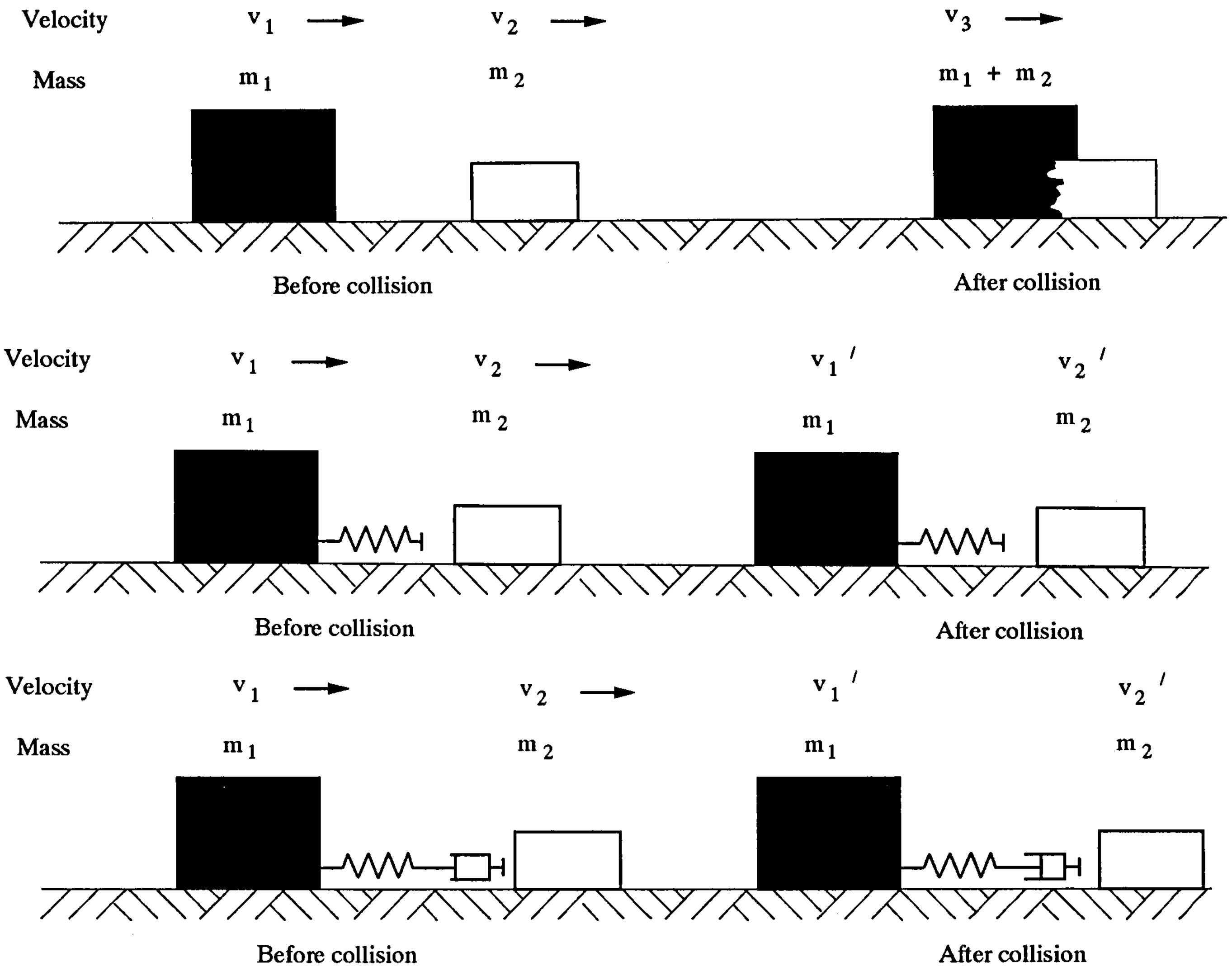


Fig. 1 Three ways of analysing collisions. (a) Vehicles interlock
(b) Spring with coefficient of restitution (c) Spring/damper system.
(b) and (c) allow rebound.

The analysis of the case seen in Fig.1(a) is carried out by considering momentum and energy principles.
Momentum before and after impact:

$$M_1 V_1 + M_2 V_2 = (M_1 + M_2) V_3 \qquad (1.)$$

Energy before and after impact:

$$\frac{1}{2} M_1 V_1^2 + \frac{1}{2} M_2 V_2^2 = \frac{1}{2} (M_1 + M_2) V_3^2 + E_D \qquad (2.)$$

where E_D is the energy dissipated by crushing. By eliminating V_3 from these equations we obtain

$$E_D = M_2 \, {V_c^2}\Big/{2} \left(1 + \frac{M_2}{M_1} \right) \qquad (3.)$$

where V_c is the closing velocity (= $V_1 - V_2$). In these equations V_1 and V_2 are considered to be in the same direction but for a head-on collision the sign of V_2 should be changed. For example, if the two vehicles collide head-on each at 13.9m/sec (=50kph) V_c has the value of 27.8m/sec (=100kph).

It is worth noting that in this case (with $V_c = 2 V_1$) of a head-on collision between a car (mass = M_2) and a heavy truck (mass = M_1) the ratio of $\frac{M_2}{M_1}$ in equation (3) can be ignored and hence the energy to be dissipated, which will be mostly that used to crush the car rather than the more rigid truck, will be four times the original kinetic energy of the car. From equation (3) we also see that for a car colliding with a stationary unyielding object E_D is simply the original kinetic energy of the car, i.e., not nearly as severe as a head-on collision with a heavy vehicle.

The average force F_{av} acting between the vehicles through a distance equal to the sum of the crush lengths s_1 and s_2 of the two vehicles is equal to E_D, i.e.,

$$E_D = F_{av} (s_1 + s_2) \qquad (4.)$$

and the average acceleration or deceleration a_1 and a_2 are

$$a_1 = \frac{F_{av}}{M_1} = M_2 \, {V_c^2}\Big/{2s} \, (M_1 + M_2) \qquad (5.)$$

$$a_2 = \frac{F_{av}}{M_2} = M_1 \, {V_c^2}\Big/{2s} \, (M_1 + M_2) \qquad (6.)$$

where $\qquad s = s_1 + s_2 \qquad (7.)$

The above relationships are conveniently graphed in Fig.2 where the lines with the arrows indicate how this diagram can be used for the analysis of a given head-on collision with the following parameters. (The diagram can be used also for design purposes by using different starting points and reversing some of the arrows.)

M_1 = 1800kg, M_2 = 1200kg and hence, $M_2/(1 + M_2/M_1)$ = 720kg

V_1 = 14m/sec, V_2 = −18m/sec and hence, V_c = 32 m/sec (= 115 kph)

The combined crush length of the two vehicles was 0.5m.

From Fig.2 we see that the energy dissipated is 370 kJ, the average force acting between the vehicles is 740 kN (= 74 tonnes) and the decelerations of the heavier and lighter vehicles are 410 and 610 m/sec, respectively.

So far we have assumed that the crushing strengths of the vehicles are constant throughout their crush lengths. In practice they will vary, resulting in non-uniform decelerations. We now model the crush strengths of two vehicles in Fig.3(a) as simple stepped relationships. During collision the weakest part will crush first and so on, so that for whatever shapes are assumed in Fig.3(a) it is possible to order the steps into a "stairway diagram" (Fig.3(b)) in which the crush strengths, $\overline{F_1}$ $\overline{F_2}$ $\overline{F_3}$ etc. are arranged in ascending order with their corresponding crush lengths $\overline{s_1}$ $\overline{s_2}$ $\overline{s_3}$ etc.

We now consider momentum and energy conservation in the first crush length of the two vehicles in a head-on collision with velocities V_1 and V_2 (i.e., $V_c = V_1 + V_2$).

$$\overline{F_1}\,\overline{t_1} = M_1 (V_1 - \overline{V_1}) = M_2 (V_2 - \overline{V_2}) \qquad (8.)$$

$$\overline{F_1}\,\overline{s_1} = \frac{1}{2} M_1 (V_1^2 - \overline{V_1}^2) + \frac{1}{2} M_2 (V_2^2 - \overline{V_2}^2) \qquad (9.)$$

where $\overline{V_1}$ and $\overline{V_2}$ are the velocities of M_1 and M_2 at the end of the crush length and $\overline{t_1}$ is the duration of this part of the collision.

These equations were solved and the result was used as the starting point for the next step in the stairway diagram and so on. The process was completed when the two vehicles had attained the same velocity in the same

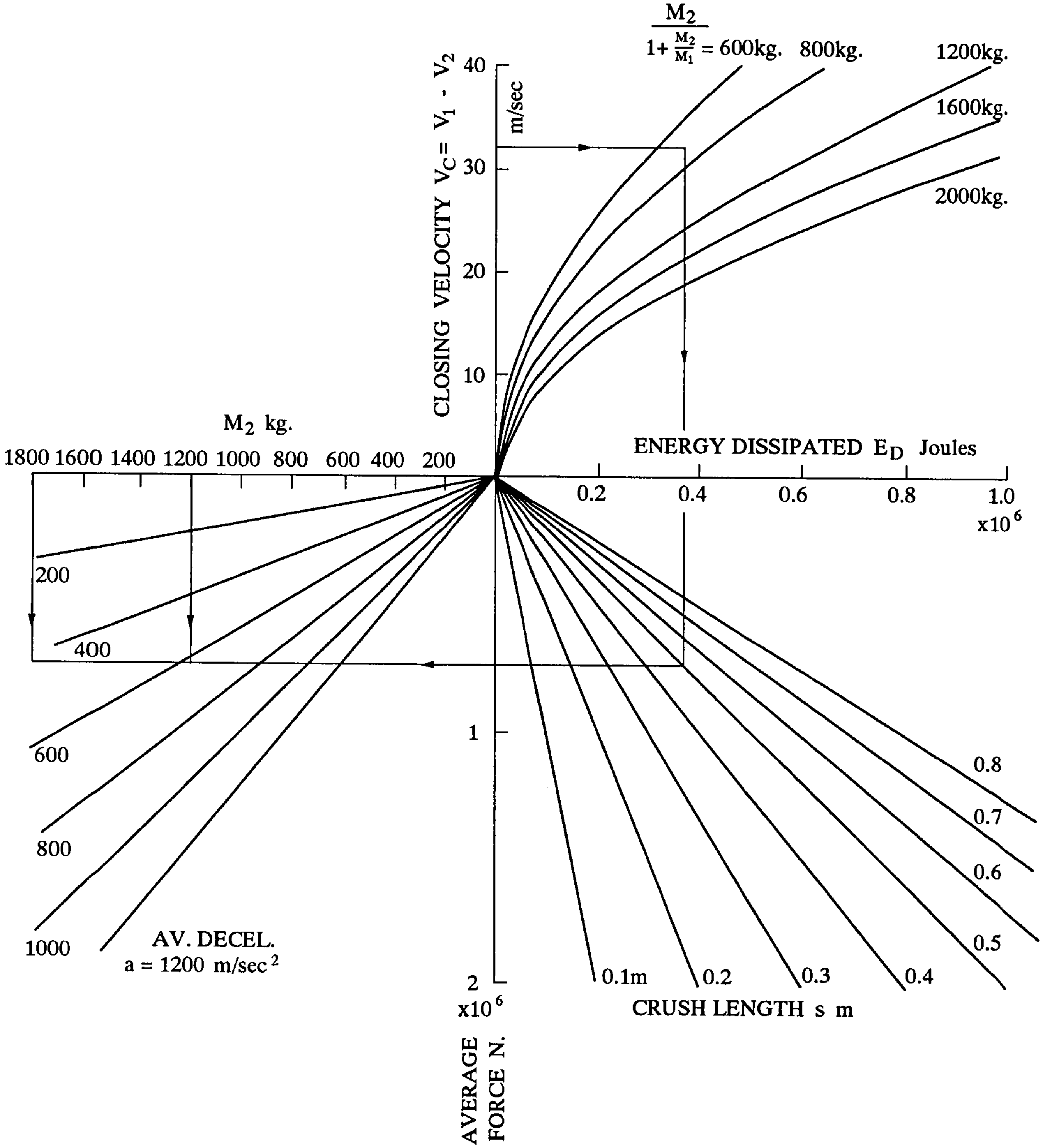


Fig.2 Chart which can be used for the analysis of collisions or for design of vehicles for average deceleration.

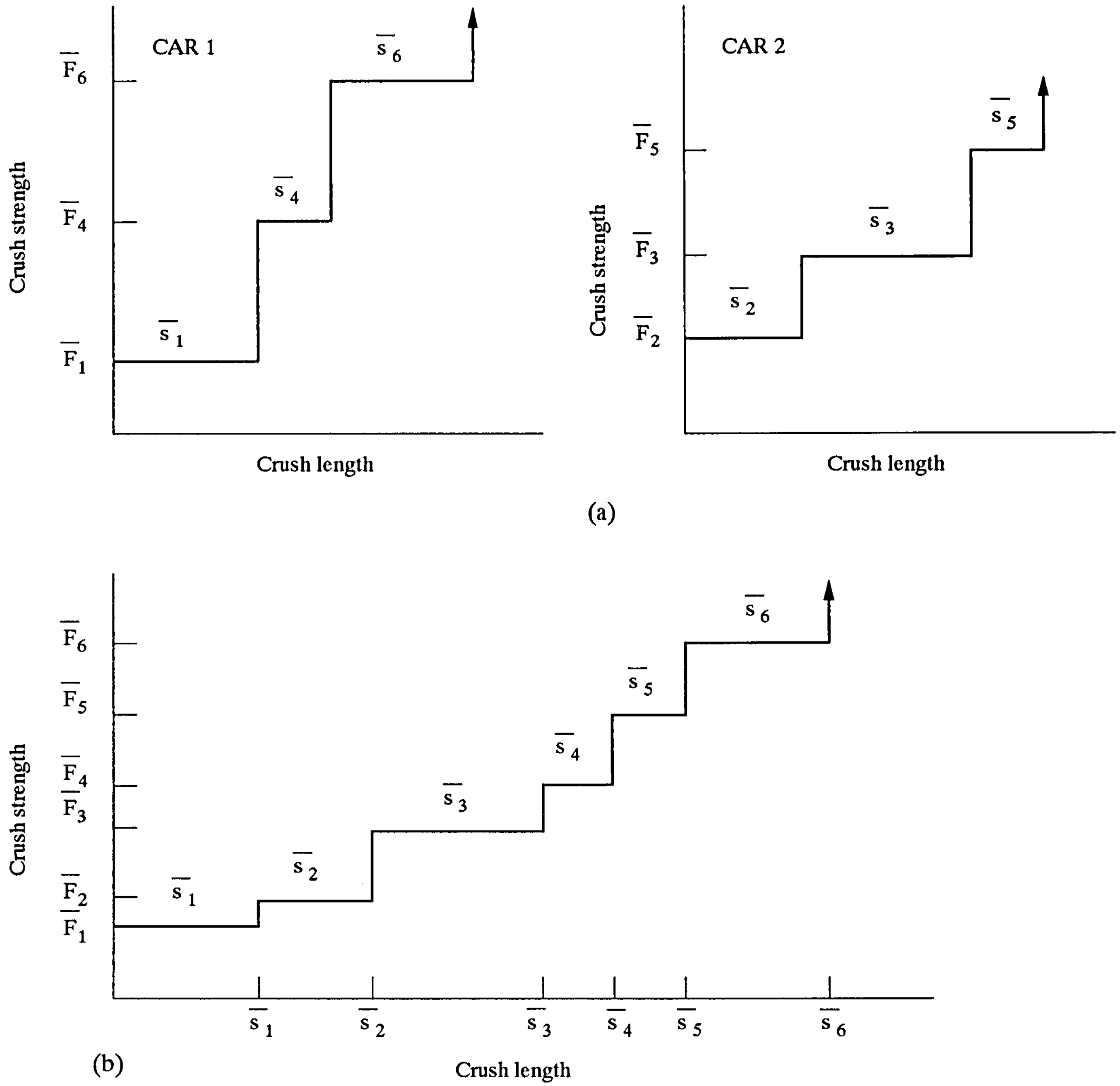
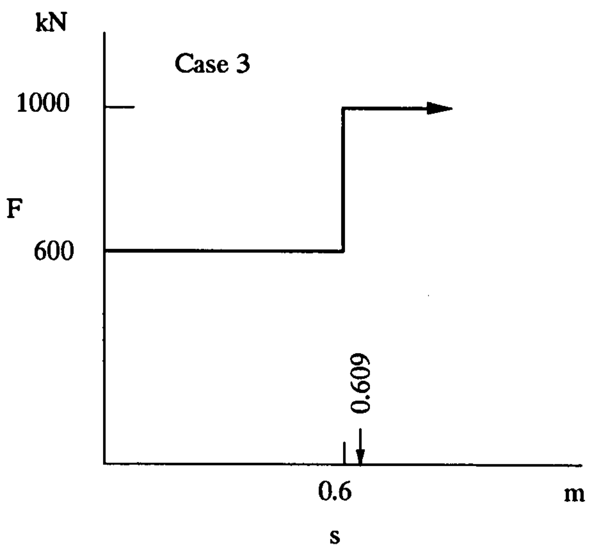


Fig.3 (a) Crush strength-crush length of two cars.
(b) When these cars collide the relationship forms a "stairway diagram"

direction. At this point the final velocity is that given by $\overline{V_3}$ in equation (1).

Five cases are now presented here to show what is the effect of different stairway diagrams on the behaviour of the two vehicles in a head-on collision with the following common parameters.

The stairway diagrams for the five cases are shown in Fig.4 which also shows the velocities of the cars during the collisions. The numerical values of the important parameters are shown in Table 1 and the velocities of the two cars during collision and crushing are plotted in Fig.5. It is seen that, although the behaviours during the collisions are quite different, at the end the velocities of the two cars now locked together are the same in all cases viz. 1.2 m/sec as predicted by equation (1).



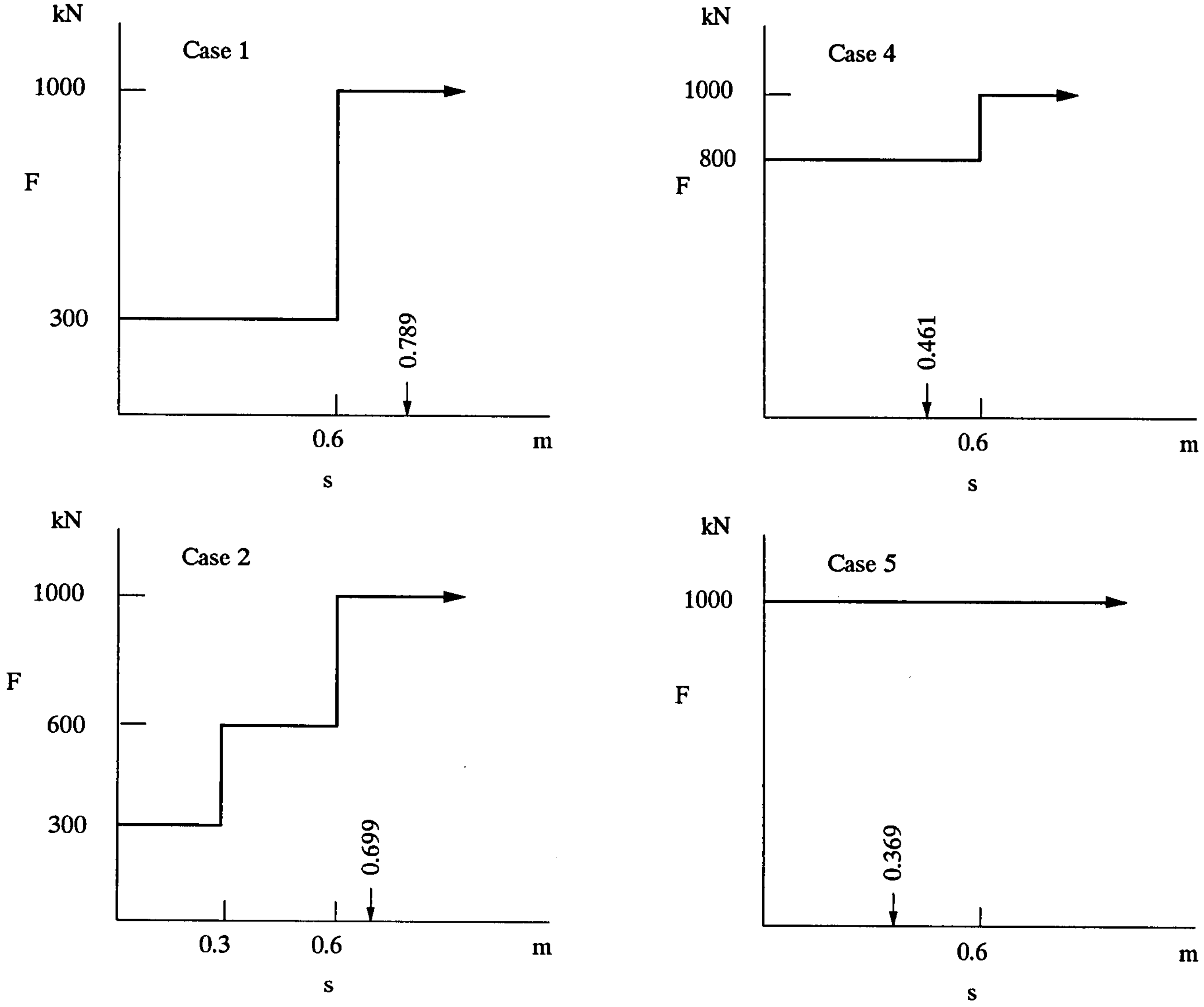
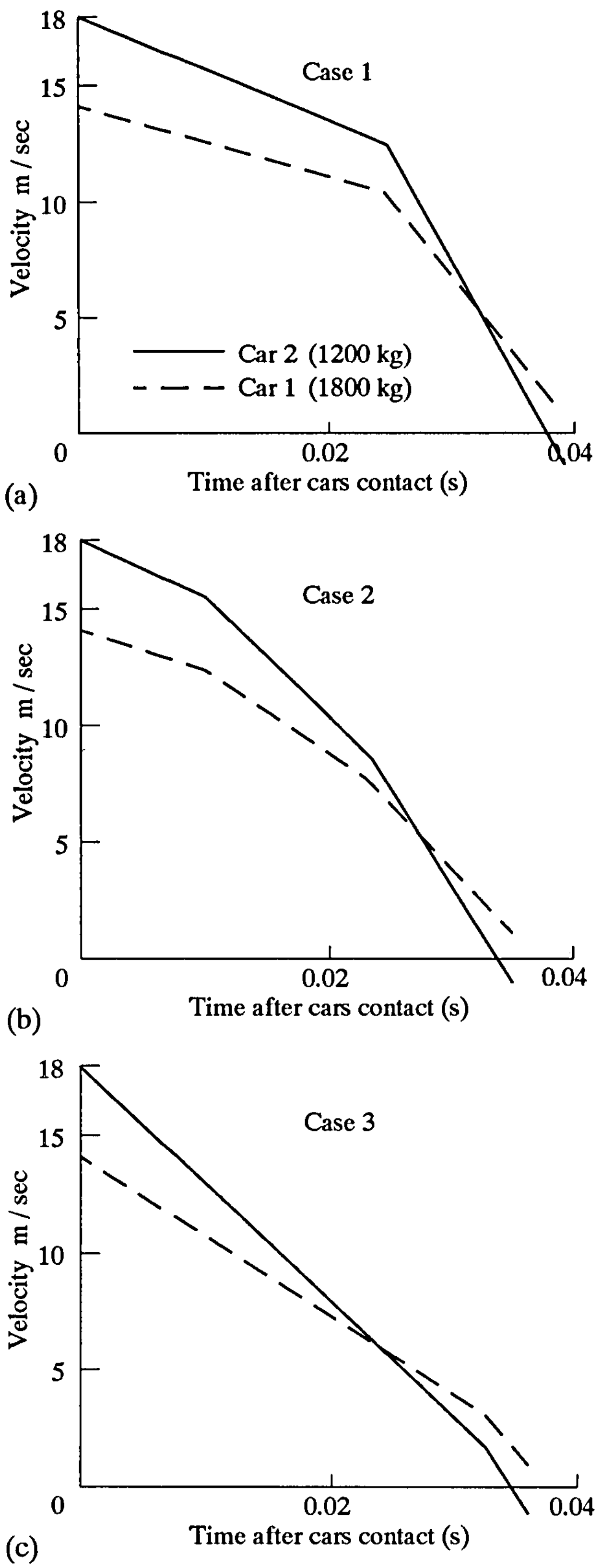


Fig.4 Stairway diagrams of five cases analysed.



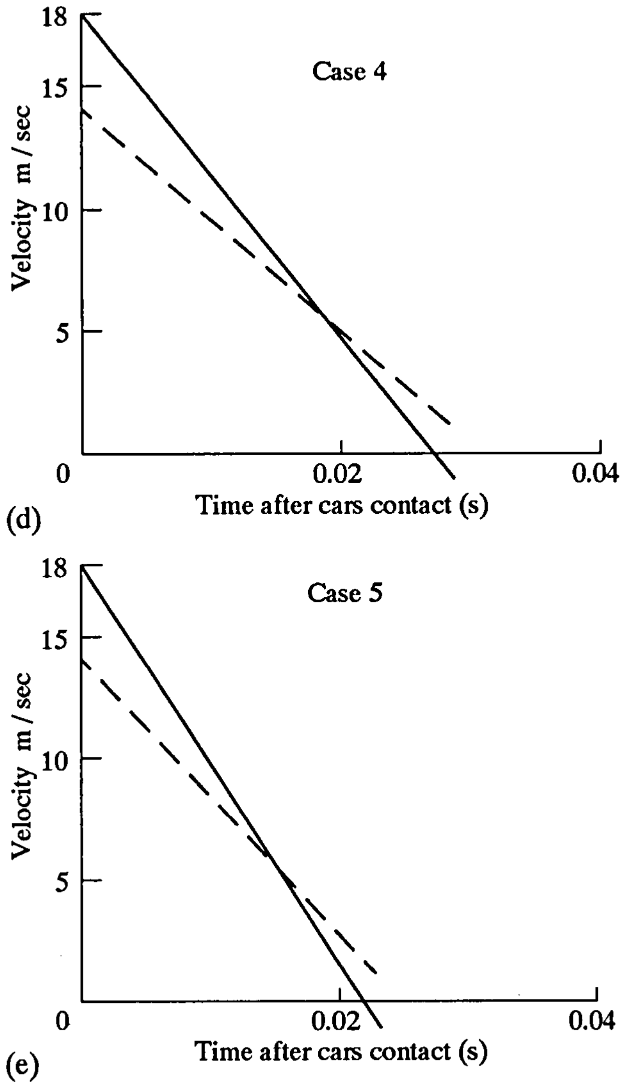


Fig.5 Velocity of Cars 1 and 2 during collision

It is seen that Case 1 gives the longest overall crush length as would be expected but it is Case 2 which has the longest overall collision duration. Cases 3, 4 and 5 are typical of collisions between more rigid vehicles and therefore have relatively small crush lengths and collision durations. However, the motion of the occupants has not yet been considered and this is done in the next section. For the purposes of explanation we shall restrict our attention to the driver and impact with the steering wheel. We wish to know the velocity with which the torso of the driver strikes the steering wheel.

Table 1

	Case 1	Case 2	Case 3	Case 4	Case 5
$\overline{V}_1$ at end of first step (m/s)	10.36	12.33	3.16	1.2	1.2
$\overline{V}_2$ at end of first step (m/s)	12.53	15.49	1.74	−1.2	−1.2
Time taken for first step (sec)	0.0219	0.0100	0.0325	0.0288	0.0229
Difference between travel of M_2 and that of the vehicle in first step (m)	0.0597	0.0126	0.2644	0.2764	0.2189
$\overline{V}_1$ at end of second step (m/s)	1.2	7.82	1.2	NA	NA
$\overline{V}_2$ at end of second step (m/s)	−1.2	8.73	−1.2	NA	NA
Time taken for second step (sec)	0.0035	0.0135	0.0035	NA	NA
Difference between travel of M_2 and that of second step (m)	0.0625	0.0796	0.0625	NA	NA
$\overline{V}_1$ at end of third step (m/s)	NA	1.2	NA	NA	NA
$\overline{V}_2$ at end of third step (m/s)	NA	−1.2	NA	NA	NA
Time taken for third step (sec)	NA	0.0118	NA	NA	NA
Difference between travel of M_2 and that of third step (m)	NA	0.1673	NA	NA	NA
Total time of collision (sec)	0.0360	0.0383	0.0360	0.0288	0.0229
Total difference between travel of M_2 and vehicle	0.3269	0.2628	0.3269	0.2764	0.2189
Impact velocity of driver on steering wheel (m/s)	19.2	19.2	19.2	19.2	19.2
Total crush length (m)	0.601	0.610	0.601	0.461	0.369

MOTION OF OCCUPANTS INSIDE VEHICLE

When we consider the motion of the occupants it would be realistic to assume that their upper torso pivots around their hip joints. To simplify the model we assume here that the motion of the centre of mass of the upper torso is in a straight line and behaving as if it were a loose object. Thus at time t seconds after collision the torso has moved forward a distance t x original velocity of the vehicle. At the same time the vehicle has slowed down and hence there will be a velocity differential between the torso and steering wheel in the case of the driver. In the following analysis we shall consider Car 2 and its driver and assume that the driver and steering wheel were originally separated by 0.5m. The difference between the distances travelled by the torso and steering wheel at the end of each stage is seen in Table 1 for each case. For example, a comparison between Cases 1 and 3 shows that with the greater crush force the torso moves forward relative to the steering wheel 4.4 times further for Case 3 (0.2644m compared to 0.0597m) in the first step.

In the penultimate line of Table 1 it is seen that the impact velocities of the torso against the steering wheel is 19.2 m/sec (= 69 kph) in each case. This is because the collision between the vehicles is complete and Vehicle 2 is travelling at 1.2 m/sec in the reverse direction when the torso strikes the steering wheel.

DISCUSSION

What would be desirable is for the torso to strike the steering wheel before the collision is complete. This would reduce the relative velocity between the torso and steering wheel. In all five cases this was not achieved. Hence other analyses with smaller constant crushing forces of 200000 and 150000 N were tried with a view to achieving contact between the torso and steering wheel before the collision is complete. With these lower crush forces this aim was achieved but the crush lengths had to be much greater, 1.843 and 2.458m, respectively. These crush lengths are probably too great to be of practical use. The velocity with which the torso strikes the steering wheel is 13 m/sec (46.5kph) and 11 m/sec (40 kph), respectively, instead of 19.2 m/sec for the driver of Car 2 in all other cases. Even though the aim of reducing the relative velocity between torso and steering wheel has been achieved in each of these two cases the velocities are still too great to be of practical importance.

It was therefore decided to see what is the effect of reducing the velocity of each car by 50%, i.e., to 7 and 9 m/sec, respectively. For Case 1 the crush length is

reduced to 0.307m so the second step in the stairway diagram is not involved. The cars complete their collision before the driver of Car 2 strikes the steering wheel so the velocity at which this occurs is 9.6 m/sec (34.6 kph). Thus, although there is no benefit from stepping the strength of the car the velocity of strike has been reduced considerably simply because the closing velocity of the cars has been decreased.

When we again consider the cases of crush strengths of 200 and 150 kN and see the effect of a 50% reduction in the closing velocity we find that the driver of Car 2 again strikes the steering wheel with a velocity of 9.6 m/sec in both cases. There has been no reduction in the impact velocity because for both crush strengths the cars complete their collision before the driver of Car 2 contacts the steering wheel.

It seems that the most effective way of reducing the impact velocity of the driver against the steering wheel is for him or her to drive slowly although reduction will occur in a few cases if the driver sets the seat further back to increase the distance to be travelled by the torso if a collision occurs.

CONCLUSION

From the studies of Cases 1 to 5 we conclude that stepping the crush strength in various ways above 300 kN does not reduce the velocity with which the torso strikes the steering wheel because the collision is complete before this happens. Smaller crush strengths of 200 and 150 kN result in large and unrealistic crush lengths and even so the strike velocities of 13 and 11 m/sec are still quite large when the closing velocity is as much as 32 m/sec.

At a closing velocity of 16 m/sec the impact velocity of the driver was 9.6 m/sec for all crush strengths above 150 kN because in all cases studied the collision was complete before the driver struck the steering wheel.

It therefore seems that in the many types of collisions studied here torso strike with the steering wheel is almost inevitable and the simple advice to occupants of older cars is to sit back as far as possible to give the seat belt the maximum opportunity to reduce the velocity of impact of the torso against the steering wheel or dashboard. To younger drivers the advice is of course the same but additionally KEEP YOUR DISTANCE and SLOW DOWN !!

REFERENCES

Murray, N.W. (1994) "When it comes to the crunch - the mechanics of car collisions" World Scientific Publishing Co Pty Ltd

Murray, N.W. (1996) "Three views of in-line collisions between cars" First Australian Congress on Applied Mechanics 96, Monash Uni. Melbourne

VISUAL HANDICAPS ALLOWED BY ROAD VEHICLE STANDARDS

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ABSTRACT

This paper is a summary of Clark (1996). Tinting of road vehicle transparencies delays driver perception and reaction. Theoretically this must increase collision probability and severity. Similar adverse effects can also result from excessive coloration in eyewear, styling excesses in transparency rake angles, obscuration in fields of view, use of long-wavelength red signal lights, and poor through-vehicle visibility. Road accident investigations generally have not been thorough enough for such contributory effects to be identified reliably. However, Australian vehicle insurance claims rates have increased substantially since 1990 when windshield tinting was first allowed and allowable tinting for windows was increased. There is scope for better matching of road vehicle standards to driver capabilities and limitations.

REACTION TIMES AND COLLISIONS

Rear end collisions account for up to 35% of road accidents. Reported values of driver reaction time t_r to begin braking are definition dependent but range from about 600 ms to 2 s. Observed headway distances between vehicles in traffic at speed u tend to overlap the minimum possible for collision avoidance, $u.t_r$, given equal deceleration. Sivak and Flannagan (1993) calculated that a 115 ms reduction in t_r (ie $\delta t_r = -115$) with a 5 m/s^2 deceleration ($\approx -0.5\ g$) would decrease the observed number of rear end collisions by 15%. Modelling can indicate the effect of positive δt_r in increasing collision energy. At 100 km/h (27.8 m/s) and likely ranges of initial conditions, a δt_r of +100 ms increases collision energy by between 0 and 7.7% of the initial kinetic energy of one vehicle.

Increments in t_r have their greatest adverse effects on collision probability and energy when braking is late and severe, the 'panic stop'. This is also when skids are more likely, with collision energy increases of up to 100% as a consequence. For conflicting vehicles travelling in any direction, the effect of a positive δt_r can be any differential result between no collision and a collision at the initial relative velocity, including the head-on case. For vehicles on a collision course, the effect of any delay for either driver may range from catastrophic to inconsequential but it cannot be beneficial in terms of collision probability and energy. Likewise, any reduction in t_r may be inconsequential but not adverse.

TRANSPARENCIES TINTING IN AUSTRALIAN ROAD VEHICLES

The Australian Design Rule (ADR) (FDTC 1992) for road vehicle safety glass initially followed long standing practice in the corresponding Australian Standard (eg AS R1-1965) by specifying the luminous transmittance for Illuminant A (T_A) at normal incidence in windshields below the upper border of the primary vision area as ≥ 85%. Clear safety glass can readily transmit 88% or more.

In 1990, Australian transport ministers agreed to vehicle industry requests to allow tinted windshields. The ADR was amended to allow $T_A \geq 75\%$ at normal incidence, 'harmonising' with ECE-Regulation 43 (eg Weigt 1986) rather than the 70% minimum in the US FMVSS 205 (NHTSA 1994). Tinted windshields almost completely displaced clear ones in new cars in Australia within a year or so. Unlike tinted eyewear, fixed tinting in vehicles cannot be removed whenever ambient conditions makes it unsafe for driving.

Raked windshields transmit less light. $T_A = 75\%$ at normal incidence becomes about 66% at 60° rake for unpolarised light (Smith and Bryant 1978). The US equivalent is 70% to 61%. Compared with clear glass having $T_A = 88\%$, the light losses are 66/88 or 61/88.

For side and rear windows in road vehicles, normal incidence $T_A \geq 70\%$ is specified. Some Australian States allow $T_A \geq 35\%$ (Vicroads 1990, White 1992). Some US States have no restriction (Cunningham 1993). In October 1995, 29% of 458 cars observed in Melbourne had clear transparencies all around and 34% had tinted windshields, which interpolates to 29% for mid 1994-95.

QUANTITY AND QUALITY OF LIGHT IN DRIVING

Light Reduction Effects of Transparency Tinting

Windshield tint decreases visibility at night (eg Zahlen and Schnell 1995, Clark 1996). Conversely, night road accident rates decrease as street lighting illumination is increased.

A model of car-following experiments (Fisher and Hall 1978) indicates that a 66/88 reduction of ambient luminance at 1.0 cd/m^2 increases follower response times to a $g/10$ lead vehicle deceleration by about 50 ms for 30 m headway and 290 ms for 158 m headway. With a 61/88 light reduction, the values are 66 ms and 380 ms. The perceptual latency contributions to the increases are 2.5 ms for the 66/88 case and 3.3 ms for the 61/88 case. These latency differentials are generally much smaller than t_r increases associated with usage of medicinal drugs, alcohol or mobile telephones (Brookhuis et al. 1994), age, and brain damage (Korteling 1990), but adverse effects from tinting are continuously present.

Bhise et al. (1981) found large effects of daytime ambient illuminance on visibility distances in rain. The equivalent effect of tinting in windshields can be calculated with the published models. For "typical" stopped car and background contrasts, and horizontal illuminances between 10 and 1000 lux, the 66/88 transmittance differential for wet windshields is a visibility distance loss of about 5%, or about 6% for the 61/88 case. The distance differentials range from 11 to 33 m, equivalent to delays of 0.6 to 1.8 s at the subject vehicle speed of 64 km/h.

The adverse effects of windshield rake on T_A and visibility grow rapidly beyond about 50°, with increases in absorption, Fresnel reflectance, polarisation, intensity of higher order images, veiling glare from interior reflections, solar glare for other road users, and obscuration and veiling glare from surface damage, dirt, and water droplets. Large rake angles also encourage wide pillars and increase solar heating.

Driver and pedestrian eye contact rates can exceed one a minute for a driver in side streets. The lines of sight often pass obliquely through the windshield and front side windows. Transparencies tinting is a hindrance to eye contact, an invitation to criminality and an officer safety hazard (Cunningham 1993).

For an observer in a moving vehicle, perceptual conflicts in localisation can arise from interocular luminance differences (Enright 1970). This can occur when looking past partly open tinted side windows. For the same reason, horizontal gradient(s) or stepwise variations in T_A for all transparencies need to be limited by regulation.

Even minimal tinting ($T_A \geq 70\%$) of rear windows increases the risk of accidents while reversing (Freedman et al. 1993). Children are often the victims. The minimum T_A for rear windows should apply at the installed rake. The current 'high back' styling of cars obscures critical areas. Rear vision mirrors with low reflectance to counter headlight glare may be made less effective again by window tinting. Dual-reflectance rear vision mirrors provide a safer solution: otherwise, the darkened view in the rear vision mirror in daylight and twilight can require extra adaptation time of tens of milliseconds or more. Such delays may be critical if a collision threatens after a rear-view glance has started.

Many drivers have reported hearing the impact before seeing the pedestrian just struck (Allen, 1970). Actual detection distances thus extend down to zero, a fact generally ignored by experimenters. Tinting generally cannot improve pedestrian safety and in the worst case will result in an unbraked collision rather than a narrow escape because of a successful swerve.

On the evidence, all vehicle transparencies used in negotiating traffic should be clear for maximum traffic safety. This would also favor lawful behavior and the safety of police. Having installed $T_A \geq 86 \pm 1\%$ avoids asymmetric tolerances and allows reasonable rake angles.

Spectral Selectivity Hazards

About 8% of males and 0.4% of females in Western populations are congenital colour vision deficients (CVDs). Acquired CVDs may be at least as common (Whillans and Allen 1992) and often have other losses in visual function. CVDs are handicapped in the road transport system (Cole and Maddocks 1995). The red insensitivity of protans is a special problem (Cole and Vingrys 1983), often ignored by or unknown to traffic authorities.

Combinations of windshields and eyewear of different spectral selectivity can result in dangerously low values of overall T_A (Miles 1954).

Some vehicle tinting is spectrally selective for visible light. ADR 8/00 ignores this and allows materials that would make red lights effectively invisible to all drivers: eg for a spectral transmittance of 88.3% between 380 nm and 610 nm inclusive, and zero for 620 nm and beyond, $T_A = 75.0\%$. Spectral selectivity effects on perception of coloured signals can be large in daytime (Clark 1993). Driver reaction may either improve or degrade for particular chromatic target-background combinations, but there is generally an overall adverse bias because of the non-linear dependence of t_r on the signal visibility (Clark 1968a, b). The problems are worse for CVDs.

Tinted eyewear can compound the adverse effects of transparency spectral selectivity (Clark 1970, Pun et al. 1986, Dain et al. 1993). For road safety, Australian consumer protection laws specify coloration limits for general purpose sunglasses and cosmetic spectacles to limit interference with the perception of red traffic signals, but there are no controls yet on the coloration of windshields, some specific purpose sunglasses, prescription spectacle and contact lenses, or cosmetic contact lenses.

Tinted side and rear windows can also affect the perception of coloured signals such as brake lights, traffic lights and emergency vehicle beacons viewed by drivers directly or via rear view mirrors. It is common for a driver's only view of a coloured signal such as a vehicle turn indicator or brake-actuated light to be through the transparencies of another vehicle, particularly in the case of Centre High Mounted Stop Lights (CHMSLs) (Triggs 1988, White 1992, Cunningham 1993).

CHMSLs have been incorporated in most new vehicles and retrofitted to others since 1988. With unexpected braking of a lead vehicle, CHMSLs reduce driver mean t_r by 90 ms (McKnight and Shinar 1992) or 63 ms (Akerboom et al. 1993). Tinted transparencies can decrease the benefit.

Spectrally selective effects are compounded when signals are seen through transparencies of preceding vehicles. A sky reflection superimposed on the transmitted image will generally further reduce signal visibility. Driver t_r can be increased by tens to hundreds of milliseconds. The effects are worse for CVDs. The red signal visibility factor R, a simple indicator of the signal/background luminance ratio, allows δt_r and the change in the missed signals rate to be predicted. Near-unity values of R are readily obtained with clear or neutral grey glass and plastics.

If $R \geq 0.8$ for tinted eyewear and $R \geq 0.9$ for installed windshields, the combination can readily have $R = 0.7$, approximately equivalent to a 30% reduction in the intensity of all red signal lights. To maintain this lower limit when the light passes through the transparencies of two preceding vehicles, for each transparency, $R \geq (0.9)^{1/5}$ (≈ 0.98). If the coloration measure takes a more precise form, eg the Q values used for sunglasses in BS 2726 (BSI, 1987), the red-signal Q factor (Q_R) should have values equal to those for R, giving $Q_R \geq 0.8$ for eyewear and $Q_R \geq 0.98$ for windshields. Q values for blue, green and amber signal colours should be similar. Less stringent limits can apply to rear side vehicle windows.

LEDs as Tail and Brake Lights

Conventional incandescent brake lights emit no light at all for the first 50 ms of current flow and take 250 ms to reach 90% of final intensity. Modified electrical circuits can shorten this time to 50 ms, allowing subjects to react 115 ms faster (Sivak and Flannagan 1993). Red light-emitting diodes (LEDs) operate almost instantly, and are used as CHMSLs and as bicycle tail lights. Those with a dominant wavelength of about 670 nm are common but can be dangerously faint for protans.

Small Headlights

Recently introduced small-diameter headlamps have greater luminance for a given intensity. This can increase the visibility of transparency scatter (Kessler, 1993) and increase glare for oncoming drivers. A glimpse of the intense blue at the beam edges can be distracting if mistaken for an emergency vehicle signal. Some US cars have these small lamps mounted closer and lower than conventional headlights, giving the dangerous illusion at night of a conventional car at twice the distance. Presumably these vehicles comply with current safety regulations.

OTHER VISUAL HANDICAPS IN CURRENT ROAD VEHICLES

Obscuration by Transparency Edge Coatings

Black coatings applied to the edges of laminated glass windshields, sometimes with a dot pattern border, frequently extend windshield pillar obscuration. No

edge coatings were found on pre-1986 models in a car park survey. For 23 different later makes and models, the mean pillar width seen from a driver's estimated left eye position was 90.0 mm, the mean extension by the fully opaque coating was 9.2 mm and the mean width of the dot pattern was 3.2 mm. The mean increase in obscuration is therefore 14%. The actual effect is worse than this when considered as an extension of the width that produces a binocular obscuration, say the excess over 64 mm: it is a mean increase of about 48%. The worst case is as much as 154%. For an eye-pillar distance of 0.5 m and a roadside object of 1.0 m width, say, the sighting distance could be reduced from 25 m to 10 m. At 60 km/h (16.4 m/s), the corresponding delay would be 0.92 s, conceivably the difference between a near miss and an unbraked collision.

The actual angular extent of the obscured field increases for smaller pupillary separations and increasing horizontal gaze angle. ADR 8/00 and SA/SNZ (1995) apparently do not prevent edge coatings from adding to the pillar obscuration.

ADR 8/00 defines the windshield primary vision area as dependent on a 95 percentile eye ellipse. The data are for a US adult male population. Adult sitting eye-heights range from 603 mm for a Vietnamese 5 percentile adult female to 858 mm for a 95 percentile adult US male (Worksafe Australia, 1995), selected as representing members of the Australian population. The range is too large for the usual fixed-height seat: drivers with small sitting eye-heights may have to look through the steering wheel or alongside the topmost part of the rim. Drivers at the other extreme may have to look through the tint band (Dunn, 1973). ADR 8/00 does not cover this point well.

Other Through-Vehicle Light Barriers

Through-vehicle visibility is degraded by the semi opaque advertising material used on the rear windows of some taxis, by window stickers, ornaments suspended from interior mirrors, and by high-mounted spare wheels on rear doors of off-road vehicles. These visual impediments are tolerated but they should not be. Wire mesh stoneguards for windshields (Triggs, 1988), wire mesh screens for parcels restraint in wagons, and head restraints also reduce through-vehicle vision, but present alternatives may introduce other safety problems.

DISCUSSION

Human Limitations in the Vehicles-Drivers System

People often drive despite reduced vision and physical handicaps (eg Johnston et al. 1976, Lings 1991, Wood and Troutbeck 1994, Szlyk et al. 1995). Driver-vehicle system performance can also be reduced by dirty headlights (Rumar, 1974), traffic signals depreciation (Janoff, 1991), sub optimal colour coding, rain, tinting and visual field obstructions. Any of these factors alone might seldom be the sole cause of an accident, but multiple factors must increase the risk.

The vehicle industry has promoted the use of tinted transparencies, overtly for air conditioner performance (eg NSWRTA, 1994). Actual measurements discount this (eg Allen and Crosley 1965, Hurst and Scroger 1974). Solar heating can be reduced more effectively by better insulation, light coloured paints with high near-infrared reflectance, and solar powered ventilation. Discomfort from direct sunlight on skin is avoidable with light clothing.

The 'Blue Skies' Case

In the US 'Blue Skies' court case, six tinting companies successfully applied for vehicle window $T_A \geq 35\%$ (White 1992, Smith 1994). The judge found $T_A = 35\%$ "actually enhances a driver's visibility by reducing glare" and "does not hamper the visibility of an individual who has to look into a vehicle", directly contradicting most responses by US road safety and law enforcement authorities to a NHTSA questionnaire (Cunningham 1993). The judge apparently placed greater reliance on house reports of industry sponsored pro-tinting results than on the much larger body of relevant scientific literature. The literature on daytime hazards of tinting was apparently ignored.

Accident Statistics

The 1990 decision to allow windshield tinting and increased window tinting in Australia provided an unusual, if not unique, opportunity to observe any accompanying effect on the accident rate. Since then, most new vehicles sold in Australia have had all transparencies tinted to the maximum allowed by ADR 8/00, clear replacement windshields have generally been phased out, and after-market window tinting companies have vigorously expanded their activities.

The accident claims rate reported by a large Australian motor vehicle insurer fell until 1990-91 (Kay, 1995), with a steady increase after 1991-92. The increases are in rear end, cross traffic, parking and other accidents, and are consistent across States, indicating that the causative factors act nationally. Another company has reported a similar upwards trend in the last four years (Jha, 1995). The claims rate excess over the established downwards trend reached about 30% in 1994-95, despite increased driver compliance with key safety laws in recent years because of enforcement by speed cameras and random breath tests.

Total petrol usage in Australia from 1991 to 1994 increased by 4%, too small to account for much of the increase in claims rate (Kay, 1995). If the excess in accident claims for 1994-95 of about 30% is solely a consequence of about 29% of vehicles having tinted windshields, vehicles of less than 4 years old would have an excess of about 100% over the accident rate of all older vehicles in 1994-95. Kay's figures allow a comparison between new vehicles, nearly all with tinted windshields, and vehicles older than 6 years, mostly having clear windshields: the newer vehicles actually had a 63% higher claims rate in 1994-95. For the second company, the excess is large only when the comparison is with vehicles over 10 years old. The differences are even greater when the comparison is with vehicles over 15 years old, when fewer Australian vehicles had window tinting. Presumably these excesses are inflated by greater usage of newer vehicles as well as visual interface shortcomings such as wide edge coatings and long wavelength LEDs, but improvements such as better brakes and handling in newer vehicles would act conversely.

As the current cost of road accident trauma in Australia is about $6 billion annually, the cost attributable to degradation of the vehicle visual interface could be about $2 billion in 1994-95. This should provide sufficient motivation for the introduction of greatly improved accident investigations to isolate visual factors such as degraded contrast, colour vision deficiencies, effects of tinting etc. Only about 1% of the total cost of road trauma would need to be attributable to vehicle window tinting to offset the claimed economic benefits of the tint film industry in Australia.

Enhancing Vehicle Safety

Both the regulatory approach to road safety and the vehicle industry's self-regulation exhibit failures in the vision part of the drivers-vehicles system. Road safety is not being taken seriously enough when there is official tolerance of hazards such as visibility reduction and signal perception delays caused by tinted transparencies, unnecessary increases to obscuration by edge coatings and pillars in the driver's horizontal field of view, inadequate rear-view mirrors, obscuring material on vehicle transparencies, dangling ornaments, red signals with spectral properties making them virtually invisible to 2% of male drivers, and no limits on the spectral properties of contact lenses and prescription lenses used by drivers. Allen (1966) made much the same points 30 years ago.

In accident cases where the transparencies of involved vehicles were degraded by built-in or after-market tinting or non-essential opacities, calculation of the effect of these handicaps on the occurrence and severity of the collision should be possible provided data collection has been adequate.

CONCLUSIONS

Light loss in vehicle tinted transparencies is a nighttime road traffic hazard. Daytime hazards also arise when transparencies or eyewear or both are tinted, especially if the tinting is spectrally selective. The effects can be exacerbated by visual and physical disabilities of drivers, tinted eyewear, rain, and in-service deterioration of lighting, transparencies and signals. Insignificant to substantial losses in visibility and increases in driver reaction time result and the outcome is increased collision probability and severity.

Other regulatory shortcomings in the drivers-vehicles system relate to use of some red brake and tail lamps that are near-invisible for about 2% of male drivers, uncontrolled tinting of prescription eyewear, undesirable limitations and obscuration of drivers' fields of view, and excessive windshield and rear window rake. An increase of about 30% in the insurance claims rate for rear end, cross traffic, parking and other accidents occurred in the four years after windshield tinting became legal in Australia in 1990. Newer cars are over-represented in the increase. The extra cost to Australia for 1994-95 appears to be about $2 billion. No causal relationship between the potential hazards described in this paper and observed

accidents has been proved but the trends are consistent with expectations.

Apart from the inappropriate allowance of tinting, existing Australian vehicle safety regulations and standards use imprecise terminology and miss necessary detail such as spatial variation limits for luminous transmittance. Completely clear glazing all around appears to be a necessary but not sufficient condition for a safe vehicle. Stringent limits for transmittance and coloration are proposed for all vehicle transparencies. Mandatory coloration and transmittance limits should apply to all eyewear used in driving. Other visual interface features of road vehicles need safety improvement. Road accident investigations and data collections need to be far more detailed than hitherto.

REFERENCES

Akerboom, S. P., Kruysse, H. W. and La Heij, W. (1993) Rear light configurations: the removal of ambiguity by a third brake light. *Vision in Vehicles - IV*, eds Gale, A. G. et al. pp 129-138. North Holland, Amsterdam, Holland.

Allen, M. J. and Crosley, J. K. (1965) Automobile liquid glass tint: a research report. *American Journal of Optometry and Archives of the American Academy of Optometry,* 42, pp 344-350.

Allen, M. J. (1966) Automobile windshields, a new car study, 1966 models. *Optometric Weekly*, 57 (28 part 2), pp 14-17.

Allen, M. J. (1970) *Vision and Highway Safety.* Chilton Book, New York, USA.

Bhise, V. D., Meldrum, J. F., Forbes, L. M., Rockwell, T. H. and McDowell, E. D. (1981) Predicting driver seeing distance in natural rainfall. *Human Factors,* 23(6), pp 667-682.

Brookhuis, K., De Waard, D. and Mulder, B. (1994) Measuring driving performance by car following in traffic. *Ergonomics,* 37(3), pp 427-434.

BSI (1987) British Standard BS 2724-1987, *Specification for sun glare eye protectors for general use.* British Standards Institute, UK.

Clark, B. A. J. (1968a) The effects of tinted ophthalmic media on the recognition of red traffic signals. *Proceedings of the 4th Conference of the Australian Road Research Board,* 4(1), pp 898-930.

Clark, B. A. J. (1968b) Effects of tinted ophthalmic media on the detection and recognition of red signal lights. *Aerospace Medicine,* 39(11), pp 1198-1205.

Clark, B.A.J. (1970) Coloration limits for sunglasses. *Australian Journal of Optometry,* 53, pp 307-315.

Clark, B. A. J. (1993) Daytime hazards of windshield tinting. *Road and Transport Research,* 2(4), pp 76-86.

Clark, B. A. J. (1996) Mismatches between driver capabilities and road vehicle standards. In press, *Road and Transport Research, 5(2).*

Cole, B. L. and Vingrys, A. J. (1983) Do protanomals have difficulty seeing red light? *Proceedings 20th Session of the Commision Internationale d'Eclairage,* 1E 04/1, The Netherlands. CIE, Paris, France.

Cole, B. L. and Maddocks, J. D. (1995) Defective colour vision is a risk factor in driving. In press, *Colour Vision Deficiencies* XIII.

Cunningham, G-R. (1993) After-market film on passenger car windows and light transmission. *Vision in Vehicles - IV,* eds Gale, A. G., et al. pp 79-88. North Holland, Amsterdam, Holland.

Dain, S. J., Pye, D. C., Bogaert, N., Cooper, S. J., Klaunzer, P. M. and Nicolson, A. (1993) The combined colour effects of tinted hydrogel contact lenses, sunglasses and tinted automotive windscreens. *Road and Transport Research,* 2(3), pp 75-82.

Dunn, A. R. (1973) *The effect of light absorbing media on driver visual performance.* Brown Engineering Co, Contract DOT-HS-089-2-453, National Highway Traffic Safety Administration, Washington DC, USA. PB 219 608

Enright, J. T. (1970) Distortions of apparent velocity: a new optical illusion. *Science*, 168, pp 464-467.

FDTC (1992) *Australian Design Rules for Motor Vehicles and Trailers, ADR 8/00, Safety Glazing Material, Package 17.* Federal Department of Transport and Communications, Canberra, ACT.

Fisher, A. J. and Hall, R. R. (1978) Motorists' information needs and freeway lighting levels. *Proceedings of the 9th Conference of the Australian Road Research Board*, Session 36, Queensland, 21-25 August 1978, pp 8-18.

Freedman, M., Zador, P. and Staplin, L. (1993) Effects of reduced transmittance film on automobile rear window visibility. *Human Factors*, 35(3), pp 535-550.

Hurst, W. S. and Scroger, M. G. (1974) *Influence of windshield tint on the temperature in automobile passenger compartments.* Report No. NBS-74-533. National Bureau of Standards, Washington DC, USA.

Janoff, M. S. (1991) Traffic signal visibility: a preliminary standard for round signal indicators derived from scientific research. *Transportation Research Record 1316*, Transportation Research Board, National Research Council, Washington DC, USA.

Jha, N. (1995) Personal communication, facsimile 23 November.

Johnston, A. W., Cole, B. L., Jacobs, R. J. and Gibson, A. J. (1976) Visibility of traffic control devices: catering for the real observer. *Ergonomics*, 19(5), pp 591-609.

Kay, M. (1995) *AAMI Crash Index, June 30, 1994 - June 30, 1995.* Australian Associated Motor Insurers Limited, Melbourne, 4 October 1995.

Kessler, F. R. (1993) Light diffusion characteristic and visibility interferences in automobile windshields. *Vision in Vehicles - IV*, eds Gale, A. G., Brown, I. D., Haslegrave, C. M., Kruysse, H. W. and Taylor, S. P., pp 69-78. North Holland, Amsterdam, Holland.

Korteling, J. E. (1990) Perception-response speed and driving capabilities of brain-damaged and older drivers. *Human Factors*, 32(1), pp 95-108.

Lings, S. (1991) Assessing driving capability: a method for individual testing. *Applied Ergonomics*, 22(2), pp 75-84.

McKnight, A. J., and Shinar, D. (1992) Brake reaction time to center high mounted stop lamps on vans and trucks. *Human Factors*, 34(2), pp 205-213.

Miles, P. W. (1954) Visual effects of pink glasses, green windshields, and glare under night-driving conditions. *AMA Archives of Ophthalmology*, 51, pp 15-23.

NHTSA (1994) *Federal Motor Vehicle Safety Standard (FMVSS) 205, Glazing Materials.* National Highway Traffic Safety Administration, 49 CFR Ch. V (10-1-94 Edition), 571.205, Washington, DC.

NSWRTA (1994) *Proceedings of Window Tinting Symposium*, Sydney Airport Hilton Hotel, 10 May, New South Wales Roads and Traffic Authority, Sydney, NSW.

Pun, H. W., Brown, B. and Lui, R. (1986) Tinted contact lenses slow reaction time in colour defective observers. *Clinical and Experimental Optometry*, 69(6), pp 213-218.

Rumar, K. (1974) Dirty headlights–Frequency and visibility effects. *Ergonomics*, 17(4)), pp 529-533.

SA/SNZ (1995) *AS/NZS 2080:1995, Safety Glass for Land Vehicles.* Standards Australia, Homebush, NSW, Australia, and Standards New Zealand, Wellington, New Zealand.

Sivak, M. and Flannagan, M. (1993) Fast-rise brake lamp as a collision-prevention device. *Human Factors*, 36(4), pp 391-395.

Smith, G. and Bryant, J. F. M. (1978) The optical properties of tilted windscreens under practical conditions. *Proceedings of the 9th Conference of the Australian Road Research Board*, 9 (Session 36), pp 1-8.

Smith, D. (1994) Automotive film industry U.S.A. Included in *NSWRTA (1994).*

Szlyk, J. P., Seiple, W. and Viana, M. (1995) Relative effects of age and compromised vision on driving performance. *Human Factors*, 37(2), pp 430-436.

Triggs, T. J. (1988) Some vehicle design factors that influence driver visual performance. *International Journal of Vehicle Design*, 9(4/5), pp 542-547.

Vicroads (1990) *Vehicle Standards Information 2*, Vehicle Safety Branch, Road Safety Division, Victoria, Australia, March 1990.

Weigt, P. F. (1986) Darker glasses in the rearward field of view. *Vision in Vehicles.* Proceedings of a conference, Nottingham, UK, September 1985, eds Gale, A. G. et al. pp 343-353. North Holland, Amsterdam, Holland.

Whillans, M. G. and Allen, M. J. (1992) Color defective drivers and safety. *Optometry and Vision Science,* 69(6), pp 463-466.

White, M. (1992) An evaluation of some recent (1988-1992) reports on the effects of car side and rear window film tinting on the visual performance of drivers. *Office of Road Safety Report Series* Number 5/92, Department of Road Transport, Adelaide, South Australia.

Wood, J. M. and Troutbeck, R. (1994) Effect of visual impairment on driving. *Human Factors,* 36(3), pp 476-487.

Worksafe Australia (1995) *Anthropometric Database.* Ergonomics Unit, Sydney, Australia.

Zahlen, H. T. and Schnell, T. (1995) Loss of visibility distance caused by automobile windshields at night. *Transportation Research Record 1495*, Transportation Research Board, National Research Council, Washington DC, USA.

THE FEATURES OF THE ACCIDENT DATA RECORDER AND ITS CONTRIBUTION TO ROAD SAFETY

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ABSTRACT

The Accident Data Recorder is a black box for the vehicle which can be compared to the flight recorder used in air planes. It records the transversal an longitudinal acceleration as well the vehicle rotations and road speed. It further knows when and how long ignition, light, indicators and brakes have been activated.

In the event of an accident, this data is recorded with high precision 30 seconds before and 15 seconds after the accident. Accident recognition is fully automatic. The device can be installed into any vehicle.

Experiences gained by VDO Kienzle show that the system has a positive effect on accident prevention and provides the accident expert with objective data on the course of an accident.

1. ROAD SAFETY AND LEGAL CERTAINTY

Road safety is one of the major challenges of traffic policy. Great achievements have been made during the last years in the European Union (EU):

- by legal regulations such as seat belts and side impact protection
- or on a voluntary basis such as airbag and ABS

These measures are efficient. The accident rates in the EU are declining. But there are still more than 1.3 million road accidents with injuries to persons within the European Union, with more than 40,000 people killed and 1.5 million people injured. This means that approx. 140 people out of 1 million inhabitants are killed per year in a road accident. Let's give these figures an economic dimension: the economic damage caused by road accidents in Western Europe amounts to approx. 40 billion ECU per year.

These figures are significant and clearly show that still greater efforts are needed to improve road safety, last but not least because the risk of accident will further increase in line with permanently increasing traffic density.

When talking about accidents, one aspect must not be neglected: legal certainty in road traffic.

In jurisdiction there are few areas where judgments have to be delivered on the basis of uncertain evidence, as is the case in traffic proceedings. Vague, subjective deposition, lacking traces (e.g. missing skid marks due to ABS), difficulties in finding out the driver's reaction right before the accident (e.g. braking, blinking and steering) are the order of the day.

There are two different problems:

- high accident rates with the related strokes of fate and economic impact
- an often unsatisfactory situation in accident analysis and lacking evidence in jurisdiction in a substantial area of life.

In the course of this paper we should like to present a possible solution to both problems. Of course, we cannot offer a 100% solution, but based on the experiences gained in the meantime, we are convinced that by using the Accident Data Recorder - in short UDS - substantial progress can be achieved in the field of accident prevention and improved accident analysis and, therefore, in the field of jurisdiction.

2. TECHNICAL FEATURES OF THE UDS

Before discussing these two aspects, i.e. accident prevention and accident analysis, it will be useful to briefly explain the functions of the black box called UDS. This device will remind you of a flight recorder for use in the passenger car.

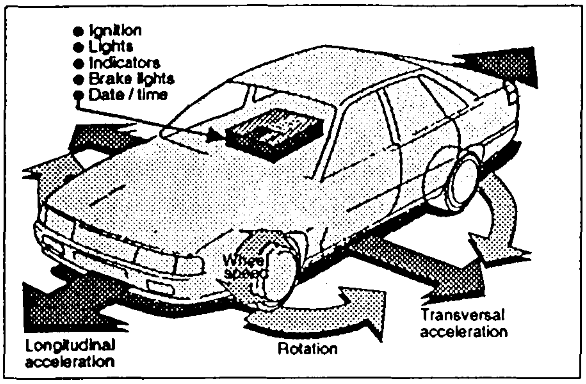

Figure 1. How the black box works.

The UDS is mainly composed of sensors detecting the transversal and longitudinal acceleration of the vehicle as well as vehicle rotations and road speed. It also records such events as overtaking, skidding, cornering and collisions. The UDS discerns when and how long ignition, lamps, indicators and brakes have been activated. In case of an accident, these data are recorded with high precision 30 seconds before and 15 seconds after the accident. The accident is automatically detected by the UDS.

Up to three accidents can be stored in the UDS. Critical traffic situations can also be manually stored.

The UDS can easily be installed into any vehicle. There is no need for additional sensors.

3. ACCIDENT PREVENTION AND ACCIDENT ANALYSIS

After this technical digression, it is easier to explain why the UDS can have an accident-preventing effect and how it contributes to optimizing accident analyses.

3.a) First of all, let's regard accident analysis:
For the accident analysis expert, the UDS is an instrument which provides him with objective accident data not available before. The analysis in view of accident reconstruction is made by a dedicated software package (see figure 2, page 3).

If an accident occurs, the UDS stores up to 500 times per second the relevant information, such as longitudinal and transversal acceleration and vehicle rotation. With this accurate information it is possible to decode and analyse at the computer even the slightest details of the critical fraction of a second.

3.b) And now to accident prevention:
As regards accident prevention, positive results have been achieved in the field of technical safety equipment in the vehicle, and further progress can be expected.

Experiences gained with the Accident Data Recorder during the last three years have shown that the UDS considerably influences the driving behaviour and thus contributes to accident prevention. In a number of vehicle fleets the accident rate and damages incurred could be reduced by up to 30 %. This paper will reflect to this point later on.

How can this development be explained?

Of course, experience gained with vehicle fleets should be generalized, but perhaps you agree with the following: It is the knowledge about the fact that the driving behaviour can be objectively checked at any time that leads the driver to behave more attentively in critical accident-bound situations if an Accident Data Recorder is installed.

In this context it is interesting to know that around 87 % of the accidents involving passenger cars and trucks are caused by inappropriate driving behaviour, only 13 % by technical defects and road problems. It is, therefore, worthwhile to take adequate measures in view of influencing the drivers' behaviour.

3.c) Besides, this impact of the Accident Data Recorder on the driving behaviour, together with improved evidence in case of an accident, is the reason why the German Traffic Court Conference has been calling for many years for the introduction of an Accident Data Recorder.

4. WHO BENEFITS FROM THE UDS?

4.a) In the field of accident analysis there are many tasks that can be accomplished more efficiently by means of the UDS.

Let's start with the accident analysis expert who will be trained by us in the field of analysing technology and who will then work on his own. A network of accident analysis centres is being established to provide adequate coverage.

His optimized accident analysis is of great help to jurisdiction, since many traffic court proceedings can be avoided and, should it come to a legal proceeding, is based on better, because objective, evidence. In this context attention must be drawn to the fact that nowadays the police

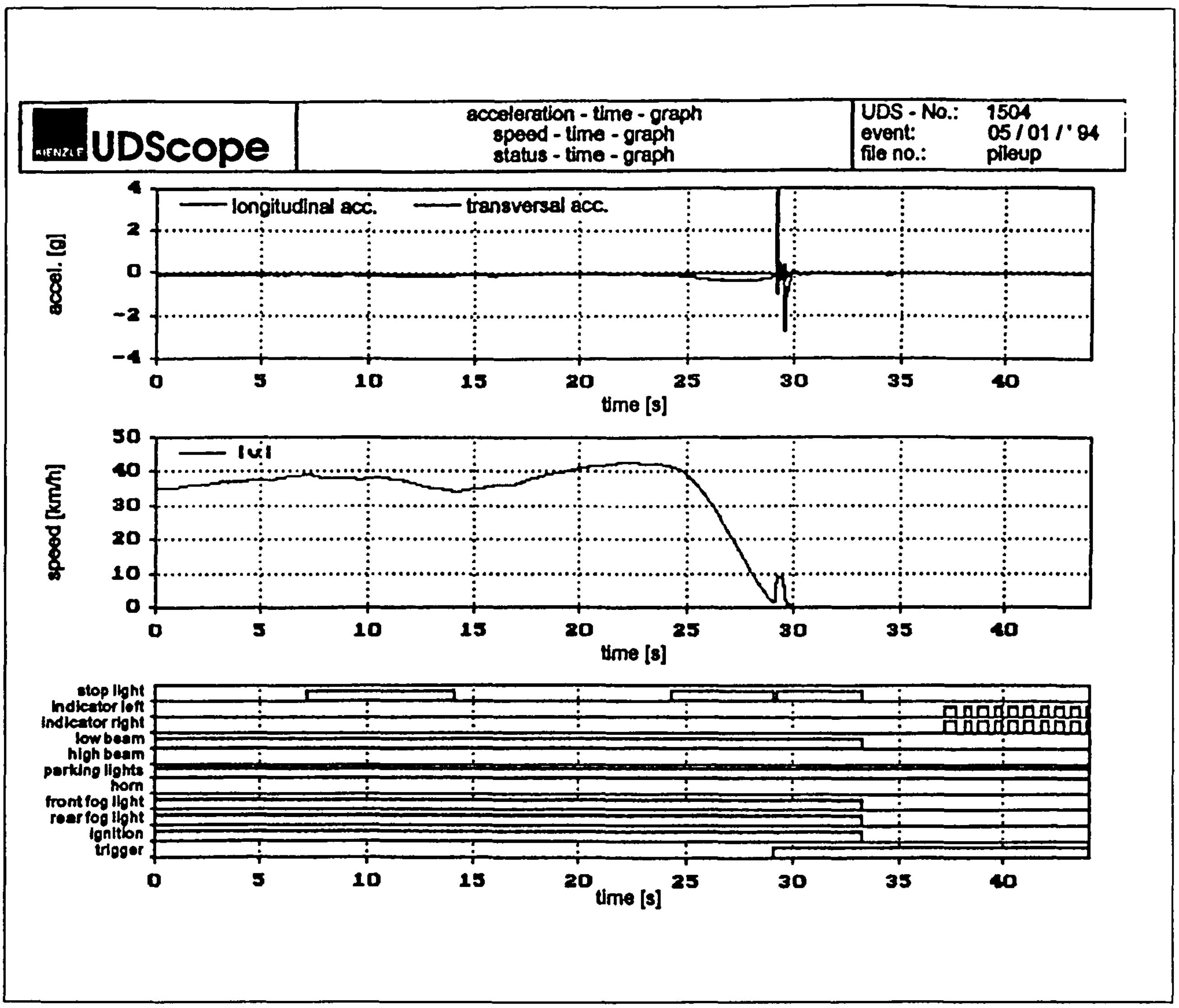

Figure 2. UDS – the analysis.

often refuse to deal with minor accidents, so that assistance from the UDS in accident and damage analysis becomes more and more valuable.

The economic benefit of this aspect comes in useful to the general public, but also to the insurance companies. It is, therefore, good to know that some insurers are already granting bonuses for vehicles equipped with the UDS or are at least planning to do so.

Last but not least the UDS can supply valuable additional information for accident research - just think of international accident data bases - as a contribution to comparability of accident data.

4.b) Regarding accident prevention, we already mentioned that a series of experiences could be gained during the 3 years' test period. The numbers of vehicles equipped with the UDS and the length of time are, of course, not sufficient for a definite evaluation. But it is possible to ascertain already now a quite positive trend towards accident prevention and cost reduction. The results presented here are based on data provided by vehicle fleets, that is fleets in Germany, Belgium and the Netherlands.

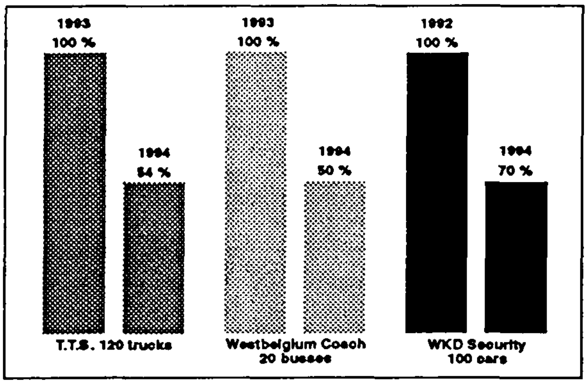

Figure 3. UDS – accident prevention.

These results clearly show that the UDS is a valuable fleet management instrument for any fleet operator, if he uses this system to purpose.

Besides these results we have gained a series of test experiences (e.g. the EU DRIVE II-project SAMOVAR and with police vehicles) which also revealed positive results.

4.c) Last but not least the UDS can be used within the framework of traffic telematics. In the event of an accident, immediate aid may be vital. If vehicles carrying dangerous materials are involved in an accident, prompt intervention is needed for the sake of environmental protection. We have, therefore, developed the technology shown in the figure 4 and will offer this technology as a traffic telematics service.

Within this concept, the Accident Data Recorder is the trigger for the automatic transmission of an emergency call (GSM) giving at the same time the exact location of the accident (GPS).

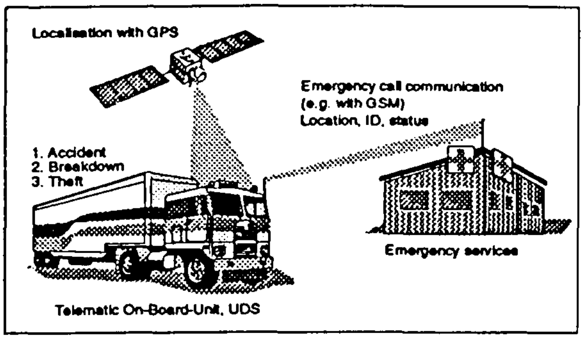

Figure 4. UDS – the traffic telematic system.

4.d) When talking about the benefits of the Accident Data Recorder, we should not forget that it is a reliable and objective witness that protects the attentive driver against unjustified assertions.

5. REQUESTS TO THE TRAFFIC POLICY

The UDS has been designed as a contribution to road safety and legal certainty. The experiences at hand show that the Accident Data Recorder can come up with the expectations placed in this system. In view of the accident rate on our roads and the resulting economic damage we should like to make traffic policy aware of the opportunities of improving traffic conditions provided by the UDS. The obvious thing to do would be to use the UDS for certain categories of vehicles with high hazard potential, such as busses, transport of dangerous goods and blue light vehicles.

Technical Session 10

Biomechanics and Advanced Dummy Components
Chairperson: Dainius J. Dalmotas, Canada

INJURIES SUSTAINED BY DRIVERS IN AIR BAG CRASHES

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Paper Number -96-S10-O-01

ABSTRACT

The William Lehman Injury Research Center has conducted multi-disciplinary investigations of fifty crashes involving drivers where an air bag deployed. In all cases, serious injuries were suspected. Eleven cases involved fatal injuries. While these cases are not representative of crashes in general, when used in conjunction with National Accident Sampling System Crashworthiness Data System NASS/CDS they provide insight into the most severe injuries in crashes of vehicles equipped with air bags.

A comparison with data from the NASS/CDS shows that head injury and abdominal injury make up a larger fraction in the Lehman data than in NASS/CDS. Examination of fatal cases indicates that head injuries are frequently caused by an intruding structure or by unfavorable occupant kinematics among the unrestrained population. The more precise injury examination provided to patients admitted to a Level I Trauma Center may contribute to the higher proportion of abdominal injuries observed at the Lehman Center.

Serious upper extremity injuries are rare in the Lehman data, but contribute a large harm fraction in NASS/CDS.

Both NASS/CDS and Lehman data indicate that lower extremity injuries are an increasing harm factor among occupants in severe crashes.

The Lehman data suggests that air bags are remarkably effective in high severity frontal crashes however, in some rare events the protection at low crash severity may be less than without the air bag.

INTRODUCTION

The William Lehman Injury Research Center sponsors a multidisciplinary crash investigation team at the Ryder Trauma Center, one of the largest Level I Trauma Centers in the United States.

Detailed crash and injury investigations are documented for each seriously and/or fatally injured motor vehicle occupant where an air bag deployed. The crash investigation is conducted by an experienced NASS crash investigator. The injuries are assessed and described by the Center's medical staff. Multidisciplinary reviews of cases include the use of crash test films and computer reconstruction of crashes by experts from the National Crash Analysis Center of the George Washington University. The criteria for admission to the study are as follows: (1) the subject must have been injured inside a post 1980 passenger car that was involved in a frontal collision; (2) the subject must have been protected by a safety belt, air bag, or both; (3) at the crash scene the subject must have met trauma center transport criteria (Table 1); (4) the subject must have agreed to have all records included in the study. All admissions to the Ryder Trauma Center were evaluated for possible admission to the study. Patients that met these criteria were asked to participate in the study.

Table 1
Adult Trauma Criteria

- Systolic BP≤ 90 (Shock)
- Respiratory rate < 10 per minute or > 29 per minute
- Glasgow Coma Scale ≤ 12
- Penetrating injury to head, neck, chest, abdomen or groin
- Paralysis
- Second or third degree burns ≥ 15% Total Body Surface Area
- Amputation proximal to wrist or ankle
- Ejection from motor vehicle
- Paramedic Judgment --- High Index of Suspicion of Injury

The Lehman Injury Research Center database provides information on seriously injured or killed occupants in frontal crashes where an air bag deployed. Since the criteria for admission to the data base is suspicion of a severe injury, cases in which minor or no injuries occurred are extremely rare. The Lehman data is useful for

examining injury patterns when injuries occur. When used in conjunction with NASS/CDS it provides in depth data on severe injury cases and the relevance of these cases to the population of injured occupants.

The purpose of this paper is to compare injury distributions in the NASS/CDS with those in the Lehman data, and to further examine injuries to drivers with air bag deployments.

HARM DISTRIBUTION BY BODY REGION

To date the Lehman data contains 50 cases of air bag protected drivers in frontal crashes. Twenty-six of these were not wearing safety belts. Twenty-two were wearing three point belts, and two had shoulder belts without the lap belt fastened. The crash severity, measured in terms of delta-v, ranged from 10 mph to 55 mph. Twenty-four percent of the crashes were above 30 mph. The 50 occupants sustained 491 injuries, 194 of which were AIS 2 (Abbreviated Injury Scale) or greater. There were 11 fatalities - 6 unrestrained and 5 restrained.

To aid in examining the distribution of injuries, the "harm" concept is applied. For this study, all injuries received by each subject are weighted according to the harm scale shown in Table 2.

Table 2
Harm Weighting Factors

MAIS	WEIGHT
1	0.0024
2	0.0411
3	0.1528
4	0.3882
5	0.8100
6	1.0000

This scale is based on research sponsored by the Department of Transportation [Miller 1991]. The harm weighting factors are based on the monetary cost of the most severe injury. For the purposes of this analysis, all injuries are weighted by the factors in Table 2.

A similar harm analysis has been made for air bag protected drivers in frontal crashes using the NASS/CDS data base for the years 1988-1994. For these years there are 647 drivers with 2730 injuries. Each case in the NASS/CDS data has a weighting factor which is used to extend the data to the national population of tow-away crashes. When these weighting factors are applied, the data is representative of 157,344 drivers with 528,740 injuries.

The documentation of injuries by the Lehman Center is very precise. For the population of air bag protected drivers, an average of 9.8 injuries per occupant were documented. Most of the injuries were AIS 1 level. The light clothing worn in the Miami region permits skin abrasions to occur easily in crashes. These skin abrasions frequently leave witness marks in the vehicle or occupant, which contribute to a more accurate estimation of the occupant kinematics.

A significant number of AIS 2+ injuries are documented in the Lehman data. An average of 3.9 injuries per occupant are present. By comparison, the NASS/CDS drivers suffered an average of 1.8 AIS 2+ injuries.

The distribution of AIS 2+ injuries in the Lehman data is shown in Table 3.

Table 3
Lehman Center Data
Injury and Harm Distribution
AIS 2+ Injuries

Body Region	Observations		Percent	
	Freq.	Harm	Freq.	Harm
Head	44	11.6	22.7%	40.8%
Face	2	0.1	1.0%	0.3%
Neck/Back	17	1.6	8.8%	5.6%
Chest	18	5.5	9.3%	19.5%
Abdomen	26	4.1	13.4%	14.5%
Lower Extremity	64	4.2	33.0%	14.8%
Upper Extremity	21	1.1	10.8%	3.8%
External	2	0.2	1.0%	0.7%
Total	194	28.3	100.0%	100.0%

A total of 194 AIS 2+ injuries were observed. The largest number, 33% are lower extremity injuries, followed by head injuries at 22.7%. Few facial injuries are present, and the remaining four body regions are about equally represented at approximately 10% each.

The harm distribution of AIS 2+ injuries shows that the head injuries are the most severe, with a harm fraction of 40.8%. The upper extremity and neck/back injuries are of lower significance with a harm fractions of 3.8% and 5.6% respectively. The thorax, abdomen, and lower extremities have harm fractions ranging from 14.5% to 19.5%.

It is instructive to compare the harm distribution of the Lehman data with NASS/CDS. Since the Lehman data represents the severe end of the injury spectrum, it is not representative of the NASS population weighted data. However, it provides insights into the severely injured population.

The population weighting factors for the 647 NASS/CDS cases in this comparison range from 0 to 5,586,

with an average value for injury weight of 194. The large weighting factors are needed to expand the low severity cases, which are under sampled. Hospital based crash research data provides additional cases at the higher injury severity cases, without regard to crash severity. These studies provide insight into severe injuries in the low crash severity cases which are undersampled by NASS.

Table 4
AIS 2+ Harm Distribution - Lehman and NASS

Body Region	Lehman	NASS		
	Harm	Rw Harm	Wt. Harm	Avg Wt
Head	40.8%	19.1%	14.7%	75
Face	0.3%	2.4%	2.9%	93
Neck/Back	5.6%	1.7%	3.9%	120
Chest	19.5%	30.1%	18.7%	71
Abdomen	14.5%	7.3%	2.6%	38
Lower Ext.	14.8%	25.6%	27.8%	77
Upper Ext.	3.8%	13.3%	28.5%	121
External	0.7%	0.4%	1.0%	139
Total	100%	100%	100%	85

Table 4 shows a comparison of NASS/CDS data and the Lehman data for AIS 2+ injuries suffered by air bag protected drivers. Table 4 shows both the raw harm and the weighted harm distribution in NASS.

The average weighting factor for each body region is also shown. In the NASS/CDS data, the chest/abdomen and lower extremities are the largest source, followed by the head. The head injuries are much less significant in the NASS/CDS than among the severely injured drivers in the Lehman study.

There is a large difference in the harm associated with upper extremity injuries. Upper extremities contribute only 3.8% of the harm among the Lehman cases compared with 13.3% in raw NASS. The NASS weighting raises the upper extremity harm from 13.3% to 28.5%.

The Lehman data suggests that abdominal injuries cause much more harm than indicated in NASS. Previous in depth analysis has shown that abdominal injuries which occur with air bags may be very difficult to detect [Augenstein 1994]. Continued surveillance for occult abdominal injuries is warranted.

INJURY PATTERNS FOR BELTED DRIVERS INVOLVING SEVERE CRASH FORCES

A general observation from the cases collected to date is that the air bag provides excellent supplemental protection to belted drivers in severe frontal crashes. Lower extremity injuries are common in the severe crashes with belted drivers. It is particularly instructive to examine the chest and abdominal injury patterns in severe crashes. These cases assist in defining the injuries at the limits of air bag plus lap and shoulder belt performance.

Table 5 contains data from four cases of air bag protected drivers in severe frontal crashes. The table shows the vehicle crush (CRS) in inches, the crash severity (DV) in mph, and the principal direction of force (DF) in clock direction. No head or facial injuries were present in any of the cases, however one or more AIS 2 level lower extremity injuries were present. The most serious injury in each case was a chest or abdominal injury.

Air Bag + 3 Point Belt - Case 93-001 involved a 40 year old male in a 1992 Honda Civic which impacted a 1993 Mitsubishi Starion with a principal force direction of 1 o'clock. The delta-V was 55 mph. The injury with highest severity level was AIS 3 rib fracture with a pneumothorax. The pneumothorax was treated with a chest tube. Although the rib fracture/pneumo has a higher AIS level, the nine AIS 2 level injuries to the left and right ankle and foot will have a more prolonged effect on the driver.

Case 92-017 involved a 63 year old male driver of a 1991 Mercury Marquis in an 11 o'clock car to car frontal crash with a delta-V of 37 mph. He sustained an AIS 2 calcaneus fracture . His chest injuries included a fracture of ribs 6-8 on the right and rib 1 on the left. He had contusions of the lung and heart. Medical complications resulted. However, after 50 days in the hospital he attained a complete recovery.

Case 95-001 involved a 37 year old driver of a 1995 VW Cabrio. He was impacted at 11 o'clock by a 1992 Ford Mustang in a 50% left offset collision. The delta-V was 33 mph. Due to the large offset, an extensive crush of 36 inches resulted. Intrusion of the toepan was 17 inches. An unrestrained passenger seated behind the driver may have increased the severity of the forces on the driver. The lower extremity injuries consisted of two AIS 3 injuries - fractured right femur and tibia, an AIS 2 fracture of the pubis rami and four AIS 2 injuries of the right ankle and foot. The upper extremity injuries were AIS 2 fractures of the ulna and humerus. The back injuries were AIS 2 fractures of the L3, L4 and L5 transverse processes. The chest/abdominal

Table 5
Chest and Abdominal Injuries to Drivers in Severe Frontal Crashes with Air Bag plus Belt Restraints

Case #	Sex	Age	Make	DV	CRS	DF	AIS	Trunk Injury	AIS	Other Injury
93-001	M	40	Honda	55	42	1	3	Fracture, rib	2	R and L lower ex.
92-017	M	63	Mercury	37	38	11	5	Surface of heart	2	Right ankle
							3	Contusion, lung		
							3	Fracture, rib		
95-001	M	37	Volkswagen	33	36	11	3	Laceration, liver	2	Right lower ex.
									2	Left upper ex.
										Back
93-020	F	53	Saturn	32	40	1	2	Laceration, liver		
							2	Laceration, spleen		
							3	Pneumothorax		
							3	Tear, Renal artery		
									2	Lower ex. (R,L)
									2	Upper ex. burn

injuries were AIS 3 fracture of rib number 5 with a pneumothorax, and AIS 3 liver laceration. The patient recovered from the chest/abdominal injuries following a 33 day hospital stay. However, significant mobility deficit resulted from the lower extremity injuries. The liver injury is depicted in figure 1.

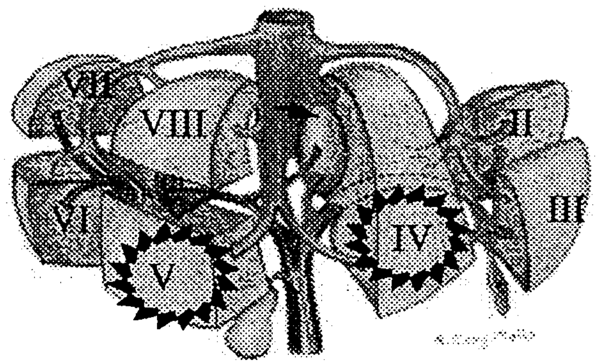

Figure 1 - Case 95-001 Lacerations of segments IV and V

Air Bag + 2 Point Belt - Case 93-020 involved a 1993 Saturn which was impacted by a 1993 Plymouth Voyager. The direction of force as 1 o'clock and the delta-V was 32 mph. The driver was a 53 year old 5'2" female who weighed 210 lb. She was wearing the automatic shoulder belt without the lap belt fastened. The steering wheel base plate was ruptured by occupant contact. The entire steering wheel was easily removed by rescue personnel on the scene. She suffered an AIS 3 pneumothorax, AIS 2 liver, spleen lacerations, AIS 3 intimal tear of the renal artery, AIS 2 upper extremity burn and seven AIS 2 injuries to the lower extremities. The location of the liver laceration is seen in figure 2.

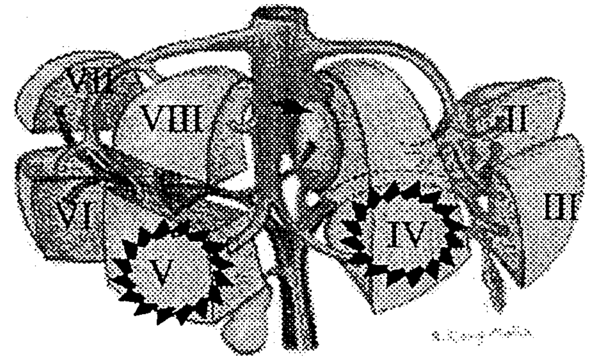

Figure 2 Case 93-020 Lacerations of segments IV and V.

CHEST AND ABDOMINAL INJURY PATTERNS

A previous analysis of air bag injury patterns documented the presence of chest and abdominal injuries which were sometimes difficult to detect by emergency care providers at the crash scene [Augenstein 1994]. Further description of these types of injuries is now possible. The cases to follow illustrate the kinds of injuries which have been observed to date.

Air Bag + 3 Point Belts -Case 92-023 involved a 50 year old, 5'11" male driver of a Porsche Carrera. He was involved in a front to rear car-to-car 12 o'clock crash with a

delta-V of 22 mph. He was wearing lap and shoulder restraints. His chest/abdominal injuries were AIS 2 fractures of right ribs 3-5, and AIS 2 liver laceration shown in Figure 3.

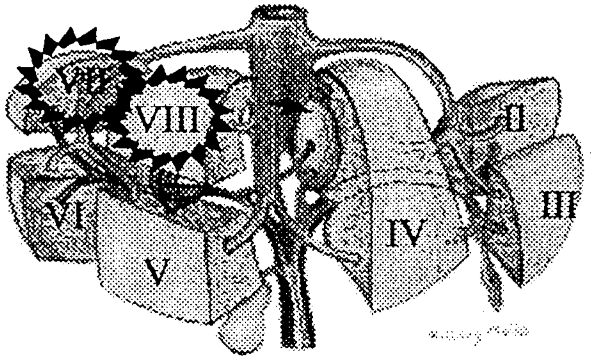

Figure 3 Case 92-023 Lacerations of segments VII and VIII

He also had an AIS 2 fracture of the left acetabulum. Although his maximum injury severity was AIS 2, he suffered respiratory insufficiency, and was hospitalized for 28 days. Two years after his physical recovery, he retained significant post traumatic stress disorder which limited his professional activities.

Air Bag Only - Case 92-006 was a 1992 Honda Civic which impacted a concrete block residence with a principal direction of force of 12 o'clock, and a delta-V of 20 mph. The driver was a 34 year old male, 5'6" tall. He was wearing no restraints. He stated at the scene that he had no injuries and was transported to a police station where he later collapsed. His only injury was AIS 2 liver laceration, shown in figure 4. He had a Blood Alcohol Content (BAC) of .079 measured 12 hours after the crash. He was hospitalized for 6 days and had a complete recovery.

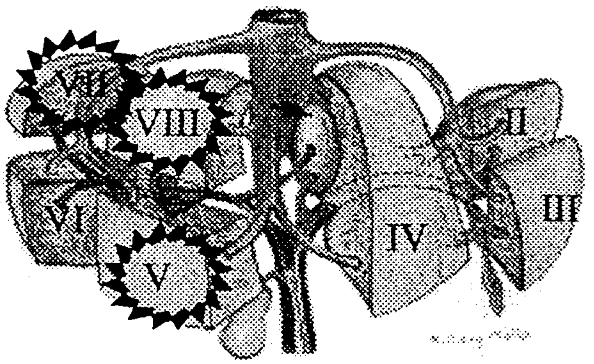

Figure 4 Case 92-006 Lacerations of segments V, VII and VIII.

Air Bag + 2-Point Belts-Case 94-005 involved a 1993 Nissan Maxima which impacted a road roller with engagement of 30% of the right front of the vehicle. The

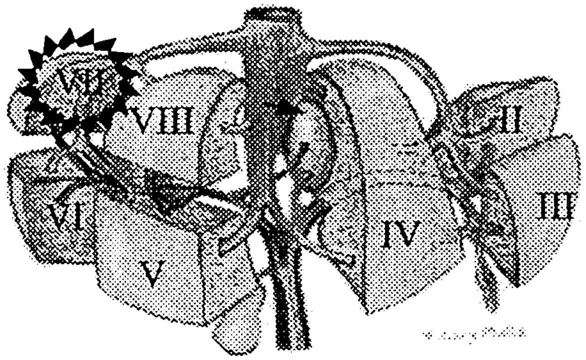

Figure 5 Case 94-005 Laceration of segment VII.

delta-V was 15 mph. The driver was a 39 year old, 5'8" female. She had 12 minor abrasions and lacerations, with no injuries to the head and face. Her only severe injury was an AIS 4 laceration of the liver, shown in figure 5.

FATAL INJURIES

The eleven fatal injuries in the Lehman Injury Research Center data base are summarized in Table 6. The Table shows the sex and weight of the occupant, the most serious injury and the associated body region, the delta-V in miles per hour, the type of restraint and the principal direction of force. The remarks column shows factors which may have contributed to the injury. The cases fall into four general categories - high severity; high intrusion; missed bag; and close to bag.

The first two cases involved heavy individuals (greater than 300 lb. body weight) in high severity crashes. In case 91-002, the individual blacked out before crash injuries to the driver of case 94-020 were aggravated by an unrestrained rear seat occupant. The most serious injury in case 91-002 was an AIS 4 avulsion of the small bowel. In both of these cases, the air bag provided sufficient protection to mitigate the injuries. Both drivers had occult abdominal injuries which contributed to the severity of their trauma. These cases illustrate that air bags can provide a high degree of protection in severe crashes. However, the residual injuries may be complex and more severe than immediately obvious. The third case, 94-010, involved a crash with severe intrusion into the upper region of the occupant compartment. In this case, the delta-V calculation does not adequately describe the severity of the crash environment to which the belt restrained driver was subjected.. The intrusion nullified the benefit of the air bag and belt system.

Table 6
Fatal Cases in Lehman Center Database

Case #	Sex	Ht	Wt	Age	Rest	MAIS	Region	DV	DF	Remarks
91-002	M	71	323	39	None	4	Abdom	50	12	High Severity
94-020	M	70	307	50	None	3	Chest	43	1	High Severity
94-010	M	72	157	19	Belt	5	Abdom	20	12	27" Intrusion
94-016	M	70	166	66	Belt	5	Head	29	2	17" Door Intrusion
94-007	M	67	156	20	None	6	Chest	37	1	Missed Bag
94-026	F	63	184	45	None	6	Head	23	1	Missed Bag
93-021	M	71	229	53	None	4	Head	32	12	Missed Bag
94-013	M	63	146	79	Belt	2	Chest	22	12	Frail Individual
93-026	M	69	137	67	None	5	Chest	23	12	Frail Individual
95-026	F	64	112	40	Belt*	5	Head	10	12	Close to Bag
95-030	F	58	199	41	Belt	5	Head	15	12	Close to Bag

* Uncertain

The victim suffered AIS-5 liver injuries and head injuries believed to be caused by an intruding vehicle.

Case 94-016 involved an impact which induced a large acceleration component from the right side, accompanied by large intrusion of the door. The driver missed the air bag and his head impacted the intruding door.

Cases 94-007, 94-026, and 93-021 are cases in which unrestrained drivers missed the air bag. Cases 94-007, and 94-026, both had large side forces. Both of these unrestrained drivers suffered a head strike with the right A-pillar, producing AIS-4 and AIS-6 head injuries. In Case 94-007, the impact also produced a hemo-pericardium, AIS-6. The unrestrained driver in Case 93-021 apparently was badly out of position - possibly asleep or unconscious. His head impacted the instrument panel at the centerline of the car, causing an AIS-4 injury.

Cases 94-013 and 93-026 involved elderly, medically frail individuals. Case 94-013 was a 79 year old male who suffered from advanced lung cancer. His AIS-2 rib fractures accelerated his respiratory deterioration. He died 16 days after the crash. The crash was a 12 o'clock impact with a tree. The Delta-V was 22 mph. Case 93-026 involved a 67 year old male who was in a frail state of health. The precrash trajectory of his car suggests that he may have passed out. His fatal injury was a laceration of the cardiac atrium.

In cases 95-026, and 95-40 the driver was probably very close to the bag at the time of deployment.

Case 95-026 involved a very low severity crash involving a 112 lb., 5'4", 40 year old female. Her fatal injury was a contusion of the pons. She also suffered a spinal fracture at C-2, and multiple AIS-2 abdominal injuries.

Case 95-030 was a 1994 Toyota Tercel in a 15 mph delta-V impact with a parking meter. The 41 year old female driver was 4'10" inches tall and her seat was in the full forward position. She was wearing the lap and shoulder belt. An unrestrained passenger in the left rear seat may have contributed to her injuries. Her fatal brain injuries were AIS 5 bilateral subdural hematoma, AIS 4 hemorrhage within the brain stem, and AIS 3 subarachnoid hemorrhage. She had AIS-3 level left pneumothorax, and AIS 2 hemorrhages of left kidney, and pancreas.

A review of the fatal cases indicates that in the head injuries are the most frequent serious form of injury. In severe crashes, head injuries are principally associated with intruding structures or with crash side impact acceleration components which cause the occupant to miss the air bag. In low severity cases, the head injuries may be associated with air bag deployment forces. Melvin and others have suggested that, based on dummy testing, small females may be vulnerable to this type of injury if they are very close to the air bag when it deploys [Melvin 1993].

DISCUSSION

Air bags have been shown to be highly effective in preventing death and serious injury. However, NHTSA has advised the U.S. Congress of certain situations in which driver air bags could have adverse side effects. [Martinez 1996]. These include the following: small statured people, older people, and out of position occupants. All of these situations have been observed and documented among the injured drivers in the Lehman database.

Among the eleven fatal cases, four involved high crash severity or large intrusion. Four cases were small statured drivers. Two of these smaller drivers may have been

very close to the bag at the time it deployed. In these two cases, the air bag probably caused the fatal injury.

Three cases involved drivers over 65 years of age. In two of these cases illness and frailness of the body were major factors in the fatal injury. In one of the cases, the occupant may have slumped over the steering wheel and the air bag may have exacerbated the injury.

Three of the unrestrained occupants missed the bag. In one case, the driver was out of position. In the other two cases, the crash forces were predominately from the side.

Four severe non-fatal cases indicate that internal chest and abdominal injuries occur at the performance limit of air bag in conjunction with belts. In one case rib fractures were the most serious injury. In the other three cases, internal injuries were more serious than the rib fractures. The observed internal injuries include contusions and laceration of the heart, lungs, liver and spleen.

Two general patterns of liver injuries are present. In the severe cases, the lacerations are on the front lobe of the liver, suggesting a compression injury from frontal loading. In the less severe cases, the pattern includes the rear lobe of the liver. Some of these injuries may have been caused by forces from the belt system. Injuries of this type from two-point belts have been previously documented [Augenstein 1995].

CONCLUSION

The data from the William Lehman Injury Research Center provides information on air bag protected occupants who have been severely injured or killed. This data is not representative of crashes in general. However, when used in conjunction with NASS/CDS it provides insight into the more severe injuries and the more severe crashes.

The subjects in the William Lehman Injury Research Center data base all suffered multiple injuries. On the average, they suffered 3.9 AIS 2+ injuries. Multiple injuries complicate the diagnosis, treatment and recovery of trauma patients. There is a continuing need to examine and characterize these multiple injury patterns.

The application of the harm weighting factor to each injury provides an initial approach for characterizing injury distributions when multiple injuries are present. The harm tables in this paper apply this approach.

An examination of Table 4 shows that severe facial injuries, are rare in the Lehman data and in NASS/CDS.

Severe upper extremity injuries are rare in the Lehman data, but are a large harm component in NASS/CDS. Based on Lehman data, upper extremity injuries constitute only 3.8% of the AIS 2+ harm to occupants protected by air bags. For the NASS/CDS data the upper extremity harm percentage is 28.5%.

Abdominal injuries are more harmful in the Lehman data than in NASS/CDS (14.5% vs. 2.6%). A previous paper discusses the difficulty of identifying abdominal injuries [Augenstein 1994]. It is likely, based on these earlier findings that some of abdominal injuries which occur in the field may be missed.

Both Lehman and NASS/CDS suggest that lower extremity injuries are an increasing hazard for air bag protected drivers (14.8% Lehman, 27.8% NASS/CDS) .

Head injuries cause much more harm in the Lehman data than in NASS/CDS (40.8% vs. 14.7%). An examination of the fatal cases suggests one reason for this difference. Three of the fatally injured drivers suffered AIS 4+ head injuries from impacts with interior components because they were unrestrained and missed the air bag. Two other fatally injured belt restrained drivers suffered head injuries from intruding structures.

The eleven fatal cases in the Lehman data contain two cases involving drivers weighing more than 300 lb. in frontal crashes above 40 mph. Even in these severe cases, the injuries were lower than expected. These cases support other statistical studies which show that air bags are remarkably effective at high severity frontal crashes. However, there are also two cases at low crash severity which involved fatalities. These minor to moderate severity crashes indicate that in rare occurrences, the air bag may actually increase the level of anticipated injury and result in fatal injuries to the driver.

The most serious abdominal and chest injuries among fatally injured drivers and the drivers in high severity crashes involve a variety of internal organs - the liver, spleen, heart, lungs, and intestine. Liver injuries are the most frequently seen. Patients who may have sustained occult liver injuries are difficult to identify on the scene. The liver injuries among belt protected occupants frequently involve the rear lobe of the liver. The head-neck injuries to small statured individuals involved the brain stem in both of the fatal cases.

The NASS weighting factors for air bag cases range from 0 to 5,586. These weighting factors may not adequately compensate for the limited sampling of low severity crashes. Studies which use injury severity as the criteria for inclusion permit the collection of data on the population being injured, regardless of crash severity. Both types of studies are needed to understand injury patterns associated with new safety technology. Hospital-based studies of the type on-going at the Lehman Center offer an opportunity to examine in detail the complex injury patterns among air bag protected occupants.

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REFERENCES

Augenstein, J., [and others], "Liver Injuries Associated with 2-Point Belt Restraints in Frontal Crashes", 39th Annual Proceedings, Association for the Advancement of Automotive Medicine, 1995

Augenstein, J., [and others]., 1994, "Air Bag Protected Occupants - The Challenge of Identifying Occult Injuries", Proceedings of 14th ESV Conference, May 1994.

Martinez, R, "Statement before the Senate Committee on Commerce, Science, and Transportation Regarding the Effectiveness of Air Bags", March 7, 1996.

Miller, T. [and others], "The Cost of Highway Crashes", FHWA Publication: FHWA-RD-91-055, October, 1991.

Melvin, J. [and other], "Assessment of Air Bag Deployment Loads with the Small Female Hybrid III Dummy", 37th Stapp Conference, SAE 933119, 1993

CHALLENGES IN INJURY MEASUREMENT TECHNOLOGY FOR TESTING OF DRIVER AIR BAG SYSTEMS

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ABSTRACT

Analysis of crash data for air bag protected occupants discloses that the combination of air bags and belt restraints offers excellent protection against serious head and chest injuries. The injury patterns which remain are different from those which were prevalent when the Hybrid III dummy was designed. The characteristics of these residual injuries are important in determining which injury measurements need to be included in the design of future crash test dummies and devices to measure injury potential.

The NASS/CDS data shows that air bag/belt systems provide large reductions in harm from injuries to the brain, face, spinal cord, chest, and abdomen. However, upper extremity and integumentary injuries are increased. The paper illustrates the extent of protection provided to each body region at low, moderate and high levels of crash severity.

More than 100 crashes with air bag deployment and severe occupant injuries are documented in files from the Special Crash Investigation Study and from the William Lehman Injury Research Center Study, both sponsored by NHTSA. These data files permit in-depth analysis of air bag related injuries and the environment in which they occurred. For the severely injured occupants, cases with chest/abdominal injuries at the limits of restraint performance are summarized. These cases suggest priority in measuring the potential for injuries to the liver, spleen, and intestine. In addition, cases of brain stem injury have been observed in low severity crashes involving small statured individuals. The fatal injuries documented by the NASS /CDS system in the U.S. suggest that heart and arterial injuries are the most common causes of death in cases where the air bag may have contributed to the injury.

INTRODUCTION

Driver air bags are in virtually all of the 1995 and 1996 model year passenger cars sold in the United States. As of July 1, 1995 about 35 million passenger cars and light trucks on US roads were equipped with driver air bags. Data from the Fatal Accident Reporting System (FARS) and the National Accident Sampling System/ Crashworthiness Data System (NASS/CDS) system now provide sufficient information on air bag crashes so that their crash performance can be examined. The 1988-94 NASS/CDS file provides data on more than 1300 crashes with air bag deployment. In addition, there are special investigations of air bag deployment crashes which provide in depth information on the injuries. The NHTSA Special Investigation Study contains investigations on selected air bag crashes. The Lehman Injury Research Center has conducted in-depth investigations of more than 50 frontal crashes with air bag deployments. These cases involved drivers with injuries that required treatment at a major trauma center.

An examination of the above data indicates a change in injury patterns for air bag protected drivers. The changes in injuries suggest the need for additional injury measurement capabilities in test devices to permit further optimization of air bag performance. The objective of this paper is to present some challenges in injury potential measurement technology, based on observations of air bag field performance.

OVERALL AIR BAG PERFORMANCE

Evaluations of air bag effectiveness indicate that the air bag is about 30% effective in reducing fatalities in pure frontal collisions In all frontal collisions (including crashes from 11:00 to 2:00 o'clock) the effectiveness is about 18%. NHTSA has estimated that air bags have saved about 1,500 lives, 570 of which were in 1995 [Martinez, NHTSA, 1996]. The number

of lives saved annually is growing rapidly as the number of air bag equipped vehicles in the fleet increases.

Exceptional reductions in head and chest injuries have been observed [Malliaris 1996]. In some cases, the chest and abdominal injuries which remain are more subtle [Lombardo 1993, Augenstein 1994, 1995]. Consequently, more sophisticated test devices for measuring chest and abdominal injury potential may be required.

Upper extremity injuries significantly increase among the air bag protected population [Werner 1996]. To date no test or criteria for this body region has been established.

A growing number of crash investigations suggest that the air bag itself may have been responsible for injuries [Malliaris, 1996, Augenstein 1996a, Werner 1996, Lund 1996]. Facial injuries are more frequent in air bag deployments, but the overall severity of facial injuries is reduced [Werner 1996, Malliaris 1996]. The cases of serious air bag induced injuries to head, chest and abdominal regions are sufficiently rare that they are difficult to detect from NASS. In some cases, driver fatalities in very low severity frontal crashes have been documented [Augenstein 1996b]. These cases involve brain, spinal, chest and abdominal injuries.

Testing techniques and injury measurement technologies to evaluate air bag induced injuries present new challenges which are being addressed by research at the National Highway Traffic Safety Administration (NHTSA). These research programs include the development of a new test dummy (TAD-50), research in upper extremity injury mechanisms and test procedures for out of position occupants, including children.

INJURY PATTERNS AND HARM BASED ON NASS

The calculation of Harm is useful in quantifying the opportunities for mitigating injuries in crashes. Harm is defined as the sum of all injured people (fatalities and injured survivors), each weighted in proportion to the outcome, as represented by the cost of the person's most severe injury. The injury costs are based on the schedules published by the Federal Highway Administration, based on research of Miller [Miller 1991]. The National Highway Traffic Safety Administration (NHTSA) normalized the weighting factors proposed by Miller, based on the cost of a fatality. The Harm is further refined by weighting injuries to various body regions according to their relative cost. The weighting factors are summarized in an earlier paper [Malliaris 1996]. The units of Harm are equivalent fatalities.

The total HARM normally is calculated by applying the harm weighing factor based on the most severe injury of each injured occupant in the population. In many of the injury producing crashes, two or more body regions are injured. When considering the benefits of countermeasures, it is desirable to consider opportunities for mitigating all injuries to occupants, not only the most severe injury. Consequently, a modification to the Harm calculation is employed. For this analysis, Harm weighting factors are applied to all injuries received.

This total Harm can be subdivided according to the crash severity, injured body region, and contact which caused the injury. The resulting fractions of the total Harm should be representative of the Harm which is occurring annually to car occupants in the United States. However, the magnitude of the total Harm is overstated, because its basis is multiple injuries rather than the single most serious injury per occupant.

For belted drivers protected by air bags, 55% of the injury weighted Harm occurs at crash severities between 16 and 30 mph. Approximately, 11% of the Harm is below 16 mph and 34% is above 30 mph.

Table 1
Harm Weighted Injury Count by Crash Severity and Restraint Type

Delta-V mph	Unrest	Belt	Bl+Bag
0-15	0.70	0.31	0.27
16-30	3.41	1.24	0.83
30+	9.60	5.62	5.33

The Harm weighted injury count provides a basis for comparing injury risk, adjusted for severity. Table 1 shows the Harm weighted injury count for different restraint conditions by crash severity [Malliaris 1996]. The values are Harm weighted injuries per 10,000 crash involved car drivers. The data is from NASS/CDS 1988-1994. The Table shows that harm weighted injury risks are greatly reduced by the use of safety belts, and further reduced by belts plus air bags.

Table 2 shows the distribution of injury weighted Harm by crash severity for belt restrained drivers in frontal crashes with air bag deployment. A comparison of the Harm distribution for belt only and unrestrained drivers is also shown in Table 2. In aggregating body region, neck, back and spinal injuries were combined under N, B & S. Shoulder and upper extremity injuries were combined. Integumentary injuries to all parts of the body were aggregated. Facial injuries included

Table 2
Injury Weighted Harm Distribution for Passenger Car Drivers by Restraint Type, Crash Severity and Body Region - NASS 1988-94

	Delta-V: 1-15 Mph			Delta-V: 16-30 Mph			Delta-V: 31+ Mph		
	Unrest	Belt	Bl+Bag	Unrest	Belt	Bl+Bag	Unrest	Belt	Bl+Bag
HEAD	39.9%	26.3%	10.3%	26.3%	25.1%	1.9%	28.3%	34.4%	30.8%
FACE	3.9%	2.2%	3.7%	4.5%	2.2%		3.4%	3.7%	0.4%
N,B&S	6.4%	12.3%	12.4%	6.4%	5.1%	4.0%	6.9%	2.5%	2.8%
CHEST	14.3%	8.5%	0.9%	21.5%	20.0%	17.9%	21.3%	19.0%	7.9%
ABDOMEN	3.3%	2.4%		1.3%	2.1%	0.5%	3.0%	6.8%	3.9%
LWR RX	6.1%	9.4%	6.1%	23.6%	21.3%	24.3%	26.2%	21.4%	30.3%
UPR EX	5.4%	6.7%	13.5%	7.7%	7.5%	37.9%	4.3%	7.3%	18.5%
INTEGU	20.7%	32.2%	53.1%	8.7%	16.8%	13.5%	6.6%	5.0%	5.4%

Note: Each column adds to 100%

fractures, avulsions, dislocations, but not integumentary abrasions, lacerations and contusions.

The Harm in each of the three crash severity ranges in Table 2 adds to 100%. However, the Harm weighted injury risks for the different categories are quite different, as displayed in Table 1. The total Harm represented by the 100% in the air bag plus belt column is less than the total Harm for the other restraint conditions. The limited data in the NASS/CDS for air bags plus belt systems introduces substantial uncertainties in the values in Table 2. However, the data is useful for examining the major trends.

Table 2 shows that integumentary Harm predominates in low severity crashes where air bags deploy. Upper extremity, and neck & back injuries each contribute around 13%.

In the 16 to 30 mph range, upper extremity injuries constitute 38% of the Harm. Lower extremities and chest contribute 24% and 18%, respectively.

In the 31 mph and above range, lower extremity injuries and head injuries are each responsible for 30% of the Harm. Upper extremity injuries contribute 19%.

Table 2 shows a change in injury patterns of air bag protected drivers compared to belt only protection, and unrestrained. Over the range of 1 to 30 mph, head harm is greatly reduced. The emerging injury patterns are as follows: (1) upper extremity injuries at all crash severities , and (2) integumentary injuries at low crash severities. These are two new areas of injury present challenges to injury measurement technology.

FATAL INJURIES IN NASS/CDS

The NASS/CDS for the years 1990-93 contains 26 driver fatalities with air bag deployments. Analysis of the fatal cases which may have been caused by the air bag was conducted by Lund [Lund 1996]. According to this study, 7 of the 26 cases, involved frontal impacts as the only harmful event. Seven more cases involved frontal impacts with multiple harmful events.

The authors found three frontal single impact cases and one frontal multiple impact case in which the air bag may have contributed to the injuries. The suspected air bag induced injuries were as follows:

Case 930512511; Belted , 62 year old female,
5'2", 179 lb.; 29mph dV, pole impact
AIS 5 - Bilateral Flail Chest
AIS 5 - Right Ventricle Laceration

Case 917902111; Unbelted, 35 year old female,
5'6", 160 lb.; 46mph dV, front to rear car-to-car crash
AIS 5 - Right Ventricle Laceration
AIS 4 - Interventricular Septum Contusion

Case 930600611; Unbelted, 64 year old male,
5'7", 160 lb.; 29mph dV, tree impact
AIS - 6 Right Atrium Laceration
AIS - 4 Bilateral Rib Fractures
AIS - 3 Superior Vena Cava Laceration

Case 920813311; Unbelted, 58 year old male,
6', 187 lb.; Unknown dV, muli-impacts with shrubs
AIS - 5 Bilateral Rib Fractures with Hemothorax
AIS - 3 Heart Laceration
AIS - 2 Pericardium Laceration

In all these cases, heart injury is present. Rib fractures are significant in the three cases involving older drivers but not in the case involving the 35 year old female.

FATAL INJURIES FROM SPECIAL STUDIES

Several cases from the Special Studies file of air bag investigations conducted by NHTSA have been selected to illustrate injuries with fatal outcome. The AIS 2+ injuries are summarized for each case.

Case 92-4; Belted, 57 year old female,
5'6", 150 lb.; 17 mph delta-V, pole impact
AIS - 3 Spleen Rupture (occult)

Case 94-22; Belted, 73 year old female,
4' 11", 128 lb.; 7 mph delta-V, front to side car-to-car
AIS 6 - Heart Laceration (multiple)
AIS 6 - Aorta Laceration
AIS 3 - Heart Contusion
AIS 2 - Neck Abrasion

Case 95-2; Unbelted, 56 year old male,
5'11", 208 lb.; 12 mph delta-V, front to rear car-to-car
AIS - 5 Aorta transected
AIS - 5 Rib Fracture -2 through 9
AIS - 4 Heart Contusion
AIS - 4 Lung Contusions left & right
AIS - 2 Liver & Intestine Lacerations

These special study cases illustrate the extent and type of chest and abdominal injuries possible in crashes at relatively low severity. In each of these cases the air bag may have contributed to the injury. In two of the cases, injuries to the chest or abdomen occurred without rib fracture.

FACIAL INJURIES

A further analysis of facial injuries, including integumentary injuries is required to understand the nature of the total facial Harm. The use of NASS for analysis of injuries by lesion is confounded by a change in the injury coding system in 1993. Consequently, the 1988-92 NASS is used to examine facial lesions.

Table 3
Facial Injuries per 100 Crash Involved Car Drivers in Frontals by Crash Severity
No Rollover or Ejection

DELTA V	UNRES.	BELT	BAG+BL
01-15	47.5	15.1	25.2
16-30	116.2	34.4	37.8
30+	168.9	128.1	63.1

Table 3 shows the risks of facial injuries to drivers by crash severity and restraint system. Only frontal crashes with no rollover or ejection are included. The data shows that air bags increase the facial injury risks at the low delta-V compared to belted drivers, but not compared to unrestrained drivers. Most of these facial injuries fall into the integumentary category in Table 2. Substantial reductions in facial injury risk occur at the higher crash severities for air bag protected drivers.

Table 4 shows the distribution of facial Harm to air bag plus belt protected drivers by injury severity and lesion. The Harm is principally (51%) from AIS 1 skin abrasions and contusions. However, 24% is AIS 2 level contusions, and 12% is AIS 1 & 2 level lacerations. Only 7.4% of the facial Harm is skeletal injuries.

Table 4
Harm of Facial Lesions by AIS for Air Bag Protected Drivers

	Injury Severity - AIS		
LESION	1	2	3
SKIN ABR.	31.7%		
SKIN CONT.	18.8%	23.8%	
SKIN LAC.	5.5%	6.2%	
EYES	2.0%		
ORAL	3.3%		
FRACTURE		3.4%	4.0%

By comparison, 32.4% of facial Harm to belted drivers is from skeletal injuries. An earlier study of facial skeletal injuries suffered by restrained drivers in frontal crashes was conducted by NHTSA staff [Zuby, 1989]. Their analysis included an in-depth review of 170 belted drivers from NASS 1981-86 who suffered facial injuries from steering system contact. This group represented a census of the usable cases of belted drivers in frontal collisions with facial injuries from steering system contact. The 170 drivers suffered 317 facial injuries. There were 16 AIS 2+ skeletal fractures. These 16 injuries constituted approximately 50% of the harm. Half of the AIS 2+ skeletal injuries were to the upper and lower jaw. There were four AIS 2 and four AIS 3 injuries to the jaw area. Orbital fractures accounted for 4 AIS 3 injuries. The nasal area suffered three AIS 2 injuries. The zygoma was represented by one AIS 2 fracture. Most of these injuries to the maxilla and mandible area occurred at the lowest crash severities.

Several physicians have published accounts of ocular injuries associated with air bag protected drivers. In some cases, eyeglasses contribute to the injury (Gault 1995). Others have reported ocular injuries which were attributed to the air bag (Whitacre, 1995; Rosenblat, 1995; and Scott, 1993). An examination of NASS facial injuries, as reported in

Table 4, indicates that eye injuries contribute about 2% of the facial harm. Ocular injuries less severe than avulsion, retinal detachment, and laceration of the globe (including rupture) are rated as AIS-1. Special considerations of AIS-1 ocular injuries may be warranted due to the impairment caused by some of these injuries.

The principal challenges in facial injury measurement are in low crash severity injuries. The predominant injuries from air bag contact are AIS 1 & 2 skin contusions and AIS 1 abrasions. Skeletal injuries with air bag deployment are relatively rare. However, skeletal injuries from facial impact with the steering wheel may be possible at speeds below the deployment threshold. At low crash severities injuries to the lower region of the face are the most likely skeletal injuries.

INJURY PATTERNS BASED ON SPECIAL STUDIES

In addition to NASS/CDS data, several special studies suggest additional areas where advances in injury measurement technology is desirable. These studies suggest several additional unusual injury mechanisms which produce undesirable outcomes.

The occult chest or abdominal injury pattern has been reported in a special study at the Lehman Injury Research Center. The in depth data from the Lehman Injury Research Center data on 50 air bag cases provides information on seriously injured occupants who were in frontal crashes and were protected by an air bag. Because the criteria for admission to the data base is suspicion of a severe injury, cases in which minor or no injuries occurred are extremely rare. The Lehman data is useful for examining injury patterns, among severely injured occupants.

Abdominal injuries are more harmful in the Lehman data than in NASS/CDS(14.5% vs. 4.3%). A previous paper discusses the difficulty of identifying abdominal injuries [Augenstein 1994]. It is likely, based on these earlier findings that some of abdominal injuries which occur in the field may be missed. The distribution of AIS 2+ lesions associated with abdominal injuries in the Lehman data are as follows: Liver 35%, Intestine 31%, Spleen 19%. These three areas appear to be the most frequently injured among air bag protected drivers. The characteristics of liver and intestine injuries have been described in another 1996 ESV paper [Augenstein 1996].

In addition, the Lehman data contains four cases of severe injuries which may have been side effects of air bag deployment. Two of the cases were fatal brain injuries, one was a fatal cardiac injury and one was a cervical spine fracture. Two were at crash severities around 15 mph, and two were around 20 mph.

Two of the cases involved small female drivers in frontal crashes with severity less than 15 mph. Both were restrained by a lap and shoulder belt. Both received fatal brain stem injuries accompanied by moderate to serious chest and abdominal injuries [Augenstein 1996]. The brain stem injuries are consistent with the dummy measurements made by Melvin [Melvin 1993].

One fatal case suffered a laceration to the cardiac atrium, accompanied by lacerations to the liver and spleen. The crash was head on at a delta-V of 23 mph. The driver was a 67 year old male who was unbelted [Augenstein 1996].

The cervical spinal injury was at C-5 and resulted in paraplegia. The crash was head-on at 19 mph. The 22 year old male driver was unrestrained.

These undesirable injury patterns indicate a need to measure injuries in low speed crashes which may be associated with air bag deployment. The most critical injuries appear to be associated with an upward and extension loading of the neck, producing brain stem injuries. However, the presence of central cervical spinal injuries suggests that more complex loading may be present, as well. The biofidelity of the neck in responding to air bag deployment loads is an essential and significant challenge. Small statured drivers appear to be particularly vulnerable. This suggests the need for continued improvements in the small female dummy. The presence of cardiac injuries in low severity air bag deployments presents a challenge in measuring this injury mode.

CONCLUSIONS

The NASS/CDS provides insight into injury patterns associated with driver air bags, and how these injury patterns compare with belted and unbelted occupants. The following observations can be made:

(1) at all crash severities, upper extremity injuries are more frequent and harmful for air bag drivers; and
(2) integumentary Harm predominates in low severity crashes where air bags deploy.

These two emerging injury patterns present new challenges in injury measurement. The upper extremity injuries are much more harmful, and therefore should be addressed with a higher priority.

Facial skeletal injuries are rare among drivers who are belted and protected by an air bag. However, skeletal injuries from steering wheel contact may pose

a threat in the event that air bag deployment thresholds are substantially increased. At low crash severities, injuries to the lower region of the face are the most likely steering wheel induced skeletal injuries. The predominant injuries from air bag contact are AIS 1 & 2 skin contusions and AIS 1 abrasions. These are most frequent in low severity crashes. The increase AIS-1 level integumentary facial injuries observed in NASS and the ocular injuries reported in the medical literature, suggests a requirement to measure these forms of injury. In addition, measurement of facial fractures in the lower face could assist in optimizing steering systems and air bag deployment thresholds.

A limited number of fatalities in NASS/CDS suggests the need for measuring the potential for heart and arterial injuries from air bag deployment. Severe rib fractures occurred in four of six fatal cases with severe heart injuries.

Special investigations such as those conducted by the Lehman Injury Research Center can be used to supplement the NASS/CDS and provide additional insight into injury patterns. Abdominal injuries are much more prevalent in the Lehman Injury data than in the NASS/CDS. The Lehman data suggests priority in measuring the potential for liver, spleen, and intestine injuries.

The special studies also provide in-depth documentation of injury cases in which undesirable injury results occurred. These cases suggest the need for measuring neck/brain steam injuries induced by air bag deployment. In addition, measurements of cardiac injury induced by air bag deployment is indicated.

The predominance small statured drivers among the population with undesirable head/neck injuries at low crash severity indicates the need for continued development and application of small statured dummies.

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REFERENCES

Augenstein, J., [and others]., 1996, " Injuries Sustained by Air Bag Protected Drivers", ESV Conference, 1996.

Augenstein, J., [and others], 1995, "Occult Abdominal Injuries to Air Bag-Protected Crash Victims: A Challenge to Trauma Systems", The Journal of Trauma, Vol.38, No.4, p.502-508, April 1995.

Augenstein, J., [and others]., 1994, "Air Bag Protected Occupants - The Challenge of Identifying Occult Injuries", Proceedings of 14th ESV Conference, May 1994.

Gault, J., et. al.,1994 "Ocular Injuries Associated with Eyeglass Wear and Airbag Inflation", Journal of Trauma, Vol 38, No.4, p 494-7, April 1995.

Lund, A., Ferguson, S., and Powell, M., 1996, "Fatalities in Air Bag-Equipped Cars: A Review of 1989-93 NASS Cases", SAE 960661, 1996.

Malliaris, A, DeBlois, J., and Digges, K., 1996, " Air Bag Field Performance and Injury Patterns", SAE 960659.

Martinez, R., 1996, Statement before the Senate Committee on Commerce, Science and Transportation, Regarding the Effectiveness if Air Bags, March 7, 1996.

Miller, T. [and others], 1991, "The Cost of Highway Crashes", FHWA Publication: FHWA-RD-91-055, October, 1991.

Melvin, J., [and others], 1993, "Assessment of Air Bag Deployment Loads with the Small Female Hybrid III Dummy", 37th Stapp Conference, SAE 933119, 1993.

NHTSA 1996, "Second Report to Congress: Effectiveness of Occupant Protection Systems and Their Use", NHTSA, February, 1996.

Lombardo, L., and Ryan, S., 1993, "Detection of Internal Injuries in Drivers Protected by Air Bags", Research Note, NHTSA, 1993

Rosenblat, M., Freilich, B., and Kirsch, D., 1993, " Air Bag Injuries Associated Ocular Injury", Arch Ophtalmol, 111:1318, 1993

Scott, I, John, G., and Stark, W., "Air Bag Associated Ocular Injury and Preorbital Fracture", Arch Ophtalmol, 111:25, 1993

Whitacre,M., and Prichard, W., 1993, "Air Bag Injury Producing Retinal Dialysis and Detachment", Arch Ophtalmol, 111:1320, 1993

Werner, J, Robertson, S., Ferguson, S., and Digges, K., 1996, "Air Bag Deployment Frequency and Injury Risks", SAE 960664, 1996.

Zuby, D. and Saul, R., 1989, "Restrained Drivers, Facial Skeleton Injuries Resulting from Steering Assembly Contact: A Conspectus", 12th ESV Conference, p. 597-602, 1989.

BELT AND AIRBAG TESTING WITH A PREGNANT HYBRID III FEMALE DUMMY

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ABSTRACT

The objective of this research was to develop a pregnancy insert for the Hybrid III female dummy which would allow evaluation of various restraint conditions on energy transmission to the fetus. The pregnancy insert includes a urethane "abdomen-uterus" surrounding an ellipsoidal "amniotic fluid" gel and simulated 28-32 week "fetus," and fits into a 5th percentile Hybrid III female dummy. The "fetus" is instrumented with accelerometers in the head and thorax. A load-measuring reaction plate records force on the abdomen. Thirty-nine crash tests were run in the driver and right front passenger position on a Hyge sled under eleven different belt restraint and airbag conditions at 10-25 mph (4.5-11.2 m/s). In the first series, fetal and maternal responses for recommended lap-shoulder belt placement were compared to improper placement of the lap or shoulder belt. In the second series, several driver airbag restraint conditions were studied.

Placement of the lap belt over the "uterus" or shoulder belt behind the back resulted in more than a three-fold increase in force transmission through the abdomen in comparison to proper belt placement. Increasing the speed of crash resulted in greater acceleration of the "fetus." Airbag deployment with or without belt use resulted in relatively low force transmission to the "uterus," but "out-of-position" airbag deployments resulted in high fetal acceleration. The fetal responses are assessed in terms of abdominal force, acceleration of the fetal head and chest, relative acceleration between the fetus and mother, and relative acceleration between the fetal head and chest. The new pregnant dummy demonstrates higher responses in all conditions of improper placement of the lap or shoulder belt. Proper use of the lap-shoulder belt and airbag appears to reduce the likelihood of crash injury to the unborn baby and mother.

INTRODUCTION

Protecting passengers in automobiles has improved in the past 30 years with the introduction of numerous safety features, including lap-shoulder belts, collapsible steering columns and airbags. Many improvements resulted from laboratory testing of safety devices using crash test dummies or anthropomorphic test devices (ATD). ATDs have been so successful in predicting injury patterns that different gender, size and age dummies have been developed. However, the safety of pregnant women and her fetus in automobiles has to this point been untested using ATDs by automobile safety researchers.

Existing data on the safety of restraint systems during pregnancy are largely based on animal data and limited field crash analysis (Crosby etal 1968, 1972, King etal 1971). With the unknown effect of new safety features in automobiles on pregnancy (e.g., airbags), and with the impracticality of repeating animal experiments, alternative methods of evaluating fetal safety need to be developed. Use of a "crash dummy within a crash dummy" may help to better understand the complex interactions between the different components of the uterine compartment and the automobile interior (including restraint devices) during a motor vehicle crash.

About 6%-7% of pregnancies experience complications from blunt injury (Fildes etal 1992, Lane 1989). The complications include premature contractions, abruptio placentae, direct fetal injury and uterine rupture (Pearlman etal 1990, Goodwin etal 1990, Williams etal 1990). In the USA, between 60%-75% of injury during pregnancy is related to motor vehicle crashes. Based on 1988 FARS and 1989 US Bureau of the Census, Culver and Viano (1990) estimated that 342 pregnant women died in passenger vehicle crashes in 1988. This is a

fatality rate of 5.4/100 female crash deaths or 9.1/100,000 births.

The incidence of fetal death is more difficult to estimate. Pearlman and Viano (1993) estimated that 3400 pregnancy losses may occur annually from motor vehicle crashes. This is a rate of 85/100,000 births, and is based on a 2% (.25%-4%) incidence of pregnancy loss from crash injury. However, there is a large uncertainty in the calculation. A study of Motors Insurance Corporation data showed a 40% lower incidence of pregnancy loss with lap-shoulder belt use in comparison to being unrestrained (10.0% versus 17.5%). Safety belt use during pregnancy is recommended by government, medical (ACOG 1991) and transportation organizations; and, limited field crash data is available to validate restraint effectiveness (Hartemann etal 1984).

The following feasibility study describes the results of initial tests with an instrumented pregnancy insert for the 5th percentile Hybrid III female crash dummy. The first series of tests involved a comparison of proper safety belt use with various conditions of improper wearing of the lap or shoulder belt in frontal crashes. The second series included combinations of safety belt use and airbags in a range of crash severities.

MATERIALS AND METHODS

A pregnancy insert was developed for use in the abdominal region of the 5th percentile Hybrid III female dummy. The insert approximates the size, shape and characteristics of the third trimester of pregnancy, and includes an instrumented "fetus" to assess responses of the unborn baby and to compare with responses of the mother.

Pregnancy Insert: The external shape of the "abdomen-uterus" was composed of a urethane casting with the size and shape for 28-32 weeks of pregnancy. Within the "abdomen-uterus" casting was a soft, urethane gel ellipsoid representing the "amniotic fluid" which allowed both stabilization of the simulated fetus in the same position within the uterus during each test, and low shear resistance for energy transfer to the "fetus" during loading. The "fetus" was composed of a representative form with the approximate size and weight of a 28-32 week fetus with a separate head and torso. There is no placenta in this ATD.

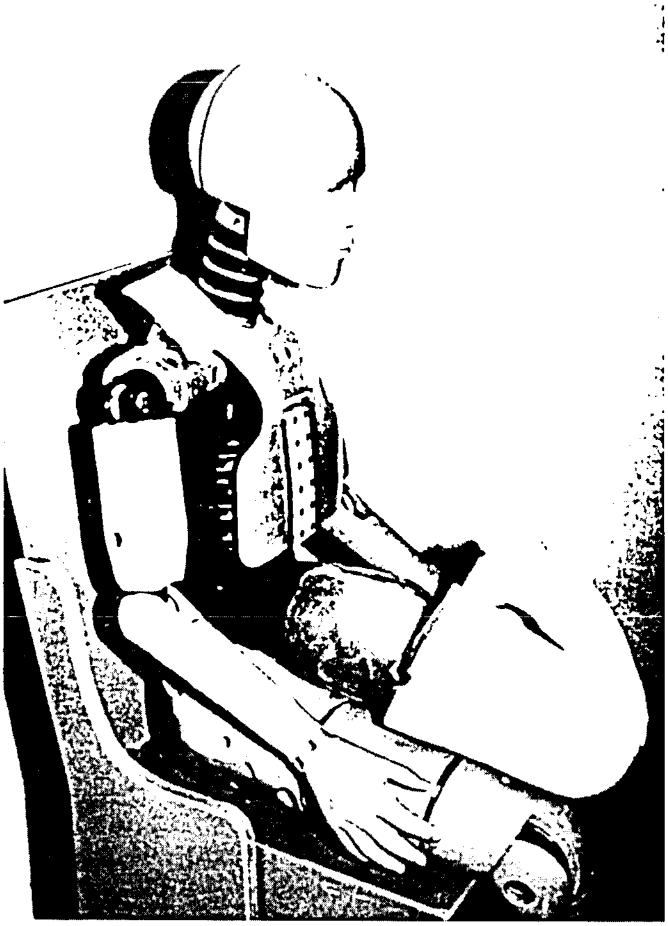
Figure 1 shows the external shape of the molded abdomen-uterus and other components of the pregnancy insert. The urethane skin has a natural skin color by pigment added to the part A and B urethane mixture. The abdomen-uterus is 16.9 cm high, 24.1 cm deep and 24.1 cm wide. The skin is split at the back to allow a close fit around an ellipsoidal gel simulating the "amniotic fluid" around the fetus.

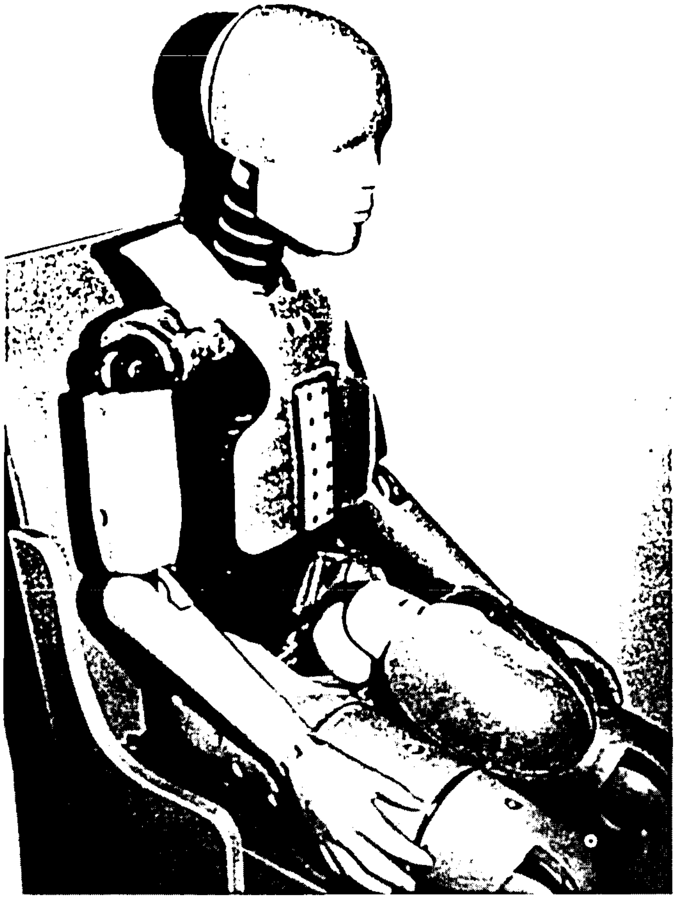
The ellipsoidal gel is a softer urethane by adding a part C, extender softener, to the part A and B mixture. The soft consistency was selected to simulate the "amniotic fluid" surrounding the fetus. The ellipsoid is 20 cm long, 14.2 cm deep and 13.3 cm wide. It was split at the back and has a cavity for the third component of the insert, a fetal shape of the head and torso molded in urethane with a size and mass approximating the third trimester. The shape is based on a 7 month anatomic fetal model (LF708U7-month, NASCO LifeForm Simulators, Fort Atchison WI) and is 17.4 cm long, 11.8 cm deep and 7.6 cm wide.

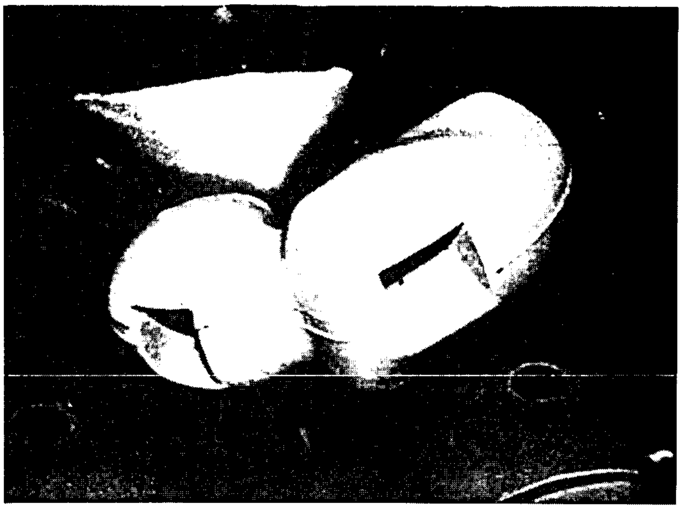
The design weight of the simulated fetus was 1.08 kg, the ellipsoidal "amniotic fluid" gel was 1.57 kg, and the outer "uterine" skin was 3.68 kg. An opening was cast into the back of the fetal head and torso to accommodate the insertion of triaxial accelerometers (Endevco Model 7264A-2000). The accelerometer cables were routed out openings in the ellipsoidal gel and skin so the splits could be closed and the insert secured against a reaction plate by screws.

Female Dummy Modifications: The pelvis and abdomen of the production 5th percentile Hybrid III female dummy were modified to accommodate the pregnancy insert. A 9.50 cm (3.75") radius was machined into the top of the pelvis to accommodate the pregnancy insert. The center of radius was on centerline and 17.4 cm (6.85") above the z = 0 point on the bottom of the pelvis. Figure 2 shows details of the pelvic modifications. A new vinyl skin was added to the pelvic structure. The conventional chest-pot was removed since the transducer occupied space in the abdomen. A reaction plate was designed to accommodate load bolts (Model 1567, RA Denton, Inc.) at each corner. In addition, the connector block between the pelvis and lumbar spine was modified to accept the new reaction plate and load bolts. Finally two clearance holes were put in the reaction plate to secure the pregnancy insert.

Other Pregnant Dummy Changes: A new molded chest skin was developed to match the extended shape of the pregnancy insert at the top. Figure 3 shows the urethane chest skin, which is made of the same urethane as the abdomen-uterus. The mass of the chest skin is 1.92 kg. Figure 4 shows the new zippered jacket which covers the pregnancy insert and chest skin. The jacket







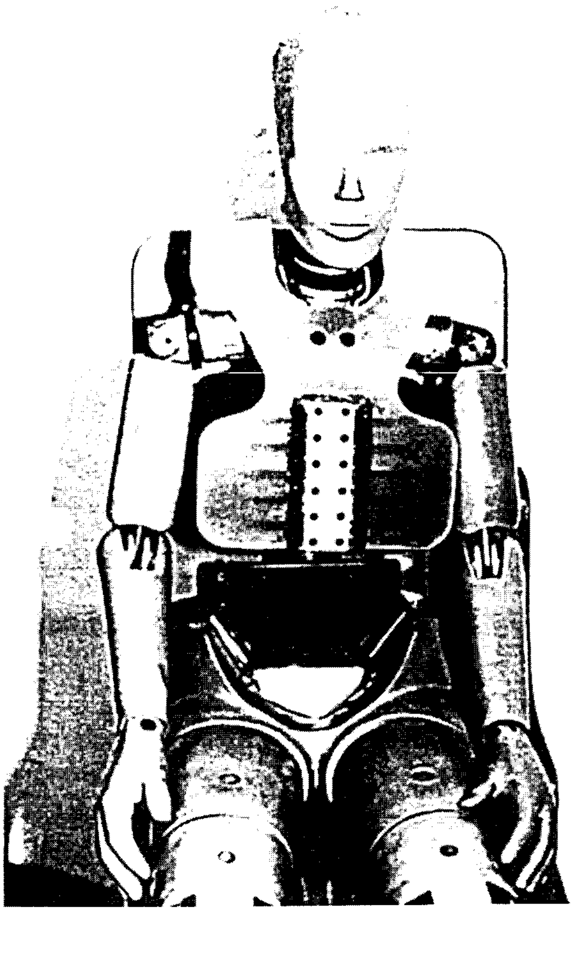


Figure 1: The shape of the simulated "abdomen-uterus," ellipsoidal "amniotic fluid" gel, and "fetus" for the pregnancy insert used in the 5th percentile Hybrid III female dummy.

Figure 2: Modification in the pelvic and abdominal region of the 5th percentile Hybrid III female dummy to accommodate the pregnancy insert.

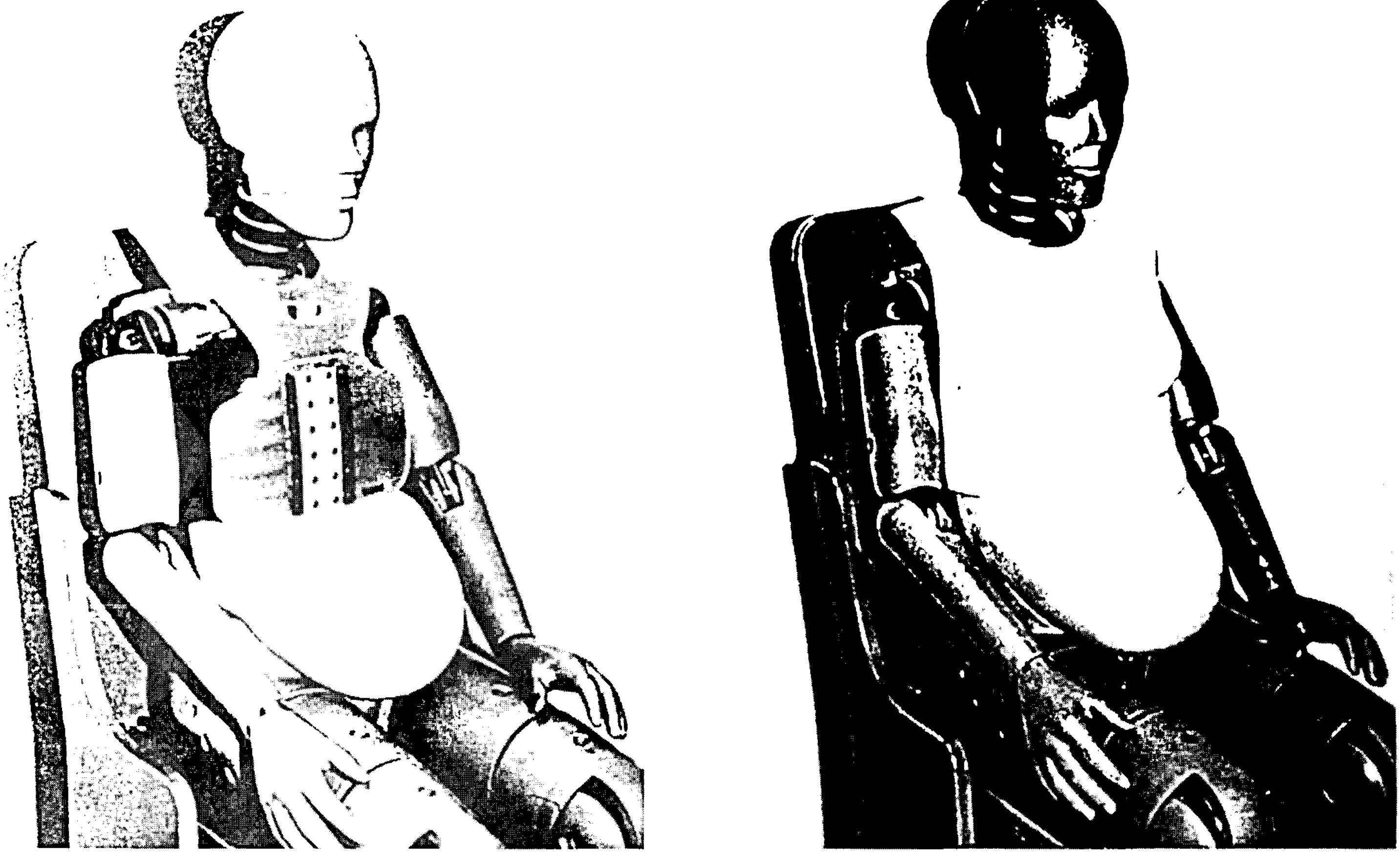


Figure 3: Urethane pregnancy insert and chest skin for the 5th percentile pregnant Hybrid III dummy.

Figure 4: Hybrid III pregnant dummy.

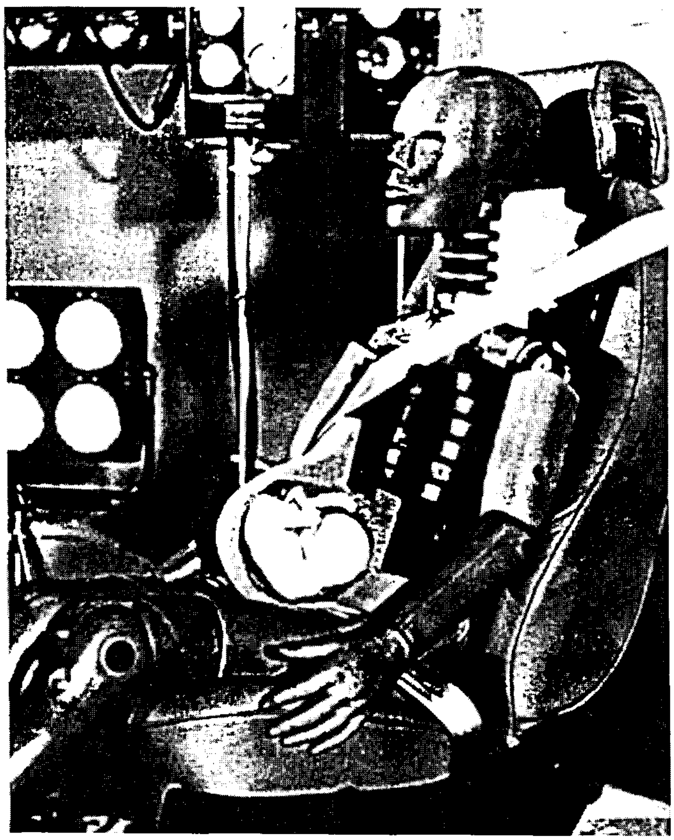


Figure 5: Early design concept for fetal placement.

contains pockets for ballast weights which were added to distribute mass over the torso and adjust the overall weight of the dummy to that of a 5th percentile pregnant women in the third trimester. The jacket is sewn using a combination of nylon and neoprene fabrics. It has a tight fit around the torso, a crotch strap to hold components in place, and a mass of 0.64 kg. The mass of the jacket and ballast is 4.05 kg.

The various component weights were selected from data in the anthropometry analysis conducted by Culver and Viano (1990). The pregnant dummy weighs 60.1 kg (132.2 lb). This is 10.0 kg (22.0 lb) more than the standard female dummy, which is consistent with the average weight gain for 28-32 weeks of pregnancy, or midway through the third-trimester. Static belt compression tests were performed on the pregnancy insert in the fully assembled dummy. AP deflection of 70-95 mm caused a normal load of 780-1,350 N via a belt. The reaction-plate force was 75% (+/- 1%) of the applied load, indicating other load-paths to the pelvis and chest. The stiffness of the insert was 12.7 +/- 1.6 N/mm (9.5 +/- 1.2 N/mm for the reaction plate).

Measurement Instrumentation: The adult female Hybrid III was instrumented in a standard fashion, including Endevco triaxial accelerometers in the head, chest and pelvis, and loadcell in the neck for moment and force measurement. Lap and shoulder belt load were measured. The "fetal" insert was instrumented using triaxial accelerometers in the fetal head and thorax. In addition, the reaction plate located behind the pregnancy insert (anterior to the spine of the Hybrid III) was instrumented for load. This data estimates the total force (pressure) transmission through the "uterus."

The response of the simulated fetus was estimated by the measurement of fetal acceleration and back-plate reaction load. The key biomechanical responses of the fetus include abdominal force, fetal head and thoracic resultant acceleration, and head injury criteria (HIC). HIC was conventionally computed as the weighted head acceleration over time, although the effect on fetal head injury risk is unknown. Figure 5 shows the early prototype concept for the pregnancy insert using the NASCO LifeForm fetus in the abdomen of the instrumented 5th percentile Hybrid III female dummy.

The instrumented fetus provided responses over the range of crash severity and restraint placement. The data is best interpreted in comparison to a baseline response, so that information is relative to a known impact condition. This allows a ranking of the relative severity of different speeds of crash and type of restraint misuse with respect to a baseline response. The system could not be calibrated for absolute injury risk assessment because of a lack of injury information about fetal responses during impact.

Interpreting Fetal Responses: Peak values are reported for the measured responses from the head and torso of the instrumented fetus, as well as HIC. The load on abdominal insert is also important, and is proportional to the pressure developed on the abdomen-uterus during deceleration or impact. Additional calculations were made to estimate the relative response differences between the head and torso of the fetus, and the fetus and mother. First, the difference in AP and SI acceleration of the fetus head and torso was determined to estimate the relative forces deforming the fetus inside the abdomen. Second, the difference in AP and SI acceleration of the mother and fetus was determined to estimate the forces displacing the fetus within the abdomen. The mother's acceleration was determined as the average AP and SI acceleration of the chest and pelvis. This estimates the acceleration at the level of the fetal insert. The AP and SI acceleration of the fetus was estimated as the average from the head and torso of the fetus.

The fetal response data can be interpreted as relative responses between various test conditions. The absolute risk of fetal injury cannot be interpreted directly from the measurements and calculations since there is no link to human tolerance information. The responses are helpful in assessing relative differences between conditions of proper and improper lap and shoulder belt use, low to higher speed crashes, and various restraint combinations such as unbelted and belt-airbag restrained. The fetal and maternal responses related to performance are:

<u>Fetal Responses</u>

- Force on Abdomen (Uterus)
- Fetal head and chest acceleration
- Fetal head HIC
- Female-to-fetal relative acceleration
- Fetal head-to-torso relative acceleration

<u>Female Responses</u>

- Head acceleration and HIC
- Neck moment and forces
- Chest acceleration (and deflection)
- Pelvic acceleration
- Shoulder and lap belt loads

Test Conditions: All tests were run on a Hyge sled. There were two separate series of tests. The first series consisted of 31 passenger tests run with various lap and shoulder belt placements and unbelted at speeds of 10, 15, 20 and 25 mph (4.5, 6.7, 8.9, 11.2 m/s). The various seat belt configurations included proper belt placement, placement of the lap belt over the abdomen-uterus and placement of the shoulder belt behind the back. The following conditions were evaluated:

Series I

- Proper lap-shoulder belt placement
- Lap belt on "uterus" with normal shoulder belt
- Normal lap belt with loose shoulder belt behind the back
- Normal lap belt with tight shoulder belt behind the back
- Lap belt over "uterus" with loose shoulder belt behind the back
- Lap belt over "uterus" with tight shoulder belt behind the back
- Unbelted with "padded" instrument panel
- Unbelted with stiff instrument panel

The second series involved 8 tests with driver airbags at speeds of 15, 20 and 25 mph (6.7, 8.9, 11.2 m/s), as well as static deployments. Use and non-use of the lap-shoulder belts were simulated with a driver's airbag module. In some of the airbag tests, the dummy was placed "out of position", so that the ATD and pregnancy insert were against the airbag when it was deployed. The following conditions were evaluated:

Series II

- Proper lap-shoulder belt placement, driver airbag and normal seating position
- Unbelted with driver airbag and normal seating position
- Unbelted with driver airbag and driver "out-of-position" against steering wheel

RESULTS

For baseline tests, the seat belts were placed in the American College of Obstetrics and Gynecology (ACOG) and National Highway Traffic Safety Administration (NHTSA) recommended positions during pregnancy. The lap belt was placed as low as possible under the protuberant portion of the abdomen, and the shoulder belt was positioned off to the side of the uterus, between the breasts and over the mid-portion of the clavicle and shoulder.

The effect of improper placement of the lap belt on force transmission through the abdomen-uterus was evaluated in a series of sled runs at 10 to 25 mph (see conditions 1 and 2 in Table 1). In all of these runs, the shoulder belt was placed in the normal position (side of the uterus, between the breasts and over the mid-portion of the clavicle). However, the lap belt was either placed properly underneath the abdomen-uterus (condition 1) or on the abdomen-uterus (condition 2). Figure 6 demonstrates more than a three-fold increase in force transmission through the "uterus" with improper placement of the lap belt on the abdomen.

Test results with other improper restraint positions are depicted in Table 1. The Table compares currently recommended seat belt positions with three other improper positions: normal lap belt with shoulder belt behind back; lap belt over uterus with shoulder belt behind back; and unbelted. In general, improper belt placement resulted in an increase in force transmission through the "uterus," but force was the highest for an improperly placed lap belt on the abdomen and the shoulder belt behind the back. The load on the abdomen was 25% higher than with the lap belt on the "uterus" but proper shoulder belt placement. The improper placement of the lap and shoulder belt directed the greatest amount of restraining load into the lap belt and onto the "uterus." Figure 7 summarizes two maternal and two fetal responses at 20 mph (8.9 m/s), and Figure 8 shows the same responses for tests at 10-25 mph (4.5-11.2 m/s).

Table 2 shows the effects of driver airbag deployment on acceleration and force transmission to the fetus. This series of tests demonstrates that abdominal force transmission through the "uterus" is relatively low for all conditions when airbags are deployed, irrespective of belt use or non-use. However, when the ATD was unbelted, a substantial increase was seen in fetal HIC (from 25 to 512) with airbag deployment at 25 mph (11.2 m/s). In this comparison, the driver airbag directs restraining loads to the torso. Finally, the effect of airbag deployment was assessed in an "out-of-position" pregnant driver (laying against the steering wheel) with and without sled movement. While force transmission was greater than in comparable tests with a normal seating position, the force level was below 1 kN (Figure 9). There were high fetal accelerations, and essentially all of the calculated fetal responses showed high acceleration (Figure 10).

Table 1: Pregnant Female Dummy Hyge Sled Tests with Belt Restraints

Run #	Sled Vel mph	Sled Acc g	Test Type	Female Responses: HIC	Head Res Acc g	Thorax Res Acc g	Pelvis Res Acc g	Neck Res Force kN	Neck Moment: Flexion (+) N-m	Neck Moment: Extension (-) N-m	Lap Belt Load: Inboard kN	Lap Belt Load: Outboard kN	Shoulder Belt Load kN
3216	10.2	2.6	1	3	4.7	4.3	3.6	0.25	12	-6	0.82	0.41	0.79
3214	14.8	4.6	1	24	13.6	11.5	9.7	0.45	31	-15	1.77	0.66	1.85
3215	20.1	7.8	1	90	22.6	20.5	14.4	0.94	46	-27	2.91	1.63	2.83
3217	25.5	11.5	1	194	30.9	30.1	31.5	1.10	52	-26	6.41	4.07	4.44
3288	19.8	7.8	1	94	26.4	21.9	19.7	0.6	37	-12	3.95	1.45	3.85
3220	10.0	2.5	2	4	5.1	4.2	3.6	0.22	15	-6	0.67	0.34	0.63
3218	15.2	4.9	2	23	12.4	10.1	6.8	0.49	28	-10	1.60	0.63	1.59
3219	20.1	7.8	2	106	23.1	16.4	12.7	0.83	48	-21	2.75	0.92	2.68
3221	25.5	11.6	2	307	46.2	23.7	17.6	1.46	72	-25	4.00	1.37	3.79
3290	19.6	7.6	2	91	25.3	21.0	16.5	0.5	37	-15	3.39	1.16	3.39
3224	10.0	2.5	3a	5	4.9	2.3	3.4	0.22	11	-4	0.49	0.50	0.10
3222	14.8	4.7	3a	38	29.2	7.6	10.0	0.34	13	-8	1.31	1.32	0.10
3223	20.3	7.7	3a	294	64.5	16.8	29.3	1.10	59	-20	3.68	4.01	0.26
3225	25.5	11.6	3a	889	116.0	32.8	41.8	2.49	119	-25	5.00	5.45	0.25
3298	19.5	7.7	3b	1595	238.0	45.8	16.4	2.2	95	-20	2.47	1.44	2.47
3291	19.7	7.7	3b	1432	231.0	43.8	16.0	2.2	94	-15	2.10	1.50	2.14
3226	10.0	2.5	4a	6	4.6	2.5	2.8	0.20	12	-4	0.40	0.44	0.00
3227	14.6	4.6	4a	43	31.0	8.9	7.3	0.30	24	-21	1.10	1.10	0.00
3228	19.7	7.6	4a	328	75.6	16.8	16.3	0.93	71	-25	2.24	2.32	0.00
3229	20.1	7.7	4a	345	76.7	18.1	19.4	0.93	74	-20	2.54	2.61	0.00
3230	25.1	11.4	4a	615	88.1	39.0	27.6	2.12	97	-27	4.18	4.85	0.00
3292	19.7	7.7	4b	1956	239.0	36.9	16.9	2.0	73	-19	1.90	1.00	2.17
3231	9.8	2.4	5a	1	3.1	3.9	4.6	0.10	8	-5	-------	-------	-------
3232	15.0	4.8	5a	29	21.0	9.1	19.1	0.70	15	-20	-------	-------	-------
3233	20.2	8.0	5a	157	42.7	29.5	33.6	2.27	77	-17	-------	-------	-------
3234	25.0	11.4	5a	456	92.5	80.0	39.6	2.51	147	-20	-------	-------	-------
3295	9.2	2.3	5b	3	4.3	2.7	4.0	0.2	8	-3	-------	-------	-------
3296	10.5	2.8	5b	4	4.5	4.2	7.9	0.3	10	-7	-------	-------	-------
3294	14.9	5.0	5b	207	80.0	28.3	12.1	1.3	34	-32	-------	-------	-------
3297	19.7	8.0	5b	634	139.0	84.5	26.5	1.4	63	-21	-------	-------	-------
3299	24.5	11.3	5b	1563	238.0	196.4	48.9	2.9	31	-21	-------	-------	-------

1. Normal Belt Position one fist of slack.
2. Normal shoulder belt lap belt over abdomen.
3a. Normal lap belt, loose shoulder belt behind back.
3b. Normal lap belt, tight shoulder belt behind back.
4a. Lap belt over abdomen, loose shoulder belt behind back.
4b. Lap belt over abdomen, tight shoulder belt behind back.
5a. Unrestrained and padded instrument panel
5b. Unrestrained and unpadded instrument panel

NA: Vertical accelerometer data was lost due to damage in the test.

Table 1 (continued): Pregnant Female Dummy Hyge Sled Tests with Belt Restraints

Run #	Sled Vel mph	Sled Acc g	HIC	Fetal Responses: Head Res Acc g	Thorax Res Acc g	Fetal Head-to-Thorax: Relative Long. Acc (+) g		Relative Vert. Acc (+) g		Res. Acc g	Abdomen Force kN	Fetus-to-Female: Relative Long. Acc (+) g		Relative Vert. Acc (+) g		Res. Acc g
						(+) g	(-) g	(+) g	(-) g			(+) g	(-) g	(+) g	(-) g	
3216	10.2	2.6	1	4.5	5.6	1.3	-1.7	4.4	-0.3	4.5	0.27	1.9	-1.2	1.1	-1.3	2.1
3214	14.8	4.6	9	12.5	15.2	5.3	-4.5	13.9	-0.6	13.9	0.05	5.4	-2.9	3.5	-4.6	6.3
3215	20.1	7.8	45	25.8	26.7	5.7	-6.2	22.2	-1.0	22.6	0.79	8.7	-9.1	7.4	-5.9	10.8
3217	25.5	11.5	103	29.1	33.6	9.2	-16.7	30.5	-11.2	31.5	2.15	11.2	-9.9	21.7	-10.4	23.6
3288	19.8	7.8	53	23.1	22.4	8.3	-7.8	18.5	-2.3	18.6	0.46	4.8	-4.4	12.7	-6.2	12.8
3220	10.0	2.5	1	2.9	3.5	1.4	-1.8	2.8	-0.5	3.1	0.88	2.1	-0.8	0.8	-1.2	2.1
3218	15.2	4.9	5	7.0	7.1	1.5	-3.6	5.5	-0.7	6.2	2.03	4.5	-2.0	1.6	-4.2	5.8
3219	20.1	7.8	23	18.4	15.5	4.1	-13.8	14.5	-7.5	16.5	4.23	10.7	-8.3	8.4	-6.9	12.1
3221	25.5	11.6	-------	NA	40.7	-------	-------	30.8	-18.2	-------	7.98	38.5	-15.2	10.3	-12.7	39.7
3290	19.6	7.6	26	20.4	20.1	5.2	-10.1	11.5	-3.6	12.1	4.93	10.7	-5.0	11.7	-3.9	12.7
3224	10.0	2.5	1	2.9	4.5	1.4	-1.1	5.0	-0.2	5.0	0.67	1.1	-1.2	1.2	-1.8	1.9
3222	14.8	4.7	7	9.4	10.9	2.6	-5.1	9.0	-0.8	9.1	1.74	4.4	-3.6	3.6	-3.2	4.6
3223	20.3	7.7	51	24.5	25.7	8.5	-6.5	25.2	-1.0	25.5	5.09	12.4	-13.3	13.1	-10.3	15.0
3225	25.5	11.6	197	52.6	49.2	17.6	-15.3	56.9	-8.0	57.6	6.86	21.9	-22.8	16.3	-26.3	31.4
3298	19.5	7.7	50	21.9	20.9	11.0	-7.8	17.1	-10.0	18.2	2.46	17.1	-10.3	14.9	-21.1	22.4
3291	19.7	7.7	41	19.1	17.2	13.0	-5.0	13.0	-9.7	13.8	2.32	17.6	-6.9	16.9	-22.4	24.1
3226	10.0	2.5	1	2.8	3.4	0.9	-1.2	2.7	-0.4	2.8	1.03	1.2	-1.6	1.1	-2.1	2.1
3227	14.6	4.6	4	6.1	6.6	2.2	-2.6	5.4	-1.0	5.7	2.43	3.0	-2.4	1.5	-4.6	4.7
3228	19.7	7.6	-------	NA	12.8	-------	-------	26.6	-1.6	-------	5.08	11.3	-3.3	12.7	-9.3	16.3
3229	20.1	7.7	24	26.9	17.5	8.1	-15.9	18.9	-6.7	20.0	6.40	11.6	-9.8	4.5	-13.9	14.3
3230	25.1	11.4	83	42.2	29.6	25.2	-30.1	27.8	-27.5	34.2	10.98	28.8	-12.5	15.6	-31.8	32.3
3292	19.7	7.7	25	19.4	17.3	11.3	-11.4	12.7	-9.7	14.9	5.69	14.9	-5.8	10.2	-13.9	16.7
3231	9.8	2.4	1	4.8	4.8	1.3	-1.9	4.3	-0.2	4.3	0.20	2.4	-1.6	1.1	-1.0	2.5
3232	15.0	4.8	25	19.4	21.0	8.3	-6.4	17.3	-2.6	17.3	0.84	13.8	-13.9	4.8	-6.2	14.0
3233	20.2	8.0	100	36.8	34.2	5.6	-10.0	29.8	-8.9	30.8	2.68	15.9	-22.3	12.0	-21.2	22.3
3234	25.0	11.4	241	48.1	52.9	29.0	-11.2	43.0	-29.4	43.9	1.51	22.1	-19.6	18.9	-39.5	40.7
3295	9.2	2.3	1	4.9	4.8	2.0	-0.4	3.4	-0.1	3.9	0.17	2.5	-1.6	2.1	-0.6	2.9
3296	10.5	2.8	5	9.2	7.8	3.6	-0.6	6.5	-0.5	7.3	0.44	3.1	-3.0	4.8	-2.1	4.9
3294	14.9	5.0	31	19.2	19.7	13.8	-11.4	16.6	-5.2	16.6	0.53	12.0	-7.7	9.6	-9.3	13.0
3297	19.7	8.0	137	31.2	32.7	28.4	-8.0	20.9	-31.6	32.0	2.11	27.1	-17.9	17.8	-33.8	39.8
3299	24.5	11.3	319	68.2	143.7	85.2	-59.9	51.5	-9.6	92.3	1.86	23.2	-35.4	25.9	-71.6	71.6

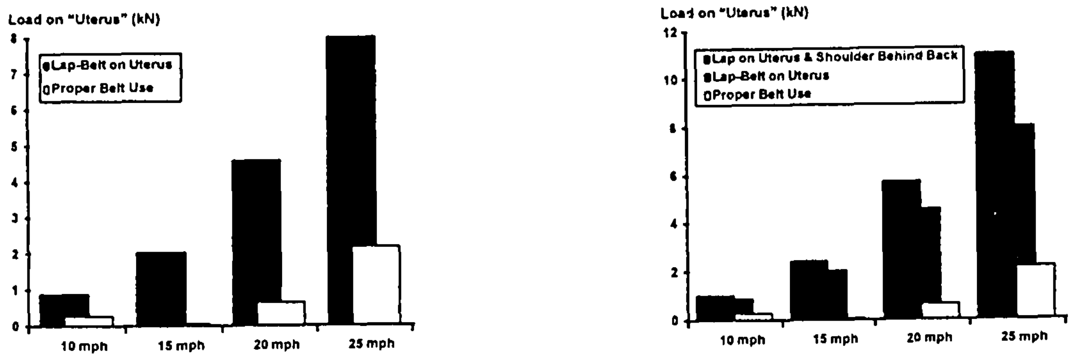


Figure 6: Peak force on the abdomen-uterus for proper (ACOG placement) wearing of the lap-shoulder belts as comparec with improper placement of the lap belt on the "uterus."

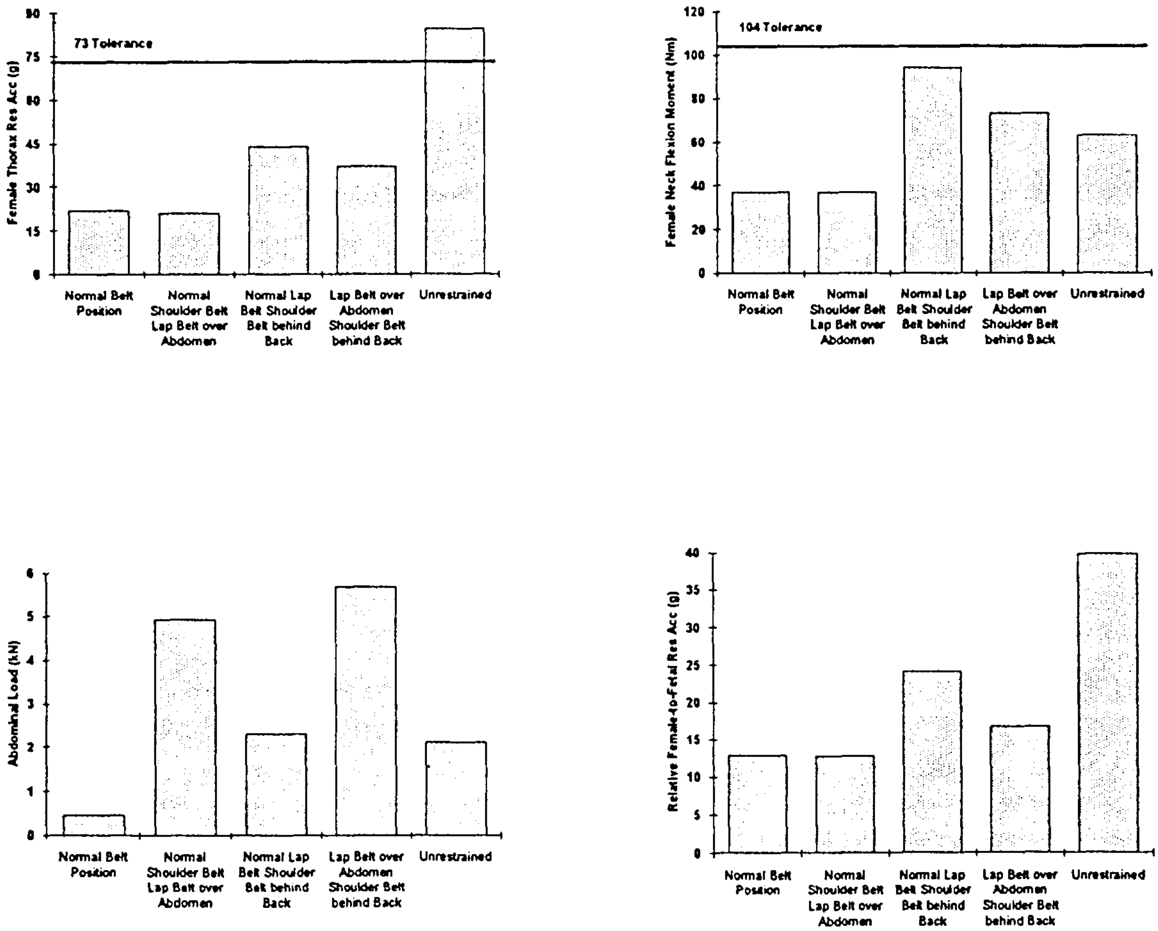


Figure 7: Summary plot of two maternal and two fetal responses for sled tests at 20 mph (8.9 m/s) for the passenger seating position with "proper" lap-shoulder belt use, improper belt placement, and unrestrained condition.

Table 2: Pregnant Female Dummy Hyge Sled Tests with Airbag Restraints

Run #	Vel	Sled Acc	Test Type	Female Responses										
				HIC	Head Res Acc	Thorax Res Acc	Pelvis Res Acc	Neck Res Force	Neck Moment		Lap Belt Load		Shoulder Belt Load	Abdomen Force
									Flexion	Extension	Inboard	Outboard		
	mph	g			g	g	g	kN	(+) N-m	(-) N-m	kN	kN	kN	kN
3437	15.1	6.2	1	14	14.6	8.7	9.7	0.41	20	-10	1.24	0.89	0.51	0.12
3440	19.4	9.3	1	58	22.1	18.0	18.9	0.60	17	-11	2.91	1.92	1.38	0.16
3441	25.9	15.2	1	272	50.0	42.1	35.2	1.71	8	-18	5.83	4.06	3.02	0.20
3438	15.3	6.2	2	17	15.2	8.8	16.0	0.37	22	-8	-------	-------	-------	0.15
3439	19.4	9.2	2	69	33.1	13.0	29.3	0.94	19	-21	-------	-------	-------	0.09
3444	25.8	15.4	2	254	48.8	28.8	48.9	1.37	16	-28	-------	-------	-------	0.04
3442	Static		3	41	30.6	17.7	6.7	1.89	10	-59	-------	-------	-------	0.68
3443	15.3	6 0	3	67	33.6	20.8	15.3	2.41	9	-84	-------	-------	-------	0.88

Run #	Fetal Responses														Steering Column	
	HIC	Head Res Acc	Thorax Res Acc	Fetal Head-to-Thorax					Fetus-to-Female						Force	Disp.
				Relative Long. Acc		Relative Vert. Acc		Res. Acc	Relative Long. Acc		Relative Vert. Acc		Res. Acc			
		g	g	(+) g	(-) g	(+) g	(-) g	g	(+) g	(-) g	(+) g	(-) g	g		kN	mm
3437	26	26.3	33.0	12.8	-17.6	27.9	-37.7	38.4	13.7	-20.5	11.9	-14.9	22.0		4.03	2.5
3440	39	18.3	37.8	15.4	-35.1	28.5	-28.4	40.6	16.3	-15.8	7.1	-15.1	16.3		5.28	1.7
3441	115	35.5	46.1	19.3	-20.2	48.3	-35.0	48.6	13.3	-10.4	11.5	-17.8	18.2		4.26	7.2
3438	24	18.9	20.6	8.7	-14.3	18.5	-16.5	21.4	10.2	-7.6	5.7	-11.6	11.7		4.84	2.6
3439	79	34.8	31.7	23.0	-24.9	32.7	-20.9	32.9	17.6	-9.9	10.1	-14.0	17.6		5.12	2.5
3444	512	87.4	70.2	33.0	-44.9	75.7	-36.1	76.0	25.4	-44.4	13.8	-43.8	58.5		4.92	39.1
3442	328	122.7	369.0	366.2	-225.5	254.6	-207.3	375.0	72.8	-154.7	126.8	-85.5	200.0		5.39	------
3443	673	139.9	294.4	266.1	-208.0	161.2	-120.5	272.6	52.7	-141.5	75.3	-32.3	159.5		7.05	59.3

1. Normal Seating Position, Lap-Shoulder belted with driver airbag
2. Normal Seating Position, Unbelted with driver airbag
3. Out-of-Position (Against steering wheel), Unbelted with driver airbag

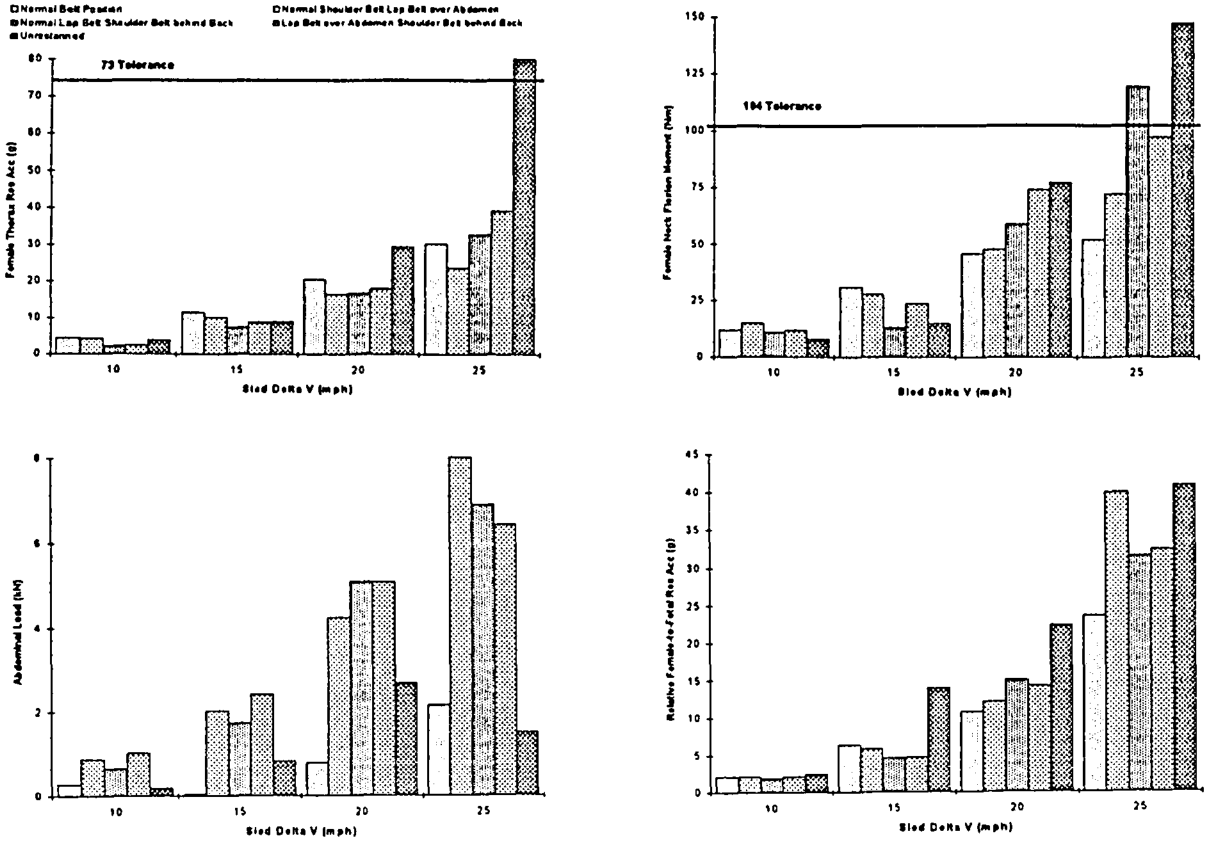


Figure 8: Summary plot of maternal and fetal responses for five restraint conditions shown in Figure 7 at four sled speeds.

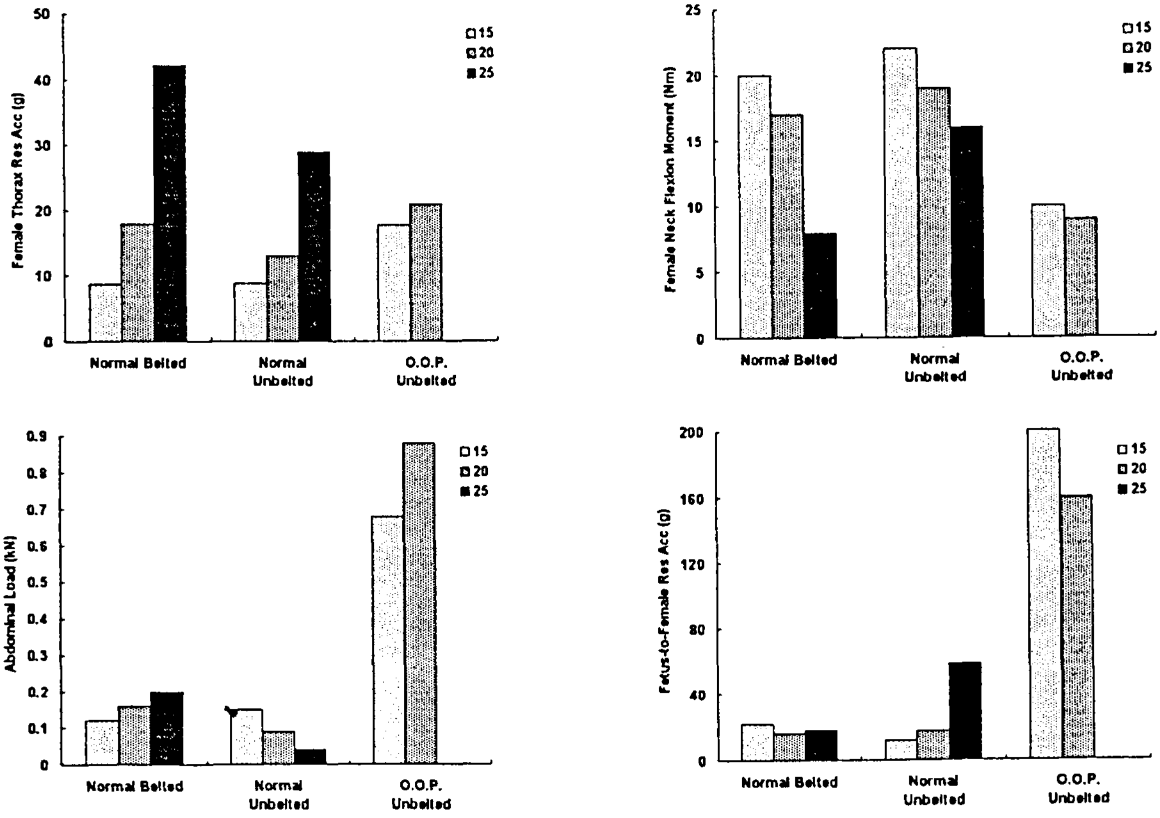


Figure 9: Summary plot of two maternal and two fetal responses for driver airbag tests.

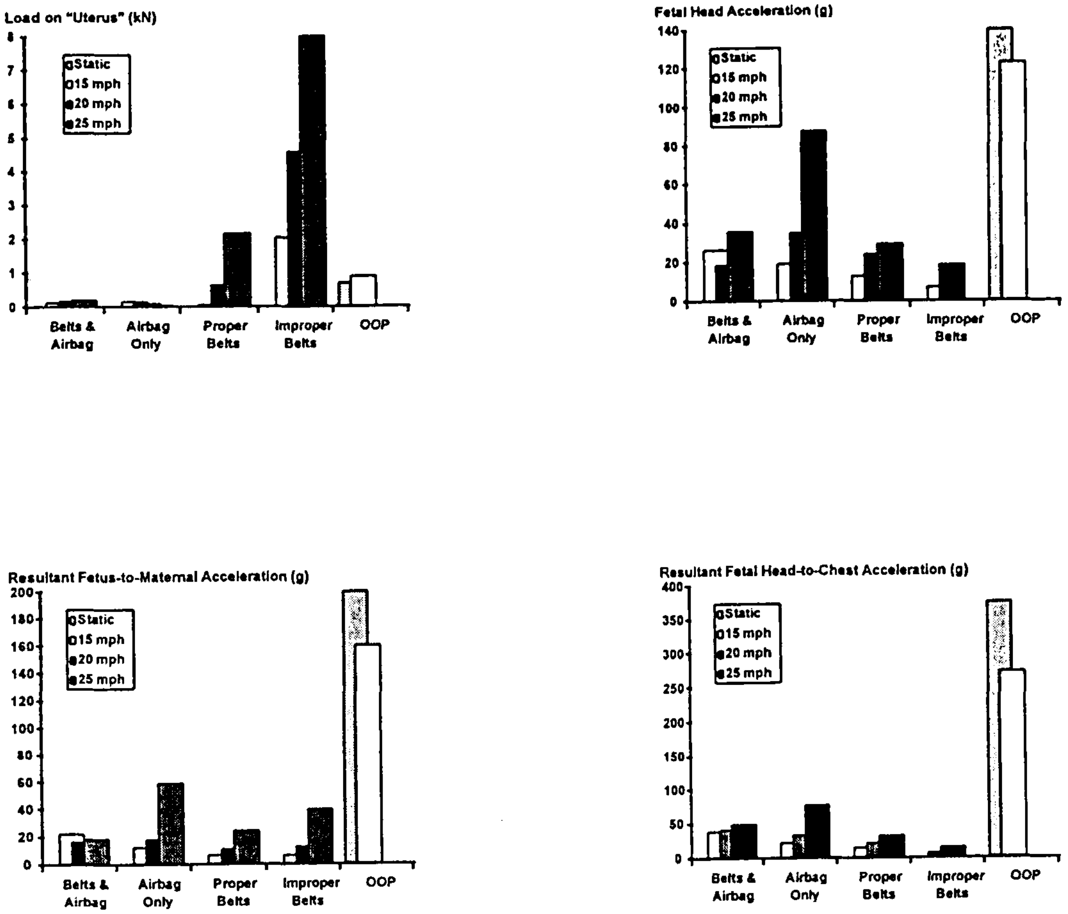


Figure 10: Summary plot of resultant fetal acceleration for various restraint conditions with belts and airbags, including "out-of-position" exposures.

DISCUSSION

Despite the implementation of various protocols to manage the pregnant woman after motor vehicle crashes, pregnancy loss occurs even following relatively minor crashes without apparent maternal injury. The use of safety belts improves protection of the mother and unborn child. However, most crashes are minor, so most pregnancy losses follow minor crashes. It is apparent from these facts that an improved understanding of the mechanism of pregnancy loss following crashes is an important first step in developing automobile restraint systems or interiors which may lessen the risk of fetal injury following crashes.

An important observation from this study is that placement of the seat belt in the recommended fashion by ACOG and NHTSA resulted in some of the lowest readings in this series of tests. These readings suggest that this restraint positioning may be the safest placement of currently existing seat belts. However, two concerns are raised from this observation. First, many women choose not to place belts in this position (if at all). Secondly, it may be difficult for some women to place or maintain a lap belt where it does not overlie the lower portion of the uterus (Pearlman and Schneider, unpublished data). Nonetheless, the current lap and shoulder belt placement recommendation appears to be consistent with the lowest recordings from the accelerometers and force transducers; and, health care practitioners should encourage pregnant women to place belts in the ACOG recommended fashion.

The safety benefits of airbags are clear in frontal crashes. However, airbag deployment has always posed some risk to an occupant, particularly among occupants who are against the airbag module when it deploys (Smock, Nichols 1995, Huelke etal 1995, Lau etal 1993). While the placement of the ATD and pregnant abdomen directly over the airbag at the time of deployment is somewhat artificial, there is some anatomic rationale for this. With the anatomic changes of pregnancy resulting in protrusion of the abdomen without any changes in arm or leg length, the pregnant driver's abdomen must lie closer to the airbag module in the steering wheel for the latter half of gestation if the pregnant woman is to maintain her ability to successfully maneuver the steering wheel, brake and accelerator pedals. On this point, there was an increase in fetal head and torso acceleration, including HIC, for these experiments whether the sled was stationary or moving to 15 mph (6.7 m/s).

While the HIC threshold necessary to predict fetal head injury is unknown, it is reasonable to assume that larger HICs are relatively more likely to cause fetal head injury in the "out-of-position" condition. The high relative accelerations possibly indicate an increased risk of abruptio placentae of direct fetal injury, if an airbag was to deploy directly against the abdomen. However, there is generally low force transmission through the abdomen-uterus to the reaction plate for the airbag tests. This is evidence of the load distribution benefits of airbags. The dynamics of seat belts in a higher speed crash with an airbag deploying in front of a pregnant driver is unknown, and estimation of this risk must balance the known protective effects for the driver. It is estimated that the use of safety belts and combined use of belts and airbag are 43% and 47% effective in preventing adult fatalities in otherwise fatal crashes of unbelted drivers (Viano 1995). At present, the authors believe it would be unwise to not wear seat belts or to deactivate airbag deployment in high-speed crashes during pregnancy. There is, however, a need for validation and more testing with an advanced pregnant ATD, preferably with a uteroplacental interface.

The overall goal of this study was to develop and test a pregnancy insert for the 5th percentile Hybrid III female dummy. While this was accomplished, several important issues must be considered regarding the biofidelity of the device. Biofidelity refers to the ability of the ATD to act in a similar manner during a crash as a human, specifically to allow reasonable predictability of injury risk. There are some data derived from this study which suggests a level of biofidelity. For example, with standard belt placement, fetal head and chest acceleration increased with crash speed. Furthermore, movement of the lap belt so that it overlies the "uterus" results in an increase of force transmission through the "uterus," an expected finding which may predict the relative risk of injury to the "uterus" and/or fetus in different restraint conditions.

Real or quantitative assessment of injury risk requires validation of the ATD model through field testing and crash investigation. Further research should specifically try to reconstruct crashes in which there were pregnancy losses to better understand the mechanism of loss (e.g., forces necessary to cause abruptio placentae or direct fetal injury). In addition, future generation of the pregnant dummy could incorporate a uteroplacental interface to help understand what type and magnitude of forces are necessary to cause abruptio placentae so that the model can reasonably predict both adverse maternal (e.g., uterine rupture) and fetal (e.g., abruptio placentae) outcome.

ACKNOWLEDGEMENT

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REFERENCES

ACOG Technical Bulletin, "Automobile passenger restraints for children and pregnant women." American College of Obstetric & Gynecology, Number 151, 1991.

Crosby WM, Snyder RG, Snow CC, Hanson PG, "Impact injuries in pregnancy." American Journal of Obstetrics & Gynecology, 101(1):100-110, May 1968.

Crosby, WM, King AI, Stoudt, LC. "Fetal survival following impact: improvement with shoulder harness restraint." American Journal of Obstetrics & Gynecology 112:1101-1106, 1972.

Culver CC, Viano DC "Anthropometry of seated women during pregnancy: defining a fetal region for crash protection research." Human Factors, 32(6):625-636, 1990.

Fildes J, Reed L, Jones N, etal "Trauma: the leading cause of maternal death." Journal of Trauma, 32:643, 1992

Goodwin TM, Breen MT, "Pregnancy outcome and fetomaternal hemorrhage after noncatastrophic trauma." American Journal of Obstetrics & Gynecology, 162(3):665-671, March, 1990.

Hartemann F, Henry C, Faverjon, G, Tarriere, C etal. "Ten years of safety due to the three-point safety belt." SAE #840193, Society of Automotive Engineers, Warrendale, PA, 1984.

Huelke DF, Moore JL, Compton TW, Samuels J, Levine RS. "Upper extremity injuries related to airbag deployments." Journal of Trauma 38:482-8, 1995.

King AI, Eppinger RH, Crosby WM, Stoudt C. "Effects of lap belt and three-point restraints on pregnant baboons subjected to deceleration." SAE #710850, Society of Automotive Engineers, Warrendale, PA, 1971.

Lane P. "Traumatic fetal deaths." Journal of Emergency Medicine 7:433, 1989.

Lau IV, Horsch JD, Viano DC, Andrzejak, DV. "Mechanism of injury from airbag deployment loads." Accident Analysis & Prevention 25(1):29-45, 1993.

Pearlman MD, Tintinalli JE, Lorenz RP. "A prospective, randomized trial of outcome following trauma during pregnancy." American Journal of Obstetrics & Gynecology, 162(6):1502-10, June 1990.

Pearlman MD, Viano DC. "Automobile safety restraints in pregnant women." Grant proposal to NHTSA/DOT, 1993.

Smock WS, Nichols GR. "Airbag module cover injuries." Journal of Trauma 38:489-93, 1995.

Viano DC. "Restraint effectiveness, availability and use in fatal crashes: implications to injury control." Journal of Trauma 38:538-46, 1995.

Williams JK, McClain L, Rosemurgy AS, Colorado NM. "Evaluation of blunt abdominal trauma in the third trimester of pregnancy: maternal and fetal considerations." American Journal of Obstetrics & Gynecology, 75(1):33-37, January 1990.

ANATOMICAL STUDY AND THREE-DIMENSIONAL RECONSTRUCTION OF THE BELTED HUMAN BODY IN SEATED POSITION

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ABSTRACT

This paper describes a method developed jointly by medical and technical staffs to improve knowledge of the anatomy of the body in the seat-belt position. the method consists of the following steps :

- a human cadaver is belted into a model driver's seat and frozen in order to fix anatomical structures ;
- the entire body is then cut into serial sections ;
- sections are individually analyzed and drawings of organs are made;
- a computer-generated three-dimensional reconstruction is made of each anatomical structure ;

The resulting reconstruction's allowed study of the position of organs in relation to seat belt straps. With further study we hope to be able to predict the type of injuries that can occur during collisions and describe the mechanisms underlying lesions that have been reported in field studies.

INTRODUCTION

Most descriptions of human anatomy have been made with reference to a standard standing position chosen for teaching purposes. The advent of new medical imaging techniques and computer-generated drawings has enabled three-dimensional representation of the human body in this anatomical reference position. However there are no data banks available for the human body in the sitting position. Radiological studies [1,2] were recently performed in the sitting position but the anatomical description was limited to skeleton in the sagittal plane.

The fact that passengers on cars, buses, trains, or planes are usually seated raises several questions. Does the sitting position increase the severity of injury in case of accident ? What are the most vulnerable regions ? What type of protection is needed ? How do the seat and support materials influence sitting position ? Is one position safer than another in case of an accident and, if so, how can this be determined ?

The purpose of the following study was to evaluate human anatomy in the seat-belt position. We have made three-dimensional reconstruction of the human body belted in the driver's seat of a car and have analyzed the relation between the seat belt and anatomical structures. The findings should provide insight into the mechanisms underlying lesions observed during traffic accidents.

METHODS

Designing a method to assess anatomical structures in the sitting position presents a difficult problem. Dissection, conventional radiology and CT-scan are unsuitable and magnetic resonance imaging cannot currently be performed in the sitting position. Our approach was based on the serial section technique that has often been used for previous anatomical descriptions. Sections were obtained of a subject seated in a standard car seat equipped with a three-point seat belt system. Data were computerized and the different components of the structure visible on each section were reconstructed in three dimensions (figure 1).

Cadavers used in our laboratory are obtained through the University and Faculty of Medicine departments. Upon delivery to the Laboratory, all cadavers are treated using Winckler preservation solution [9] to insure good muscle and joint quality. Two cadavers with suitable morphologic features and no pathologic lesions were selected. The first was a female measuring 157 cm and weighing 55 kg. The second was a male measuring 174 cm and weighing 75 kg. The results presented here are those obtained from the first cadaver. Study of second cadaver is currently under way.

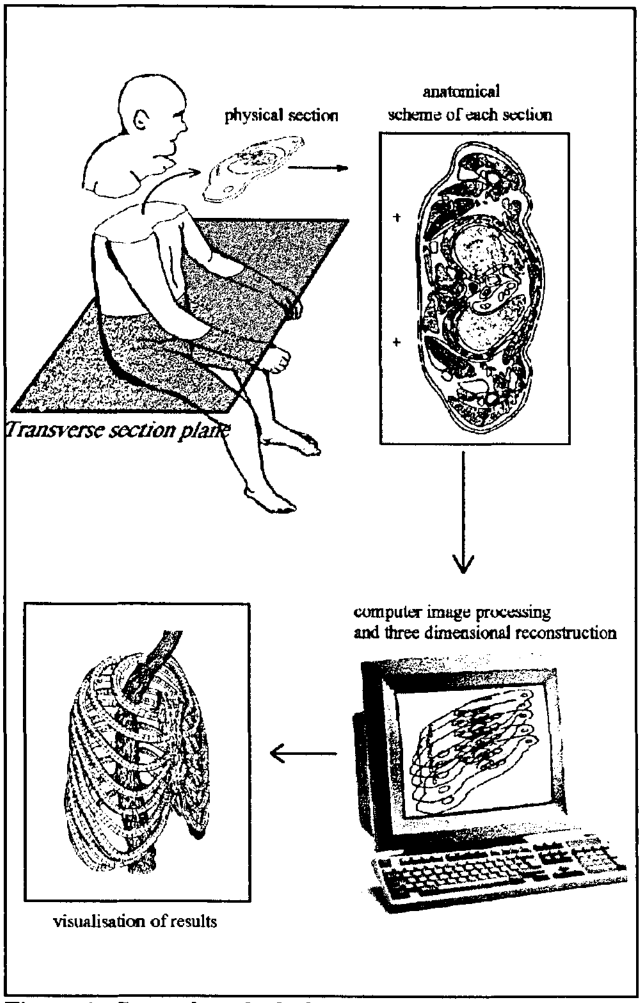

Figure 1. General methods from physical sections to three-dimensional reconstruction.

Sitting position

Our Laboratory is equipped with a model driver's seat from a mass-produced car. In addition to the seat itself, the model includes flour mountings, a steering column and wheel, control pedals, and a three-point safety belt system. The seat is equipped with a head-rest and adjustments for seat and seat back position.

After adjustment of the seat to the cadaver's morphotype, the cadaver is placed in the driving position with feet on the pedals and hands on the steering wheel (figure 2). The seat belt is fastened. In order to analyze and reference the posture of the subject with relation to the seat and to the rest of the passenger cabin, it is necessary to measure at least three points on the body with respect to the given point on the vehicle.

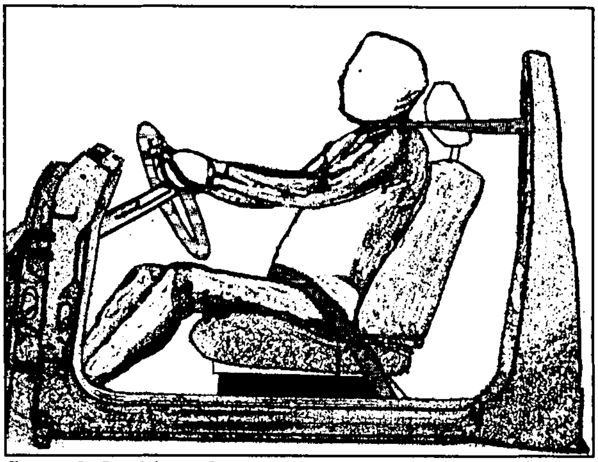

figure 2. Position of a seat-belted cadaver inside the model car.

Previous studies performed on living subjects (anthropometric studies) have been based on measurements of the position of landmarks on the skin surface. In the present study we identified and located landmarks in six regions (shoulder, elbow, wrist, hip, knee, and ankle). Seat posture was referenced by three-dimensional measurements with respect to these targets. After positioning and reference measurements, the cadaver was frozen in -25°C chamber in order to fix the position of the anatomical structures.

Sectioning

The frozen subject is placed on a rectangular polypropylene 10-millimeter-thick template with reference marks perpendicular to the section plane. These marks will be visible on each section and will be used for calibration purposes during digitalization. To maintain the cohesion of anatomical structures during sectioning and to stabilize their position in relation to the reference marks, the frozen cadaver is attached to the template in a highly-rigid single component polyurethane foam shell (see [4]). The course of the seat belt straps is represented by attaching a strip of heat-molded plastic to the skin of the cadaver.

A transverse section plane was used for the first cadaver. Serial sections were made strictly parallel at ten millimeters intervals. A total of 107 transverse sections were made from the top of the head to the lower part of the thighs. the extremities were cut in the sagittal plane. After cleaning, sections were photographed. Slides were projected on a viewing table and anatomical drawings were made. This drawing step is necessary to ascertain the identity of anatomical structures visible on the slide and must be done by a skilled anatomist.

Digitalization and three-dimensional reconstruction

Two-dimensional data from the anatomical drawings were digitalized and used for three-dimensional reconstruction. This was a two-step process. The first step consisted in analyzing raw data to select the anatomical structures to be displayed. Curved profiles were calibrated and integrated into the overall reference system. The second step (three-dimensional reconstruction) involved defining a surface to represent the structure to be displayed. Several specific tools were developed to reconstruct organs. A standard CAD software was used to generate the thoracic cage : each rib was drawn based on a primary geometric shape determined by a circular section following a three-dimensional path curve.

RESULTS

We have obtained a number of three-dimensional anatomic reconstructions from the transverse sections of the female cadaver used in this study. The full skin surface has been reconstructed and the course of the seat belt straps has been visualized diagonally across the thorax and horizontally across the abdomen (figure 3). We have also reconstructed the following structures (figure 4):

- bones including parts of the spine, pelvis, ribs, and sternum ;
- thoracic organs and vessels including the lungs, esophagus, trachea, aorta, and caval system ;
- thoraco-abdominal aorta, and vessels including the liver, spleen, stomach, abdominal aorta, and superior vena cava ;
- two organs in the retroperitoneal space, i.e. the right and left kidneys.

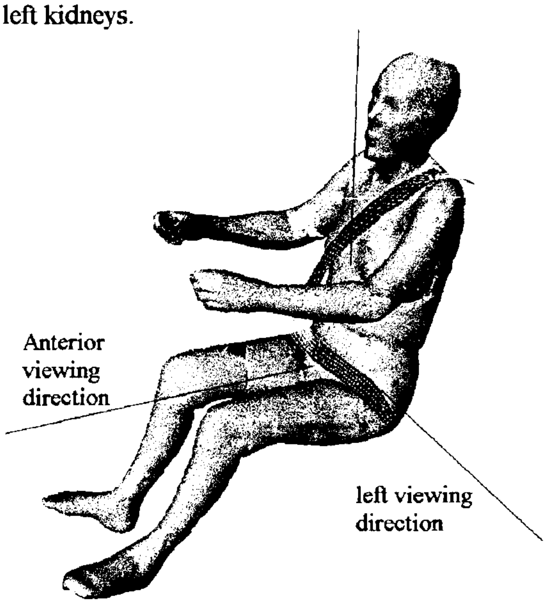

Figure 3. 3D reconstruction of the skin and the seat belt.

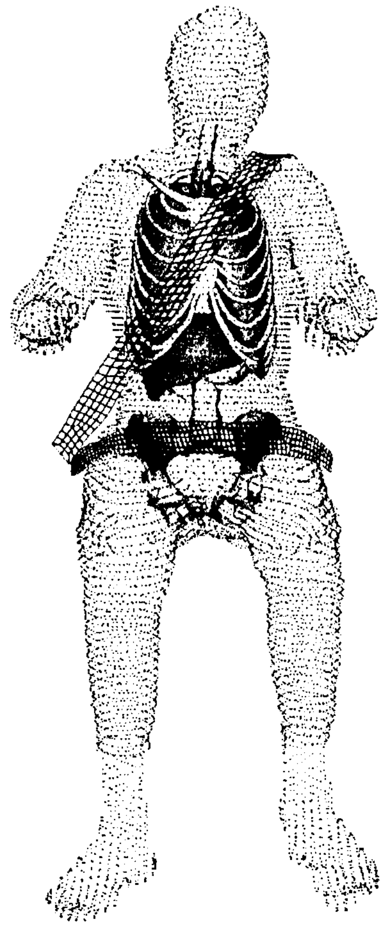

Figure 4. Anterior view of the skin and organs below. the viewing parameters used to define the next figures are shown in figure 3.

Diagonal Thoraco-Abdominal Strap

For the driver, the shoulder belt passes from back to front of the left clavicle, then descends over the upper part of the sternum at an angle of about 45° successively crossing (figure 5) :

- on the left: the sterno-clavicle joint and the first and second sterno-costal joints;
-on the right: the second through the fifth sterno and chondro-costal joints and the lower chondro-costal joints.

The thoracic strap is in contact with the skin from the acromio-clavicular joint of the shoulder to the base of the right side of the thorax at the level of the sixth rib. The strap crosses but is not in contact with the last chondro-costal joints. An anterior view shows that the diagonal strap crosses the spine at the level of the fourth through the ninth thoracic vertebrae (figure 5).

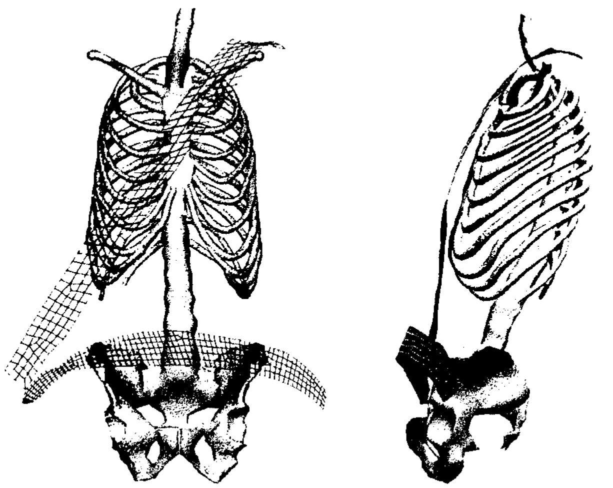

figure 5. Anterior and lateral left views of the computer-generated skeleton.

The shoulder belt overlays a number of organs and vessels of the thorax and abdomen. On the left, the only underlying structure is the apex of left lung behind the clavicle and the first rib. On the right, the belt crosses nearly two-thirds of the antero-lateral aspect of the lung. More deeply under the sternum lie the large mediastinal organs including the heart which is crossed at the base and the origins of the pulmonary arteries and the aorta (figure 6). On an anterior view the aortic arch, the superior vena cava are completely covered.

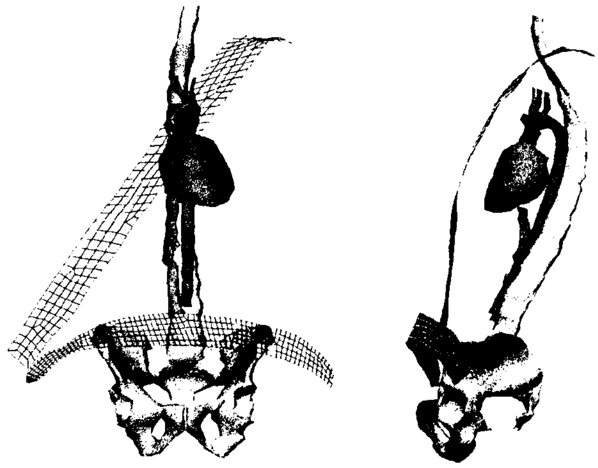

figure 6. Anterior and left views of the heart and large vessels (aorta, large vessels of the aortic arch and superior vena cava).

Laterally, the safety belt is in close relation with the liver from the sixth to the tenth rib and the right lobe can be injured in case of rib fracture (figure 7).

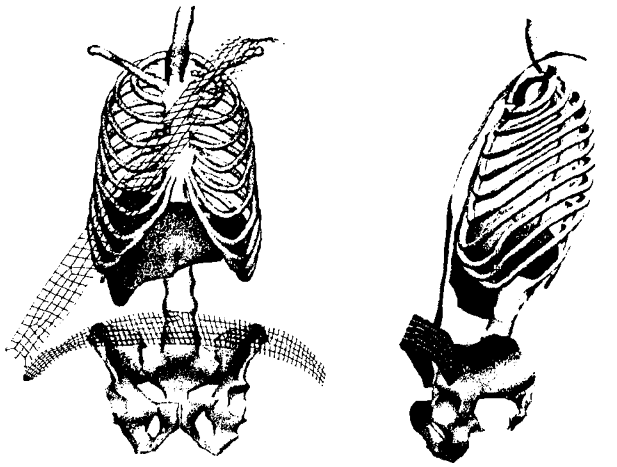

figure 7. Anterior and left views of the localization of the liver and the spleen.

Horizontal abdominal strap

Proper position of the lap belt with respect to the pelvis is an essential factor in case of head-on collision. The risk of lesions is enhanced if the belt is not pulled tight enough. The role of the abdominal strap in case of head-on collision is to keep the pelvis from postero-anterior displacements. For optimal protection, the abdominal strap must be run across the top of the hips and remain in constant contact with a fixed area below the iliac crest during the collision phase in order to avoid the so-called submarining effect [3,6,7]. Tilting of the pelvis in the sitting position, muscle mass, and fat tissue on the thighs and abdomen are factors that affect the location of the lap strap with respect to the pelvis. Three-dimensional reconstruction of the right and left coxa of the cadaver used in this study revealed that the abdominal strap of safety belt was located with regard to the iliac crest. A lateral view shows the effect of backward tilting of the pelvis due to sitting position (figure 8). If the belt is loose, the abdominal strap slides above the hips enhancing the risk of abdominal injuries involving the bladder, the abdominal aorta, the inferior vena cava, or the duodenal-pancreatic region.

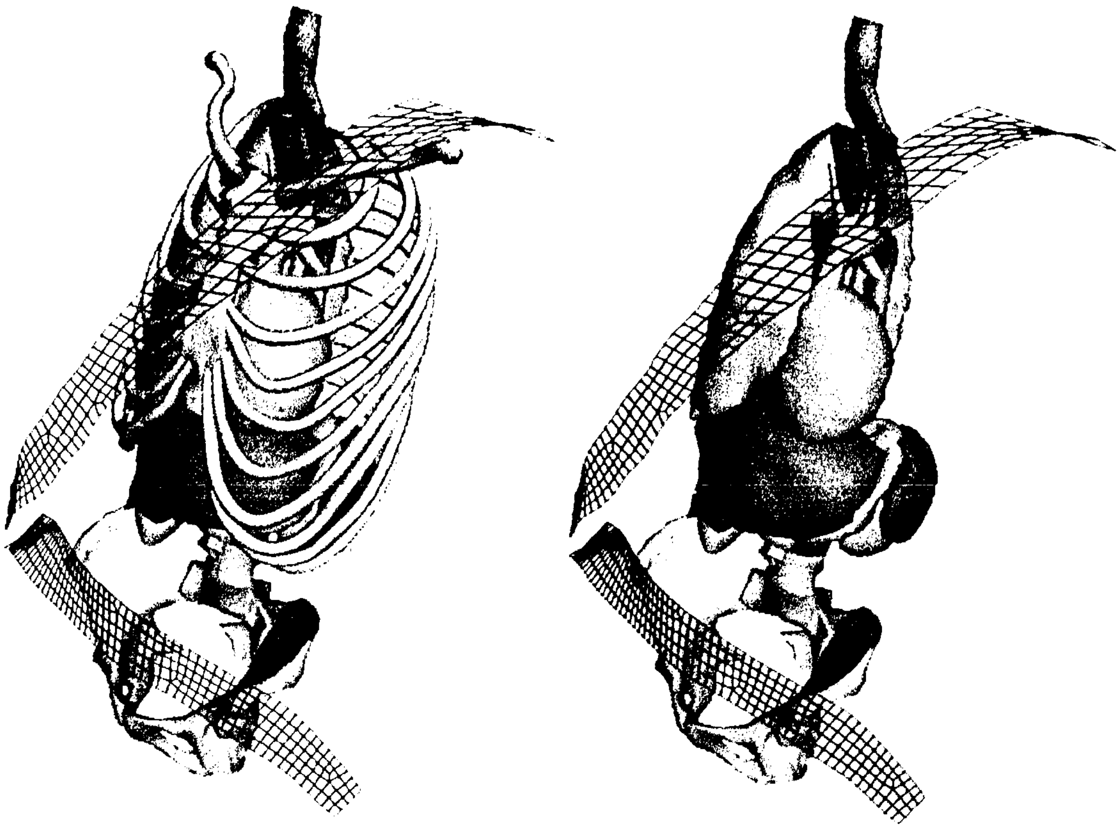

Figure 8. This no conventional anatomic view of the whole set of generated organs (except the left lung) allows a visualization of the relations between the seat-belt, the skeletal structures and the organs below. The stomach can be seen between the liver and the spleen, the left kidney below the spleen.

DISCUSSION

Section plane

Since our ultimate goal is to analyze the interactions between the safety belt and anatomic structures that might be implicated in lesions, we choose to make sections in the transverse plane in order to obtain a more realistic anatomical visualization. Results were satisfactory both for bone structures (pelvis, sternum, rib cage, and clavicle) and for soft tissues (lungs, liver, heart, spleen, kidneys, stomach, esophagus, trachea, aorta, vena cava, etc.). However reconstruction of the spine is problematic with transverse sections because it is difficult to distinguish vertebrae and intervertebral discs. In another study using the sagittal plane we were able to obtain a more detailed representation of the spine allowing differentiation of bone and cartilaginous components (figure 9).

Using a 10 mm section interval is also an impairment for realistic reconstruction of the spine. In future studies we plan to use a section interval of 5 mm.

Reconstruction position

While data obtained in this study improve our understanding of the geometry of the human body and position of anatomical structures, the immobile sitting position used was not ideal for analysis of mechanisms responsible for lesions in a seat-belted occupant. The main drawback is that this position corresponds to the optimal protection position and thus does not take into account detrimental factors such as :

- morphologic variations between individuals ;
- unorthodox sitting positions (« out of position »);
- dynamic forces generated on the occupant during a collision.

Creation of a data bank from measurements made using different cadavers should enable a full-scale assessment of the behavior of the human body in the sitting position. The main advantage of our method of three-dimensional reconstruction is to allow visualization of the position and geometry of anatomical structures and of the contact zones between the rider and the seat. Analysis of the laws of mechanical behavior of the different structures involved should allow construction of a biologically accurate model. The initial sitting position, the dynamic forces applied to the body during a collision, and morphologic variations between individuals will be taken into account to predict the fate of a rider in case of a collision.

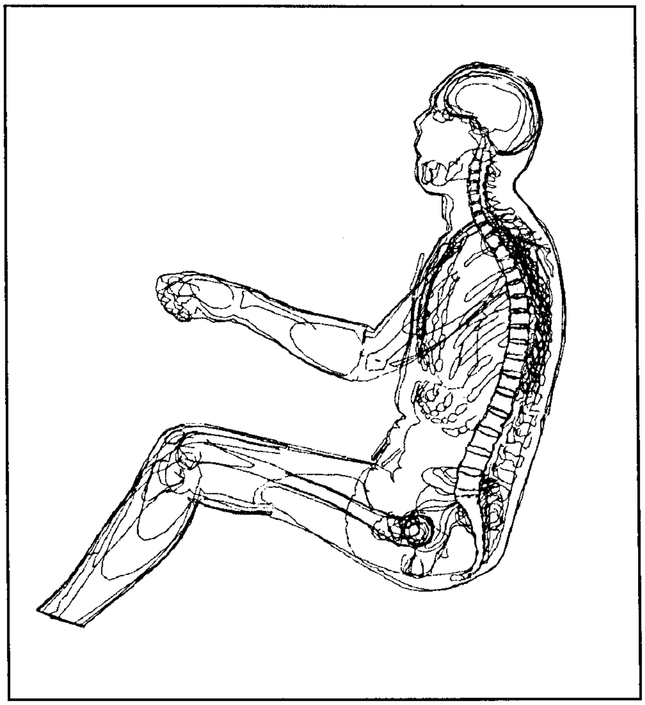

Figure 9: sagittal slices showing the realistic position of the spine.

Authenticity of the study model

Although the anatomical criteria used to select cadavers for study were strict with regard to morphology, anatomical integrity, and previous disease, we performed additional tests to verify that the seat position and spinal posture in our model were authentic. Our preliminary findings are consistent with previous reports [1,5,8]. A radiological study was performed on 35 volunteers seated in the same seat used for the anatomical study. A panoramic lateral view of the whole spine was made in the sitting and standing positions. Regardless of age or morphotype the variations in the curvature of the spine as well as the flattening of the lumbar spine and forward tilting of the pelvis were comparable to those observed in the cadavers tested (figure 9).

Right belted passenger

For a passenger in a seat equipped with a three-point seat belt system, the course of the straps can be deduced by symmetry with respect to the median sagittal plane of the body. Computer analysis indicates that the course of the diagonal strap is « symmetrically » the same as for the driver with regard to bone structures. With regard to deep structures, the belt covers the heart and the pericardium to a greater extent for the passenger than driver. Laterally in the thoraco-abdominal region the belt runs across the passenger's spleen (figure 10).

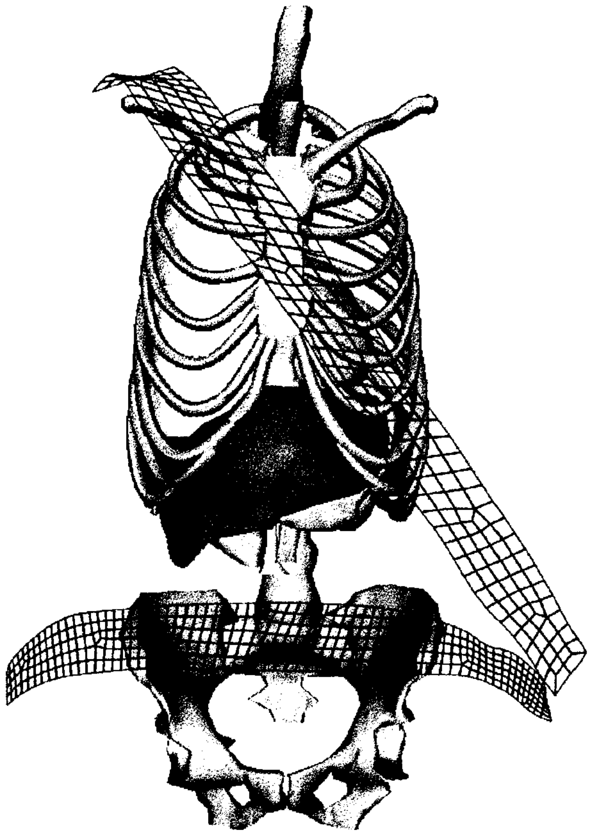

figure 10. Right belted occupant. Anterior view (without the left lung) showing the relations between the seat belt and generated organs.

CONCLUSION

This report describes a method of three-dimensional representation of the human body in the sitting position. This method allows accurate assessment of the relationship between an occupant and interior components of a vehicle. Our work has so far been limited to describing the relationship between the safety belt and underlying components of the thorax, abdomen, and pelvis. We have been able to gain insight into the role of thoraco-abdominal folding and deceleration-induced movement on injuries observed during collisions.

Three-dimensional reconstruction in the sitting position is interesting for two other reasons. First it allows a geometric definition of anatomical structures and a realistic evaluation of initial organ topography in the sitting position thus improving the biological authenticity of the volume definition of each model organ. Second it provides a digital model to which laws of mechanical behavior can be applied in order to simulate a rider in a passenger vehicle. This type of simulation will allow assessment of the mechanisms underlying collision-related lesions and prediction of the efficacy of future safety devices.

ACKNOWLEDGMENTS

We wish to acknowledge the support of the « Université de la Méditerranée - Marseille - France » for medical assistance. We also wish to acknowledge ECIA « Equipements et Composants pour l'Industrie Automobile - Audincout - France » to help us with technical problems and mainly for realization of driver's seat.

REFERENCES

1. B Biot, R Fauchet, JC De Mauroy, L Josselin, "Etude radiologique de la statique du rachis en position assise". Le siège dans les véhicules de transport, Journées d'étude ONSER, 1984.

2. E Colombini, E Occipinti, "Biomechanical electromyographical and radiological study of seated positions". Ergonomics of Working posture. Published by Taylor & Francis, london, 1986.

3. F Dehner, "Seatbelt injuries of the spine and abdomen". Radium therapy and Nuclear Medicine. 4. 1983. pp. 833-843.

4. S. Ghannouchi, A. Ghorbel, C Cavallero, J Bonnoit, "Anatomy of the seated position. Methodologic approach and initial findings". Surgical-Radiologic Anatomy, volume 15. 1993. pp. 315-319.

5. E Grandjean, W Hunting, "Ergonomics of posture - Review of various problems of standing and sitting posture". Applied ergonomics, volume 8. 1977. pp. 135-140.

6. JR Hill, GM Mackey, AP Morris, MT Smith, S Little, "Car occupant injury patterns with special reference to chest and abdominal injuries to restrained drivers in frontal impact". Proceedings of IRCOBI conference., Verona, Italy. 1992. pp. 357-372.

7. F Kramer, "Abdominal and pelvic injuries of vehicle occupants wearing safety beltss incurred in frontal collisions - Mechanisms and protection". Proceedings of IRCOBI Conference, Berlin, Germany. 1991. pp. 297-308.

8. JJ Keegan, MD Omaha, "Alterations ofthe lumbar curve related to posture and seating". Journal of Bone and Joint Surgery, volume 35. No 3. 1953. pp. 589-603.

9. G Winckler G, "Manuel d'Anatomie Topographique et Fonctionnelle". Masson, Paris. 1974.

THORACIC TRAUMA ASSESSMENT FOR THE HYBRID III DUMMY IN SIMULATED FRONTAL CRASHES

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ABSTRACT

In an effort to better understand thoracic trauma in frontal impacts, sled tests with cadaveric specimens and test dummies in various restraint environments were conducted.

Analysis of the measured mechanical and physiological responses and anthropometric data of the human subjects suggested that for the same mechanical response (either acceleration, deflection, or a combination of both), belt restraint systems have a higher associated injury rate than air bag restraint systems. The *Dichotomous Process* was developed to provide better injury evaluation from measured mechanical parameters without prior knowledge of what restraint system was used. Based on multiple chest deflection measurements, this process first determines whether the chest deflection patterns were localized *(belt like)* or distributed *(bag like)*. It then uses separate injury criteria for each of the two categories.

Analysis of the test data and the first version of the Dichotomous Process has already been presented in the 38th Stapp Car Crash Conference in 1994. This paper presents further validation of the Dichotomous Process and its application to the Hybrid III dummy (with additional chest deflection gages) in vehicle crash tests. Separate injury criteria based on chest acceleration, chest deflection, and age of the cadaver for the *belt like* and *bag like* categories are presented. A relationship to scale internal rib deflections measured on the Hybrid III dummy to represent external deflections of a tensed human chest is presented. A method of eliminating the age parameter from the injury function is also demonstrated.

BACKGROUND

Based on studies in the late sixties and seventies by Stapp [1], Mertz and Gadd [2], and Viano et al. [3], among others, an injury threshold of 60 G's was established for chest acceleration. Experimental studies beginning with Kroell et al. [4-10], found that the risk of thoracic trauma due to frontal blunt impact at the midsternal level was associated with various formulations of the maximum normalized chest deflection, the age of the subject being impacted, and the maximum time rate of change of that chest deflection. Kroell et al. [4,5,11,12] developed average response corridors adjusted for the muscle tensed human using human cadaver and volunteer data. These response corridors were subsequently used in the development of the Hybrid III dummy. [13]

More recent investigations have focused on the extrapolation of this information-- blunt impact to subjects at the midsternal level--to an environment where the subject is restrained by an air bag or a belt system. Backaitis and St-Laurent [14] and Cesari [15,16] loaded the chests of volunteers, Hybrid III dummies, and human cadavers with a diagonal belt and found that the location of the maximum chest deflection was often situated somewhere other than the midsternal location. Matsuoka et al. [17] found that initially positioning the shoulder belt in diverse positions on the Hybrid III's chest results in measuring different maximum chest deflections during sled testing. In part, this difference is a consequence of the Hybrid III having only a single midsternal deflection gage. Katz et al. [18] loaded the chest of the Hybrid III dummy with either a shoulder belt or an air bag and concluded they did not see the chest deflection in the Hybrid III that they expected to see as a result of these loading conditions. Mertz [19] recommended that midsternal chest deflection be limited to 50 mm for shoulder belt loading and to 75 mm for distributed loads such as from an air bag.

Morgan et al. [20] examined 63 simulated frontal impact sled tests with cadaveric specimens in various restraint systems. For this data set, Morgan observed that belt only restraint systems generally had higher thoracic injury rates than air bag only restraint systems for the same level of mechanical response in the human cadaver. In order to provide better injury evaluations from observed mechanical parameters without prior knowledge of what restraint system was being used, a Dichotomous Process was developed. This process first determines the dominant restraint system and then applies different injury criteria for evaluating *belt like* and *bag like* restraints.

To minimize injuries in a combined restraint environment of three point belt and air bags, the interaction of the belt and air bag with the thorax have to be optimized. Mertz [21] investigated the effects of a prescribed set of shoulder belt force limits on head and thoracic responses with and without air bag deployment using an occupant simulation model of the Hybrid III dummy. A 2 kN shoulder belt force limiter was found to substantially reduce thoracic and head injuries.

Kallieris et al. [22] conducted frontal impact sled tests with cadavers and the Hybrid III dummy using a combined 3-point belt and air bag restraint system. For this combined restraint system, they found that the injury pattern remained under the shoulder belt and the chest contours showed high local compression along the shoulder belt path. In order to optimize the air bag-3 point belt combined restraint system, Kallieris force limited the belt and found that for a force limit of 4 kN, cadaveric injury was reduced and the chest deformations were more distributed.

References 20 and 22 suggest that for the same level of loading, localized loading of the chest, as from a belt, causes more cadaver thoracic trauma than distributed loading, as from an air bag. This paper, further develops the Dichotomous Process, which distinguishes between distributed and localized forces applied to the chest, and applies it to vehicle crash tests with Hybrid III dummies.

EXPERIMENTAL SETUP AND TRAUMA RESULTS OF CADAVER TESTS

The details of the cadaver sled test experiments and the results have already been reported in the 38th Stapp Car Crash Conference. A brief overview of the experimental setup and the trauma summary is presented in this section.

Experimental Setup

Human cadaver sled tests were conducted at three Impact Trauma Laboratories: the Medical College of Wisconsin (MCW), the University of Virginia (UVA), and the University of Heidelberg (UH).

Each cadaver was tested once in a laboratory sled impact designed to simulate a vehicle frontal crash. Each cadaver was restrained by one of five possible system configurations at the driver's position: (1) 3 point belt, (2) 2 point belt/knee bolster without lap belt, (3) driver air bag and lap belt, (4) driver air bag/knee bolster without belt, or (5) combined driver air bag and 3 point belt. For each laboratory test, the sled ΔV was chosen to fall in a range from 23-50 kmph. Typical sled pulses are shown in Figure 1 for different ΔVs. Following the sled tests, the cadavers were radiographed and autopsy was performed to delineate any trauma that occurred during the impact event.

The cadavers were fitted with triaxial accelerometers at the first thoracic vertebrae. Chest bands [27, 28] were wrapped around the chest at the location of the fourth and the eighth rib to obtain continuous measurements of chest deformations during impact. The locations of the chest bands relative to the rib cage are shown in Figure 2. The chest band process allowed the continuous calculation of chest contours (at the spatial location of the bands) throughout the impact event.

A total of 63 cadaver sled tests were conducted at the three trauma laboratories. Details of the experimental setup and cadaver preparation have been presented elsewhere. [20, 23-26]. The sled ΔV and restraint system for each cadaver sled test are listed in Appendix A. Table 1 summarizes the number of cadavers tested for each of the given test conditions.

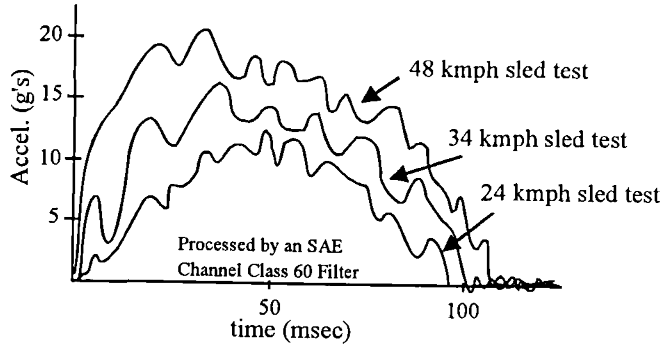

Figure 1. Representation of sled pulses used in the trauma laboratories.

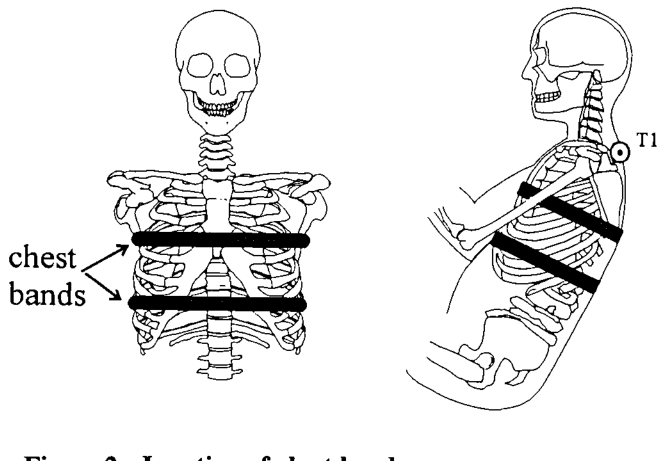

Figure 2. Location of chest bands.

Table 1. Cadaver sled tests by sled ΔV and restraint system

Velocity kmph	Restraint System				
	3 point belt	AB/lap belt	AB/bolster	3 pt belt/AB	2 pt/bolster
23-25	8	0	0	0	0
31-37	3	2	6	2	5
44-50	18	3	7	4	5

Trauma Summary

The AIS 1990 manual was used in evaluating the injury level in the human cadavers. [29] For the 63 cadaver sled tests, the distribution of significant trauma (AIS≥3) in various body regions that was observed at autopsy is summarized in Figure 3. Most of the trauma in the cadavers was either thoracic skeletal fracture or hemo/pneumothorax. In addition, there were nine AIS = 2 soft tissue injuries (spleen or liver lacerations). Most of these soft tissue injuries were observed in the 2 point belt sled tests. Most of the human subjects in the sled tests were 50 years of age or older at the time of death. As in many past cadaver trauma studies, there were more males tested than females.

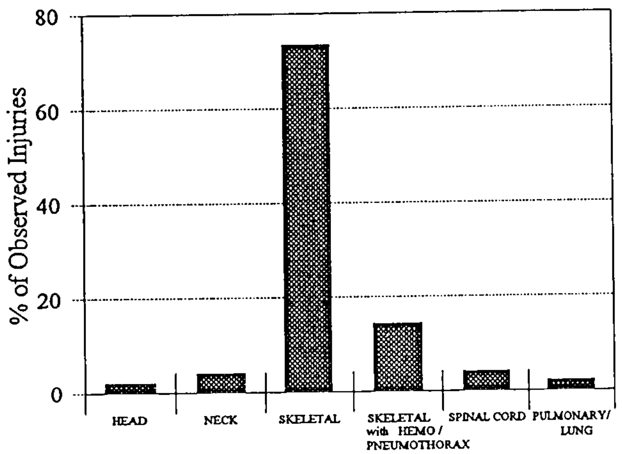

Figure 3. All AIS≥3 injuries in 63 cadaver sled tests.

DIFFERENCES IN BELT AND AIR BAG RESTRAINT PERFORMANCE

The details of the statistical procedures used to analyze the data have already been presented in Reference 20. A brief synopsis of the methods used and some results are presented in this section to acquaint the reader with terminology and concepts.

A categorical AIS classification scheme was used to define the dependent variable. All the cadaver sled tests were divided into two categories: all sled tests with maximum thoracic AIS = {0, 1, 2} were classified into the first category (Cat-AIS=0) and all the sled tests with maximum thoracic AIS = {3, 4, 5, 6} were classified into the second category (Cat-AIS=1). [29, 30]

Probability of injury curves to predict AIS≥3 thoracic trauma for a measured engineering parameter was developed using a 2-parameter Weibull distribution and maximum likelihood method [32, 33, 34]. Probability of injury curves were also developed using other methods such as Logistic regression, Probit, Loglogistic, and Lognormal distributions. These probability curves were found to be similar and all fell within the standard error bounds of the probability of injury curve developed using the Weibull distribution.

During the development of the cadaveric probability of injury curves, the authors found all the cadaver sled tests divided naturally into two groups: (1) predominantly belt restraint tests, and (2) predominantly air bag restraint tests. Regardless of the level of complexity of the predictor functions used in Reference 20, the authors found that there existed an injury bias between the belt restrained population and the air bag restrained population for this data set. The air bag restrained cadavers experience lower injury probabilities for a given response level than the belt restrained cadavers. For example, the probability of AIS ≥ 3 thoracic injury with chest acceleration as the predictor function is shown in Figure 4 for belt restraints and for air bag restraints. The 3-millisecond clip value of resultant chest acceleration of 60 G's results in an 80% probability of cadaver injury with belt restraints while it results in a 33% probability of cadaver injury with air bag restraints.

Examination of typical chest band contours produced in cadavers restrained by the two systems provided a qualitative explanation for this result. That is, cadavers restrained by a torso belt generally experienced larger,

asymmetric, and more localized torso deformations along the path of the belt while the cadavers restrained by an air bag generally experienced smaller, more distributed and symmetric deformations, as shown in Figure 5.

These observations suggested that if an analytical process could first determine if a particular test was *belt like* (localized chest deformations) or *air bag like* (distributed chest deformations), then these two groups could be individually evaluated by either (1) the previously discussed functions and the appropriate probability functions or (2) separately derived injury discriminators and associated probability functions. The biases introduced by attempting to predict injury with one overall general function could then be possibly eliminated. The Dichotomous Process was developed based on this concept.

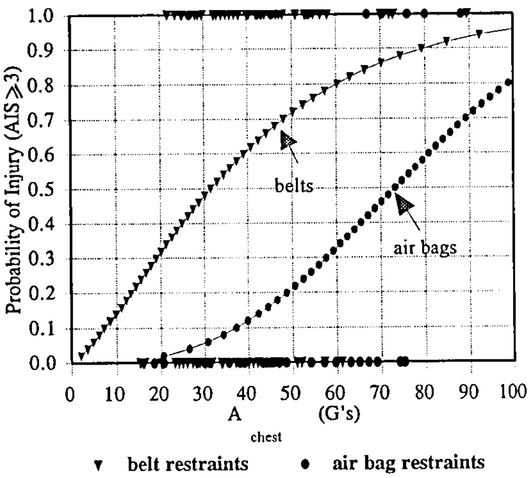

Figure 4. Probability of AIS≥3 thoracic trauma vs. T1 acceleration.

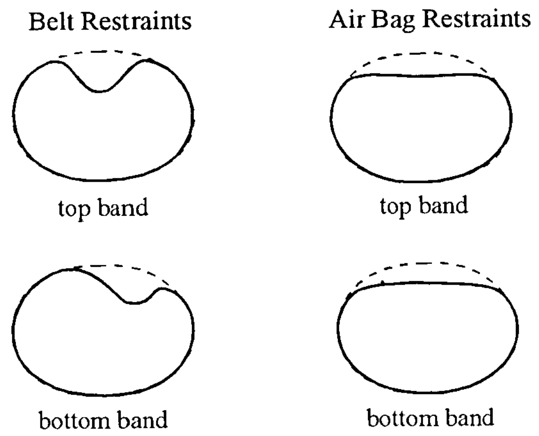

Figure 5. Typical chest band contours of a driver in a frontal impact, restrained by belt or air bag restraints.

DICHOTOMOUS PROCESS

The concept of the Dichotomous Process is shown schematically in Figure 6. Based on chest deformation patterns, the Analytical Sorter classifies a test as *belt like* or *bag like.* Then individual injury criteria are applied to these two categories to determine the probability of injury.

The Analytical Sorter was developed using discriminant analysis to determine a set of independent variables and linear combination of these independent variables that best discriminates between the two categories of restraint systems: *belt like* and *bag like.* This Analytical Sorter uses normalized chest deformation from five locations on the torso to determine whether the chest deformation pattern is *belt like* (localized) or *bag like* (distributed).

The five locations of chest deformation considered in the Dichotomous Process are shown in Figure 7. These locations are analogous to those found in both the advanced ATD and the Hybrid III dummy with four additional deflection measuring gages [37]. A central chest deflection, D_C, is computed at a point located mid-sagittally on the sternum at the level between the fourth and fifth intercostal space and along a straight line from the sternum to the thoracic spine. A second deflection, D_{UL}, is approximately 3.8 cm to the left of, slightly above the first, and along a line initially parallel to the central chest deflection. A third deflection, D_{UR}, is similarly defined to the right of and above the central chest deflection. The lower thoracic deformations D_{LL} and D_{LR} are similarly computed at a lateral distance of 8.3 cm on either side of the sternum at the level of the eighth rib. Each chest deflection is normalized by dividing by the initial thoracic depth of the cadaver at that particular torso location to obtain X_{LL}, X_{LR}, X_{UL}, X_C, and X_{UR}.

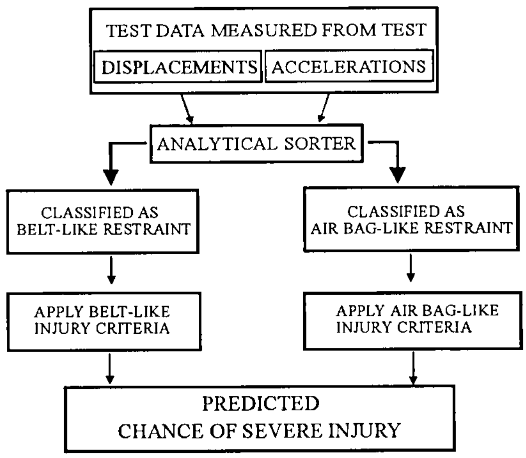

Figure 6. Schematic of the Dichotomous Process.

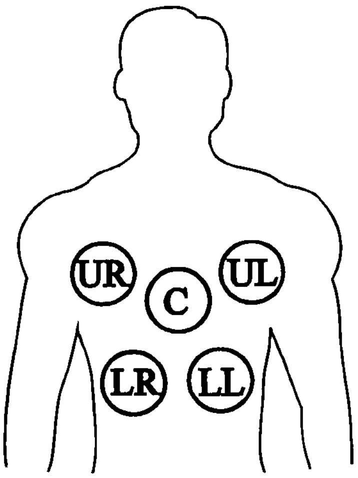

Figure 7. Chest deflections calculated at sites similar to those in the dummy.

The *Analytical Sorter* obtained from discriminant analysis is

$$2.62X_{dia\_dif} + 3.88X_{top\_dif} + 1.91X_{\max\_dif}, \quad (1)$$

where:

$$X_{dia\_dif} = \frac{X_{top\_\max} - X_{bot\_\min}}{X_{\max}},$$

$$X_{top\_dif} = \frac{X_{top\_\max} - X_{top\_\min}}{X_{top\_\max}},$$

$$X_{\max\_dif} = \max\left[\frac{X_{top\_\max} - X_{top\_\min}}{X_{top\_\max}}, \frac{X_{bot\_\max} - X_{bot\_\min}}{X_{bot\_\max}}\right],$$

$$X_{top\_\max} = \max[X_{UL}, X_C, X_{UR}],$$

$$X_{top\_\min} = \min[X_{UL}, X_C, X_{UR}],$$

$$X_{bot\_\max} = \max[X_{LL}, X_{LR}],$$

$$X_{bot\_\min} = \min[X_{LL}, X_{LR}],$$

$$X_{\max} = \max[X_{top\_\max}, X_{bot\_\max}].$$

The sled tests presented in Appendix A were then processed through the Analytical Sorter to determine its ability to classify the tests correctly into *belt like* and *bag like* categories.

Figure 8 shows the 54 cadaver tests (Appendix A) that were classified by the authors into air bag or belt restraint tests plotted against the output of the Analytical Sorter. This figure suggests that there is a critical value or critical region of the Analytical Sorter, (approximately 2.7) above which the test is classified as *belt like* and below which the test is classified as *bag like*. Of the 54 tests submitted to the Analytical Sorter, only 1 author judged belt test was classified as *bag like* and 2 author judged air bag tests were classified as *belt like*. The percentage error in the Analytical Sorter's performance is approximately 5% for this data set.

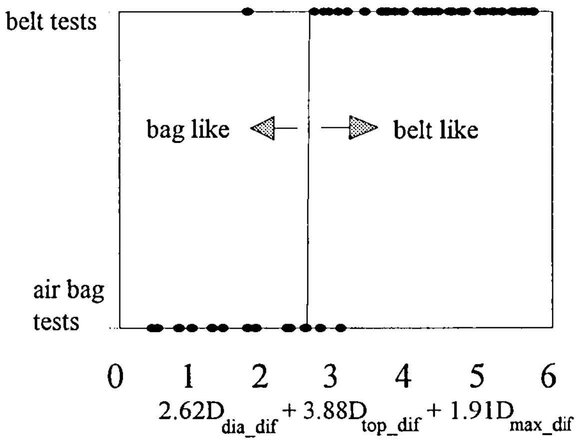

Figure 8. Analytical sorter-to separate belt and air bag restraint tests.

It has been noted in the previous section that for the same level of mechanical response (chest acceleration), the probability of injury is higher for *belt like* tests than *bag like* tests. Hence, in order to provide a better injury prediction model, it is necessary to have separate injury criteria for these two categories.

The authors in Reference 20 found that a linear combination of maximum normalized chest deflection (maximum of the deflections measured at five locations on the chest as shown in Figure 7), $X_{\max}$, 3 millisecond clip value of spinal resultant acceleration, A_{chest}, and age (age of the human subject at the time of death) did a better job of separating trauma into AIS < 3 and AIS ≥ 3 than other injury models. The linear combination was obtained using discriminant analysis and is given by

$$9.9 \times X_{\max} + 0.04 \times A_{chest} + 0.03 \times Age. \quad (2)$$

Using this linear combination as the injury predictor

function, separate probability of injury curves for the *belt like* and *bag like* categories were developed using the maximum likelihood method and the Weibull distribution [20, 32, 33, 34].

Figure 9 presents the probability of injury for all the tests which were classified as *belt like* by the Analytical Sorter. Figure 10 presents the probability of injury for all the tests that were classified as *bag like* by the Analytical Sorter. For the same value of the linear combination (Equation 2), the probability of injury is lower in the *bag like* tests than the *belt like* tests.

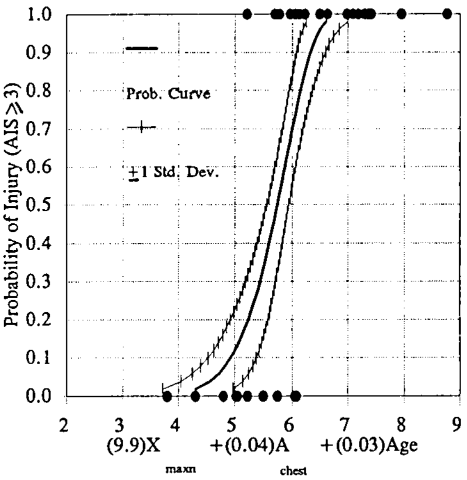

Figure 9. Probability of AIS≥3 thoracic trauma vs. linear combination for *belt like* tests.

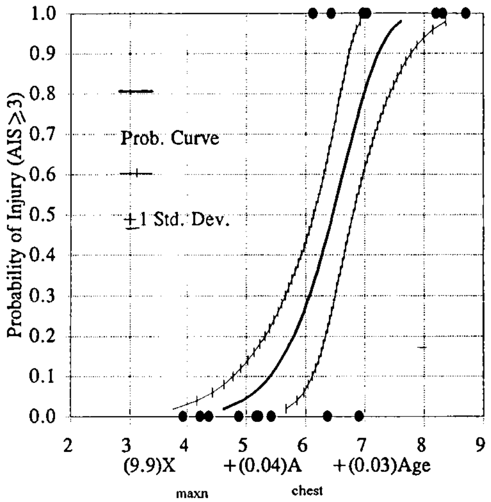

Figure 10. Probability of AIS≥3 thoracic trauma vs. linear combination for *bag like* tests.

The injury predictor function (Equation 2) is based on external chest deflections measured by the chest bands which are wrapped around the cadaver torso. However, the Hybrid III dummy with multiple deflection gages measures internal rib deflections. In order to apply the Dichotomous Process to the Hybrid III dummy, it is necessary to find a relationship between the external cadaver deflections and the dummy internal rib deflections. In addition, the age parameter in the predictor function has to be eliminated when the Dichotomous Process is applied to the Hybrid III dummy.

SCALING OF HYBRID III CHEST DEFLECTIONS TO REPRESENT TENSED HUMAN CHEST DEFLECTIONS

The cadavers in the sled tests used to develop the Dichotomous Process had two chest bands wrapped externally around the torso. The cadaver chest deflections were computed using the curvature data from the chest bands. Hence, the Dichotomous Process is based on external chest deflections (rib deflection+skin deflection).

Human cadavers are flaccid because muscle tensing is lacking. Though no data is available which indicate the frequency, nature, and degree of muscle tensing which typifies vehicle occupants at the onset of an accident, it is reasonable to assume that the average forewarned occupant would be in a tensed condition.

Hence, to extend cadaver data to a more realistic crash environment, it is necessary to adjust the cadaver external deflection (computed from chest band data) to represent muscle tensing.

The Hybrid III dummy with the multiple chest deflection gages has string potentiometers to measure internal rib deflections. In order to predict injury on the Hybrid III dummy using the Dichotomous Process, the internal deflections measured on the Hybrid III dummy have to be scaled to external cadaver deflections which have been adjusted to account for muscle tensing. This section describes the development of a relationship between internal dummy deflections and external cadaver deflections adjusted to account for muscle tensing.

More Background

Kroell et al. [4,5,11,12] developed average response corridors based on 8 cadaver tests at high speed and 3 cadaver tests at low speed. The corridors were developed by taking a ±15% data band around the averaged adjusted cadaver response. The cadaver response was adjusted for muscle tensing by i) uniformly increasing the load levels by 150 lbs to estimate the probable muscle tensing of a car occupant exposed to a collision environment, ii) subtracting 0.5 inches from the chest deflection to account for tissue thickness thereby yielding an estimated sternal deflection.

Kroell et al. [12] showed that none of the dummies available at that time had a response within the cadaver corridors since they were too stiff. Kroell reported approximate thorax stiffness of volunteers in static tests to be 240 N/cm in tensed state and 70 N/cm in relaxed state.

The volunteer tests conducted by Patrick [35] suggested thoracic stiffness is greater in dynamic tests than in static tests. Patrick reported dynamic thoracic stiffness of the tensed volunteer to be 2500 N/cm and of the relaxed volunteer to be 570 N/cm. In this study, Patrick made correction for the soft tissue covering the rib cage by estimating the tissue thickness and the force required to compress the tissue. Skin deflection of 0.76 cm at 1780 N with a parabolic force deflection characteristics was used to determine rib deflections from external chest deflections.

In a study by Stalnaker et al. [36] with similar experimental setup as Patrick, dynamic thoracic stiffness of the cadaver was found to be approximately 2200 N/cm.

Backaitis [14] investigated the differences in thoracic deflections between volunteers and dummies when they are dynamically loaded by diagonal shoulder belts. The average dynamic stiffness of the tensed volunteer was determined to be 1937 N/cm and that of the relaxed volunteer was determined to be 1197 N/cm.

Cesari et al. [15,16] dynamically loaded the thorax of unembalmed cadavers and Hybrid III dummies in a controlled manner using a similar setup as that used by Backaitis [14] and is shown in Figure 11. In all the tests, thoracic external deformations were measured using string potentiometers and two chest bands.

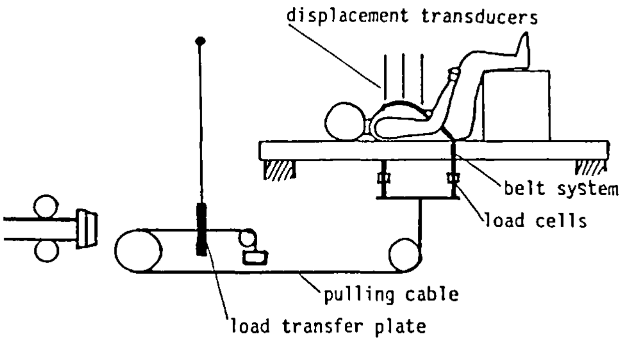

Figure 11. Expermintal setup used in References 14, 15, and 16.

A detailed analysis of Cesari's data was conducted and is presented in this section. The objective of this analysis was to get a relationship between the internal rib deflections measured by the string potentiometers of the Hybrid III dummy and the external cadaver deflections measured by chest bands under similar dynamic loading environments.

Establishing a relationship between external cadaver chest deflections and Hybrid III internal chest deflection

In the tests conducted by Cesari [15,16], the human surrogate was placed horizontally on its back on a rigid table with the legs in a sitting position. A thoracic seat belt was placed diagonally across the thorax from the left clavicle to the right lower ribs. The thoracic belt was pulled dynamically by the impulse of a dynamic impactor. The two chest bands located at the top and bottom of the thorax as shown in Figure 12 enabled determination of the changes in the chest external contour during the dynamic loading. The external displacement linear transducers, also shown in Figure 12, were also used to measure external chest deflection as the belt loaded the chest. The chest deformation measured at point 1 in Figure 12 corresponds to D_C (mid-sternal deflections) as shown in Figure 7. The chest deformation measured at point 8 in Figure 12 corresponds to D_{LR} (lower right chest deflection) in Figure 7. The most extensive deformations were located at points 1 and 8.

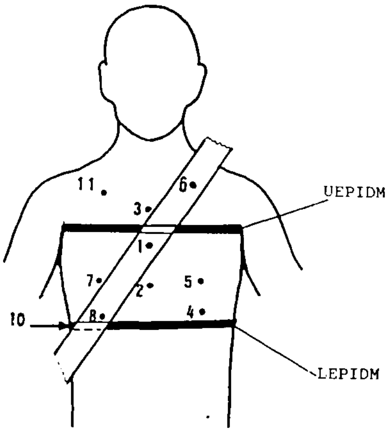

Figure 12. Location of chest bands and displacement trancducers on the thorax in References 15 and 16.

The maximum normalized chest deflections recorded by Cesari at point 1 (mid sternal) and at point 8 (right rib 7) were correlated with the maximum belt loads for 9 cadaver tests and 6 Hybrid III tests. The data points shown in Figure 13 were analyzed by linear regression analysis. The regression equations at mid-sternum for the cadaver tests and the Hybrid III dummy tests are:

Cadaver:

$$F_{belt}=33.5(X_C)_{cadaver}-1.89 \qquad (3)$$

Hybrid III Dummy:

$$F_{belt}=55.93(X_C)_{dummy}+0.33$$

where F_{belt} is the belt loads in kN, $(X_C)_{cadaver}$ is the normalized cadaver deflection at mid sternum (normalized with respect to the chest depth), and $(X_C)_{dummy}$ is the normalized dummy rib deflection at mid sternum (normalized with respect to chest depth without the outer skin= 20.6 cm). The average chest depth of the nine cadavers is 19.7 cm. The normalized cadaver deflection $(X_C)_{cadaver}$ can be replaced by $(D_C)_{cadaver}$ / 19.7 in Equation 3, where D_C is the maximum cadaver chest deflection at midsternum. Similarly the normalized dummy deflections can be replaced by $(D_C)_{dummy}$ / 20.6, where $(D_C)_{dummy}$ is the maximum dummy chest deflection at midsternum. Equation 3 can then be written as

Cadaver:

$$F_{belt}=1.7(D_C)_{cadaver}-1.89 \qquad (4)$$

Hybrid III Dummy:

$$F_{belt}=2.77(D_C)_{dummy}+0.33$$

Equation 4 suggests that the stiffness of the cadaver is 1.7 kN/cm. Similarly, the stiffness of the dummy is 2.7 kN/cm. The dummy is 1.6 times stiffer than the cadaver. The dummy stiffness is similar to the stiffness of the tensed volunteer reported by Patrick [33].

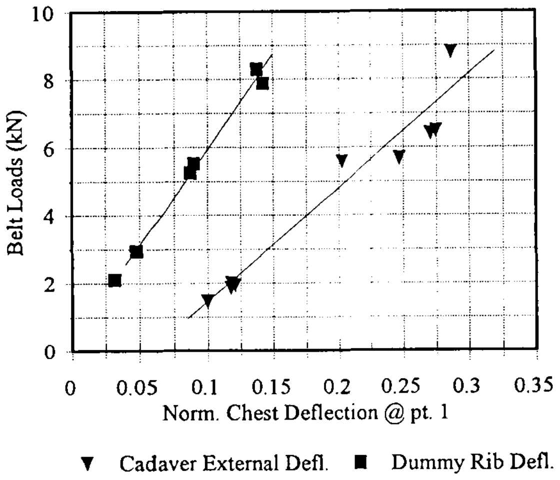

Figure 13. Normalized chest deflections at point 1 vs. belt loads (using Cesari's data [15,16].)

For the same level of belt loads on the Hybrid III and cadaver chests, the relationship between $(X_C)_{cadaver}$ and $(X_C)_{dummy}$ at mid-sternum is

$$33.52(X_C)_{cadaver}-1.89 = F_{belt} = 55.93(X_C)_{cadaver}+0.327$$

$$\therefore (X_C)_{cadaver}=1.67(X_C)_{dummy}+0.066 \qquad (5)$$

Following a similar procedure, the linear regression equations for $(X_{LR})_{cadaver}$ and $(X_{LR})_{dummy}$ at point 8 (figure 14) are

Cadaver:

$$F_{belt}=30.58(X_{LR})_{cadaver}-1.58 \qquad (6)$$

Hybrid III Dummy:

$$F_{belt}=51.2(X_{LR})_{dummy}+0.23$$

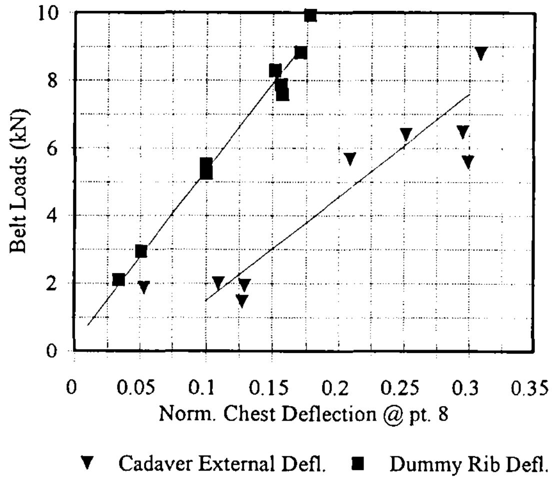

Figure 14. Normalized chest deflections at point 8 vs. Belt loads (using Cesari's data [15,16].)

For the same level of belt load on the Hybrid III dummy and the cadaver, the relationship between $(X_{LR})_{cadaver}$ and $(X_{LR})_{dummy}$ at point 8 is

$$(X_{LR})_{cadaver}=1.67(X_{LR})_{dummy}+0.059 \qquad (7)$$

The relationship between $(X_{LR})_{cadaver}$ and $(X_{LR})_{dummy}$ is similar to the relationship between $(X_C)_{cadaver}$ and $(X_C)_{dummy}$. This suggests that the same relationship in Equation 3 may be valid at all the locations of the string potentiometers.

Adjusting Cadaver Deflections for Muscle Tensing

The average cadaver dynamic thoracic stiffness in Cesari's tests [15,16] is 1.7 kN/cm (Equation 4). Using a similar test setup as Cesari, Backaitis reported average dynamic thoracic stiffness of tensed volunteers to be 1.94 kN/cm [14]. Hence, the ratio of the average thoracic stiffness of a cadaver to that of a tensed volunteer in a dynamic belt loading environment is 0.88 (=1.7/1.94).

Patrick [35] reported tensed volunteer thoracic stiffness in dynamic blunt impacts to be 2.5 kN/cm. Stalnaker [36] reported cadaver thoracic stiffness in the same impact environment as Patrick to be 2.2 kN/cm. Again, the ratio of dynamic thoracic stiffness of a cadaver to that of a tensed volunteer under blunt impacts is 0.88 (=2.2/2.5).

Therefore, Equation 3 was adjusted so as to reflect muscle tensing by dividing the coefficient for $(X_C)_{cadaver}$ by 0.88 (Figure 15), thereby yielding

Cadaver with muscle tensing:

$$F_{belt} = 38.1 (X_C)_{cadaver+tensed} - 1.89 \quad (8)$$

Then the relationship between Hybrid III dummy normalized internal rib deflections and cadaver normalized external chest deflections adjusted for muscle tensing is

$$(X_C)_{cadaver+tensed} = 1.47 (X_C)_{dummy} + 0.058 \quad (9)$$

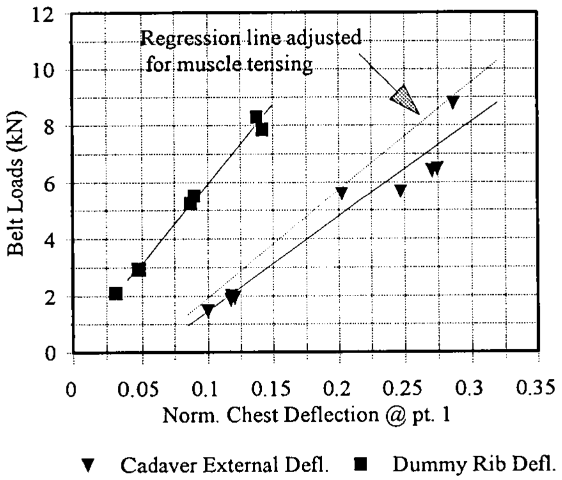

Figure 15. Normalized chest deflections vs. belt loads for Hybrid III and cadavers (adjusted for muscle tensing.)

The relationship in Equation 9 between cadaver external chest deflections at mid-sternum adjusted for muscle tensing and dummy rib deflections at mid-sternum is expected to be the same at all five locations on the chest shown in Figure 7.

ELIMINATING THE AGE PARAMETER IN THE INJURY PREDICTOR FUNCTION

In general, there is a strong influence of age on cadaver data. This is reflected in that the discriminant analysis picked age as one of the parameters in the linear combination (Equation 2) which best discriminates between AIS < 3 and AIS ≥ 3 thoracic trauma. However, while applying the injury predictor function to dummies, the age parameter has to be eliminated.

The probability curves can be transformed to be independent of age by considering the age distribution of the population at risk. The age distribution of the USA population exposed to frontal collisions based on NASS files is shown in Figure 16. To transform the probability curves, an algorithm is followed in which for each value of $(9.9\ X_{max} + 0.04\ A_{chest})$, the age term is expanded in terms of the population distribution shown in Figure 16 to obtain a new probability of injury number for each value of $(9.9\ X_{max} + 0.04\ A_{chest})$.

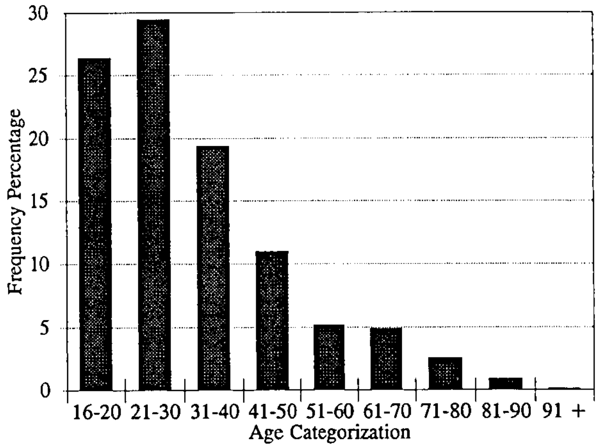

Figure 16. Frequency distribution of age in frontal impacts. (NASS files)

The probability of injury curves for *belt like* and *bag like* tests shown in Figures 9 and 10 were transformed using this algorithm to eliminate the age parameter and are presented in Figures 17 and 18. These curves then represent the probability of injury that a population with the age distribution of Figure 16 would have when experiencing an impact of a severity classified by the injury predictor function $(9.9\ X_{max} + 0.04\ A_{chest})$.

As already presented in the trauma summary, the

average age of the cadavers in the sled tests is much higher than the average age of the population at risk shown in Figure 16. Therefore, eliminating age in the predictor function reduces the probability of injury for the same value of $(9.9\ X_{max} + 0.04\ A_{chest})$.

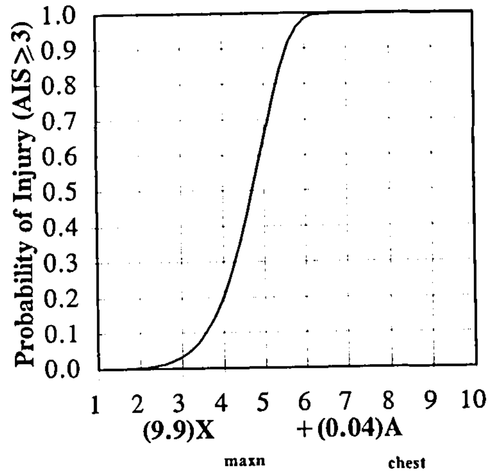

Figure 17. Probability of AIS≥3 thoracic trauma (adjusted for age) for *belt like* tests.

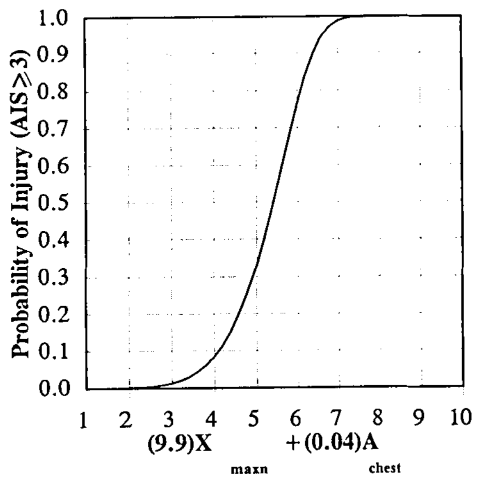

Figure 18. Probability of AIS≥3 thoracic trauma (adjusted for age) for *bag like* tests.

Having eliminated the age parameter in the injury function and developed a relationship to transform dummy rib deflections to reflect tensed human chest deflections, the Dichotomous Process was applied to the Hybrid III dummy in vehicle crash tests.

APPLICATION OF THE DICHOTOMOUS PROCESS TO VEHICLE CRASH TESTS

Five vehicle crash tests involving a Chevy Corsica were used to test the Dichotomous Process. The details of these tests are shown in Tables 2 and 3.

Tests 1 and 3 are of the same test configuration (Vehicle to Vehicle crash of a Chevy Corsica into a Honda Accord at 30 degrees impact angle and 50% overlap). The velocity change ΔV of the Corsica in Test 1 is 53 kmph while that in Test 3 is 62 kmph. Tests 2 and 4 are collinear vehicle to vehicle crashes of a Chevy Corsica into a Honda Accord with a ΔV of the Corsica of 60 kmph. The overlap in Test 2 is 50% while that in Test 4 is 70%. Test 5 is a full frontal fixed rigid barrier crash test of a Corsica at 65 kmph change in velocity.

The crash tests are presented in Tables 2 and 3 in the order of increasing crash severity. The severity of the crash is based on ΔV and the overlap percentage. Increase in ΔV and overlap percentage increases peak vehicle acceleration and decreases crash pulse duration, and therefore increases crash severity. Test 1 is the least severe due to the lowest ΔV. Tests 2, 3, 4, and 5 are in the order of increasing severity due to increase in overlap percentage. Though test 3 and test 2 are of similar ΔV and overlap percentage, test 3 is more severe than test 2 since 30° oblique offset crash tests have been noted to be more severe than similar collinear offset crash tests [40].

The Hybrid III dummy analyzed was located in the driver's seat of the Chevy Corsica and was restrained by a 3 point belt and an air bag. The Hybrid III dummy was equipped with the additional chest deflection gages.

The chest accelerations and the chest deflections measured on the Hyrbid III dummy for these tests are presented in Table 3. When chest acceleration alone or central chest deflection alone is used for determining the probability of AIS≥3 thoracic injury, the order of crash severity is disparate from that noted above. With chest acceleration alone, Test 3 (oblique offset crash) produces higher probability of thoracic injury (from Reference 20) than Test 5 (rigid full frontal rigid barrier crash). With central chest deflection alone, the probability of injury (assuming the greater the central chest deflection, the higher the risk) in Test 3 is the same as that of Test 1 though there is a large difference in impact energy levels between Test 3 at ΔV=62 kmph and Test 1 at ΔV=53 kmph. Hence, chest acceleration alone or central chest deflection alone appear to order the crash tests differently from the order of crash severity noted earlier. The dichotomous process was then applied to these five crash tests to determine probability of thoracic trauma.

Based on the multiple chest deflection measurements of the Hybrid III dummy in the drivers position of the

Table 2. Frontal Impact Vehicle Crash Tests

Test No.	Test Type	ΔV kmph	overlap %	Impact angle
1	VTV	53	50	30°
2	VTV	60	50	0°
3	VTV	62	50	30°
4	VTV	61	70	0°
5	VTB	65	100	0°

VTV= vehicle to vehicle crash test. In all the VTV tests, vehicle 1 was a Chevy Corsica and vehicle 2 was a Honda Accord. The change in velocity (ΔV) noted on the table is that of the Chevy Corsica.
VTB= vehicle to rigid barrier test.

TABLE 3. Response of the Hybrid III Dummy in Vehicle Crash Tests

Test No.	Chest Deflection (cm)					Sorter	Rest. Type	A_{chest} (G's)	$(X_C)_{cadaver+tense}$	Injury Func	Prob. Injury
	UL	C	UR	LL	LR						
1	1.52	1.68	2.38	0.84	1.52	3.94	belt	37	0.235	3.8	0.13
2	2.95	2.97	3.15	1.47	1.65	1.87	bag	42	0.290	4.5	0.15
3	1.8	1.68	2.36	0.63	0.58	3.97	belt	76	0.233	5.3	0.78
4	2.79	3.4	3.58	1.37	2.36	3.25	belt	57	0.32	5.4	0.8
5	2.84	2.79	4.42	1.01	2.84	4.67	belt	60	0.38	6.2	0.98

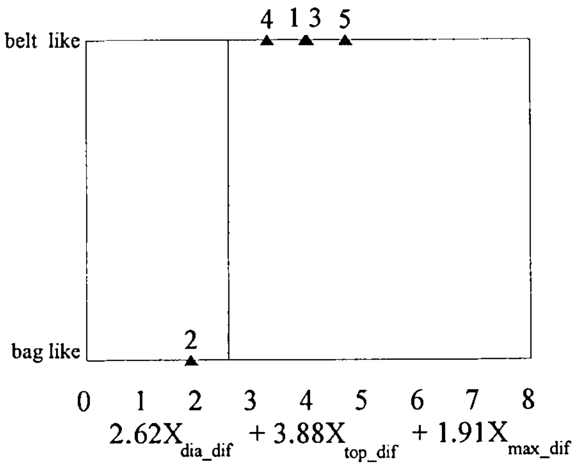

Figure 19. Classification of the vehicle tests by the Analytical Sorter into *belt like* and *bag like* categories.

Chevy Corsica, the Analytical Sorter of the Dichotomous Process was used to classify the crash tests as *belt like* or *bag like*. Figure 19 presents the crash tests classified into the two categories by the Analytical Sorter.

In general it has been noted in sled tests that in a combined belt and air bag restraint condition, the dominant restraint is always the belt [22]. Hence, all the crashes of the Chevy Corsica were classified as *belt like* except for Test 2. It is expected that at 50% overlap in collinear crashes, there is significant intrusion of the steering column and interior which would result in the dummy interacting with the air bag far earlier and to a greater extent than in the other crash tests. Hence, Test 2 was classified as *bag like* by the Analytical Sorter.

The mechanical measurements from the Hybrid III dummies were then used to determine the probability of AIS≥3 thoracic injury using the separate probability curves for the *belt like* and *bag like* categories presented in Figures 17 and 18. Table 3 presents the 3 millisecond clip

value of maximum chest acceleration of the Hybrid III dummy and the scaled maximum normalized dummy rib deflections to represent chest deflections of a tensed human thorax ($(X_C)_{cadaver+tensed}$ in Equation 9). Using these values, the linear combination was calculated and the probability of injury was determined from the appropriate curves in Figures 17 and 18. The maximum probability of injury was in the full frontal rigid barrier crash (Test 5) followed by the 70% overlap collinear crash (Test 4). The order of increasing probability of AIS≥3 thoracic trauma using the dichotomous process is the same as the order of crash severity noted earlier for these five tests.

Though the dichotomous process appears to order the five crash tests according to the severity of crash, the calculated probability of injury seem to be higher than that found in actual crashes. While detailed autopsy was used to determine rib fractures in the cadaver sled tests, only standard clinical X-rays are used to determine rib fractures in trauma centers.

Some investigators have expressed concern because cadaver impact studies report more rib fractures than are found in accident files for crashes of similar severity. This disparity in the number of rib fractures can be partially explained by a difference in procedure. [38] Standard clinical X-rays performed prior to an autopsy identify roughly one-fifth of the rib fractures subsequently found during the autopsy in cadaver studies. A recent review of blunt trauma patients found that roughly 84% of missed injuries were fractures. [39] Hence, the injuries reported in the cadaver tests may be as much as 6.7 times higher than those reported by trauma centers.

This disparity in the assessment of injuries in cadaver tests and trauma centers is a probable cause of higher probability of injury predicted by the dichotomous process than that found in actual crashes of similar severity.

DISCUSSION

This paper presents further investigation of the Dichotomous Process which was already presented at the 38th Stapp Car Crash Conference in 1994. A more robust Dichotomous Process was developed that better distinguishes between *belt like* and *bag like* tests.

Separate injury criteria for the *belt like* and *bag like* categories were developed using the same injury predictor function. This injury predictor function is based on maximum normalized chest deflections, maximum chest acceleration, and the age of the subject.

The explicit age parameter in the injury predictor function was eliminated by considering the age distribution of the population at risk in frontal crashes from NASS files. Therefore, the injury criteria adjusted for age, for the *belt like* and *bag like* categories, is only a function of maximum normalized chest deflection and maximum chest acceleration.

A scaling relationship was developed which scales Hybrid III dummy rib deflections to represent external deflections of a tensed human thorax. These scaled deflections were then used with the injury criteria (adjusted for age) to predict thoracic trauma for a Hybrid III dummy.

Five vehicle crash tests with Hybrid III dummy were examined. Chest acceleration alone or central chest deflection alone as an injury predictor do not order the tests according to their presumed crash severity levels.

The Dichotomous Process was then applied to these five vehicle crash tests and it was demonstrated that the Dichotomous Process sorts the tests into *belt like* and *bag like* and correctly assigns the probability of injury in the same severity order as expected from the crash tests.

The probability of injury using the dichotomous process is higher than those reported in actual crashes. Disparity in the assessment of injuries in cadaver tests and in trauma centers has been identified as a probable cause. A method of scaling the injuries in cadaver tests to represent those reported by trauma centers is required so that the developed probability of injury curves can reflect injury severity levels in actual crashes.

Having successfully applied the dichotomous process to the Hybrid III dummy, future studies will involve the application of the dichotomous process to the advanced ATD.

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REFERENCES

1. Stapp, J. P., "Voluntary Human Tolerance Levels," *Impact Injury and Crash Protection*, ed. Gurdjian, Lange, Patrick, and Thomas, published by Charles C. Thomas, 1970.

2. Mertz, H. J., and Gadd, C. W., "Thoracic Tolerance to Whole-Body Deceleration (710852)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

3. Viano, D. C., Schreck, J. W., and States, J. D., "Dive Impact Tests and Medical Aspects of a 70 Year Old Stunt Diver," Nineteenth Conference of the American Association for Automotive Medicine, November 1975.

4. Kroell, C. K., Schneider, D. C., and Nahum, A. M., "Impact Tolerance and Response of the Human Thorax (710851)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

5. Kroell, C. K., Schneider, D. C., and Nahum, A. M., "Impact Tolerance and Response of the Human Thorax II (741187)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

6. Nahum, A. N., Schneider, D. S., and Kroell, C. K., "Cadaver Skeletal Response to Blunt Thoracic Impact (751150)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

7. Neathery, R. F., Kroell, C. K., and Mertz, H. J., "Prediction of Thoracic Injury from Dummy Responses (751151)," Nineteenth Stapp Car Crash Conference, November 1975.

8. Kroell, C. K., Pope, M. E., Viano, D. C., Warner, C. Y., and Allen, S. D., "Interrelationship of Velocity and Chest Compression in Blunt Thoracic Impact to Swine (811016)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

9. Kroell, C. K., Allen, S. D., Warner, C. Y., and Perl, T. R., "Interrelationship of Velocity and Chest Compression in Blunt Thoracic Impact to Swine II (861881)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

10. Lau, I. V., and Viano, D. C., "The Viscous Criterion -- Bases and Applications of an Injury Severity Index for Soft Tissues (861882)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

11. Neathery, R. F., "Analysis of Chest Impact Response Data and Scaled Performance Recommendations (741188)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

12. Lobdell, T.E., Kroell, C.K., Schneider, D.C., and Hering, W.E., "Impact Response of the Human Thorax," *Human Impact Response Measurement and Simulation*,eds. W. F. King and H. J. Mertz, Plenum Press, New York, 1973.

13. Foster, J. K., Kortge, J. O., and Wolanin, M. J., "Hybrid III -- A Biomechanically-Based Crash Test Dummy (770938)," Twenty-First Stapp Car Crash Conference, October 1977.

14. Backaitis, S. H., and St-Laurent, A., "Chest Deflection Characteristics of Volunteers and Hybrid III Dummies (861884)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

15. Cesari, D., and Bouquet, R., "Behaviour of Human Surrogates Thorax Under Belt Loading (902310)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

16 D. Cesari, R. Bouquet, "Comparison of Hybrid III and Human Cadaver Thorax Deformations Loaded by a Thoracic Belt," Proceedings of the Thirty-Eighth Stapp Car Crash Conference, 1994.

17. Matsuoka, F., Kumagai, K, and Takahashi, H., "Problem and Improvement of Hybrid III Dummy Rib Cage Features," Twelfth International Technical Conference on Experimental Safety Vehicles, June 1989.

18. Katz, E., Grosch, L., and Kassing, L., "Chest Compression Response of a Modified Hybrid III with Different Restraint Systems (872215)," Thirty-First Stapp Car Crash Conference, November 1987.

19. Mertz, H. J., "Injury Assessment Values for Hybrid III Chest Measurements in Frontal Impacts," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

20. Morgan, R. M., et al., "Thoracic Trauma Assessment Formulations for Restrained Drivers in Simulated Frontal Impacts (942206)," Thirty-Eighth Stapp Car Crash Conference, 1994.

21. Mertz, H. J. Williamson, J. E., Vanger Lugt, D. A., "The Effect of Limiting Shoulder Belt Load with Air Bag Restraint (950886)," SAE Exposition, February, 1995.

22. Kallieris, D. et al., "On the Synergism of the Driver Air Bag and the 3-Point Belt in Frontal Collisions (952700)," Thirty-Ninth Stapp Car Crash Conference, November, 1995.

23. Yoganandan, N., Skrade, D., Pintar, F. A, Reinartz, J., and Sances, A., "Thoracic Deformation Contours in a Frontal Impact (912891)," *Biomechanics of*

Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

24. Yoganandan, N., Pintar, F. A., Skrade, D., Chmiel, W., Reinartz, J. M., and Sances, A., "Thoracic Biomechanics with Air Bag Restraint (933121),"*Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

25. Crandall, J. R., Pilkey, W. D., Klopp, G. S., Sieveka, E., Morgan, R. M., Eppinger, R. H., Kuppa, S. M., and Sharpless, C. L., "A Comparison of Two and Three Point Belt Restraint Systems," Proceedings of the Twenty-Second International IRCOBI Conference on the Biomechanics of Impact, September 1994.

26. Kallieris, D., Stein, K. M., Mattern, R., Morgan, R., and Eppinger, R., "The Effectiveness of Active and Passive Restraint Systems for Driver Protection in Frontal Collisions," Thirty-Eighth Stapp Car Crash Conference, October 1994.

27. Eppinger, R. H., "On the Development of a Deformation Measurement System and Its Application Toward Developing Mechanically Based Injury Indices (892426)," *Biomechanics of Impact Injury and Injury Tolerances of the Thorax-Shoulder Complex*, ed. Stanley Backaitis, SAE Publication PT-45, Society of Automotive Engineers, Inc., Warrendale, PA, 1994.

28. Hagedorn, A. V., Eppinger, R. H., Morgan, R. M., Pritz, H. B., and Khaewpong, N., "Application of a Deformation Measurement System to Biomechanical Systems," Proceedings of the Nineteenth International IRCOBI Conference on the Biomechanics of Impact, September 1991.

29. *The Abbreviated Injury Scale*, Association for the Advancement of Automotive Medicine, Morton Grove, Illinois, 1990 Revision.

30. Hair, J. F., Anderson, R. E., and Tatham, R. L., *Multivariate Data Analysis, Second Edition*, Macmillan Publishing Company, 1987.

31. *SAS/STAT User's Guide, Version 6, Fourth edition* , SAS Institute Inc., SAS Campus Drive, Cary, North Carolina, USA, 1990.

32. Hertz, E.: *A Note on the Head Injury Criterion (HIC) as a Predictor of the Risk of Skull Fracture*, Thirty-Seventh Annual Proceedings of the Association for the Advancement of Automotive Medicine, November, 1993.

33. Koch, M, "Recent Work with a Method for the Fitting of Injury versus Exposure Data into a Risk Function," International Research Council of Biokinetics of Impact, Germany, September 1988.

34. Mann, N.R., Schafer, R.E., Singpurwalla, N.D.: *Methods for Statistical Analysis of Reliability of Life Data*, John Wiley & Sons, 1974.

35. Patrick, L. M., "Impact Force-Deflection of the Human Thorax," Twenty-Fifth Stapp Car Crash Conference, 1981.

36. Stalnaker, R. L., McElhaney, J. H., Roberts, V. L., Trollope, M. L., "Human Torso Response to Blunt Trauma," Symposium on Human Impact Response-Measurement and Simulation," ed: W. F. King and H. J. Mertz, Plenum press, 1973.

37. Pritz, H. B., "Development and Evaluation of Hybrid III Multi-Point Thoracic Deflection Measurement Sensors," US Department of Transportation Final Report No. DOT HS 807-948, May 1990.

38. Yoganandan, N., et al, "Evaluation of Thoracic Trauma in a Frontal Impact," Fourteenth Intl. Tech. Conf. Enhanced Safety of Vehicles, May 1994.

39. Rizoli, S. B., and Boulanger, B.R., "Injuries Missed Druing Initial Assessment of Blunt Multisystem Trauma Patients," Thirty-Seventh Annual Proceedings of the Association for the Advancement of Automotive Medicine, November 1993.

40. Stucki, S. L., Ragland, C., Hennessey, B., Hollowell, T., Fessahaie, O., "NHTSA's Improved Frontal Protection Research Program," SAE International Congress & Exposition, February, 1995, SAE Paper No. 950497.

Appendix A

The purpose of this appendix is to present the details of the the 63 human cadaver sled tests used in this paper. The tests in the shaded rows were not used in the analysis.

Test Number	Vel. kph	Restraint	Occ. Age (yrs)	Occ. sex	Occ. Wt. (kg)	max thor AIS	no. rib FX	A_{chest} (g's)	Max. Normalized Chest Defl.					Instantaneous Velocity (m/s)				
									UL	C	UR	LL	LR	UL	C	UR	LL	LR
UH9013	48	3PT	34	M	71	0	0	27	0.41	0.42	0.26	0.10	0.09	4.06	4.06	2.62	5.45	1.50
UH9014	48	ABG/KNE	31	M	70	0	0	35	0.20	0.19	0.12	0.07	0.12	2.16	2.16	1.33	1.45	2.60
UH9207	48	ABG/KNE	25	M	74	0	0	48	0.08	0.10	0.11	0.10	0.13	1.16	1.37	1.18	1.30	1.52
UH9212	48	ABG/KNE	38	M	79	0	0	46	0.13	0.15	0.15	0.13	0.07	2.02	2.04	2.16	2.28	1.77
UH9216	48	3PT	20	M	86	2	0	34	0.25	0.18	0.10	0.11	0.10	2.23	2.62	2.16	0.70	0.97
UH9309	49	3PT	29	M	69	2	2	38	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UH9310	47	3PT	52	F	68	2	1	29	0.30	0.27	0.19	0.02	0.13	2.31	1.97	1.47	0.78	1.37
UH9311	48	3PT/ABG	47	F	76	2	0	31	0.23	0.23	0.14	0.04	0.19	2.19	2.17	1.61	1.00	1.36
UH9312	48	3PT/ABG	32	M	85	2	3	32	0.13	0.16	0.15	0.02	0.17	1.88	2.13	1.56	0.98	1.57
UVA25	47	3PT	63	M	75	4	13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UVA47	33	3PT	65	M	66	1	1	NA	0.16	0.21	0.27	0.13	0.15	1.65	1.51	1.65	0.73	1.55
UVA48	34	3PT	75	M	99	3	8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UVA53	35	2PT/KNE	61	F	61	4	19	38	0.25	0.31	0.39	0.12	0.07	3.98	2.73	2.60	1.11	1.65
UVA55	37	2PT/KNE	52	F	90	3	12	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UVA61	47	3PT	62	M	67	4	19	43	0.19	0.28	0.28	0.29	0.33	2.12	3.21	3.23	4.66	2.81
UVA66	48	3PT	57	M	51	4	17	NA	0.29	0.29	0.26	0.13	0.24	3.30	2.51	2.48	1.62	2.91
UVA77	32	ABG/LAP	69	M	119	4	10	NA	NA	5.8	NA	NA	NA	NA	NA	NA	NA	NA
UVA79	48	3PT	68	M	67	4	19	42	0.35	0.36	0.19	0.06	0.32	2.52	2.69	2.12	0.89	2.39
UVA93	49	ABG/KNE	66	M	89	4	25	67	0.27	0.33	0.39	0.27	0.32	5.30	6.22	7.14	4.78	5.31

Test Number	Vel. kph	Restraint	Occ. Age (yrs)	Occ. sex	Occ. Wt. (kg)	max thor AIS	no. rib FX	A_{decel} (g's)	Max. Normalized Chest Defl.					Instantaneous Velocity (m/s)				
									UL	C	UR	LL	LR	UL	C	UR	LL	LR
UVA94	50	ABG/KNE	66	F	62	5	18	88	0.25	0.25	0.26	0.23	0.34	1.97	1.93	2.05	3.35	5.38
UVA96	34	ABG/KNE	58	F	97	4	14	111	0.05	0.05	0.05	0.04	0.08	1.00	0.92	1.44	0.83	1.09
UVA97	34	ABG/KNE	67	M	74	5	14	70	0.11	0.13	0.14	0.13	0.13	1.36	1.49	1.53	3.00	1.77
UVA102	33	2PT/KNE	60	M	95	5	19	25	0.22	0.3	0.32	0.06	0.08	3.71	4.61	4.26	1.32	2.22
UVA103	32	2PT/KNE	57	M	102	5	13	NA	0.12	0.15	0.16	0.06	0.08	3.44	5.01	5.69	2.01	2.19
UVA104	32	2PT/KNE	66	F	104	5	11	28	0.40	0.52	0.43	0.04	0.32	2.29	3.08	3.16	0.59	2.84
UVA113	47	2PT/KNE	24	F	57	5	12	43.4	0.33	0.40	0.29	0.12	0.20	1.64	1.92	1.41	0.81	1.65
UVA114	47	2PT/KNE	60	F	65	5	23	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UVA173	25	3PT	61	M	72	3	7	26	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
UVA174	26	3PT	57	F	62	3	12	30	0.24	0.33	0.33	0.03	0.3	2.50	3.21	2.94	0.87	0.71
UVA175	26	3PT	58	M	117	2	3	28	0.27	0.31	0.24	0.05	0.17	2.87	2.88	2.22	0.67	1.66
UVA223	55	2PT/KNE	59	M	61	4	13	47	0.37	0.45	0.26	0.0	0.13	3.00	3.69	2.17	0.69	1.41
UVA224	54	2PT/KNE	58	M	65	4	16	42	0.19	0.33	0.44	0.08	0.13	1.90	2.92	2.96	4.29	1.44
UVA225	53	2PT/KNE	36	M	72	4	16	43	0.35	0.26	0.15	0.08	0.29	4.20	3.59	2.12	1.27	4.16
MCW101	50	3PT	58	M	85	4	10	40	0.10	0.11	0.06	0.11	0.34	3.03	3.46	3.78	2.25	3.70
MCW102	48	3PT	58	M	73	4	12	89	0.17	0.22	0.16	0.14	0.49	3.40	3.71	3.11	1.40	3.13
MCW103	48	3PT	66	M	76	3	8	NA	0.36	0.43	0.36	0.09	0.11	0.67	0.75	0.42	2.04	2.54
MCW104	48	3PT	58	M	70	3	13	40	0.08	0.15	0.19	0.06	0.20	1.52	2.32	2.86	0.96	4.75
MCW105	48	3PT	67	M	73	3	19	73	0.40	0.41	0.37	0.09	0.29	5.67	5.36	4.02	1.35	3.70
MCW106	38	3PT	44	M	90	4	9	53	0.32	0.34	0.31	0.23	0.07	11.99	12.17	9.35	1.65	2.38
MCW107	48	3PT	63	F	77	4	22	47	0.38	0.37	0.26	0.17	0.28	2.53	2.57	2.40	2.19	3.38
MCW108	48	3PT	57	M	73	4	8	55	0.35	0.22	0.12	0.08	0.03	5.56	3.96	2.47	1.43	1.29

Test Number	Vel. kph	Restraint	Occ. Age (yrs)	Occ. sex	Occ. Wt. (kg)	max thor AIS	no. rib FX	A_{chest} (g's)	Max. Normalized Chest Defl.					Instantaneous Velocity (m/s)				
									UL	C	UR	LL	LR	UL	C	UR	LL	LR
MCW109	38	3PT	59	M	91	3	12	32	0.27	0.36	0.46	0.14	0.22	4.70	5.15	4.94	6.54	3.40
MCW110	48	3PT	63	F	61	4	24	56	0.21	0.29	0.34	0.05	0.35	1.52	1.98	2.39	1.08	4.55
MCW111	34	3PT	65	F	75	4	14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
MCW112	48	ABG/LAP	67	F	50	2	3	44	0.14	0.15	0.18	0.11	0.09	2.21	2.23	2.20	2.53	2.91
MCW113	48	ABG/LAP	64	M	70	2	3	43	0.35	0.32	0.29	0.04	0.08	1.98	2.39	2.44	2.27	2.22
MCW114	48	ABG/LAP	58	M	73	0	0	60	0.24	0.23	0.20	0.21	0.14	2.14	2.40	2.53	3.67	2.36
MCW115	48	3PT/ABG	67	F	57	3	13	NA	0.20	0.26	0.30	0.17	0.28	2.14	2.98	2.72	3.46	3.49
MCW116	24	3PT/ABG	68	F	75	4	10	29	0.31	0.24	0.20	0.10	0.11	2.40	1.85	1.49	2.28	2.22
MCW117	23	3PT	76	M	58	3	9	24	0.19	0.25	0.27	0.03	0.17	2.97	3.84	3.42	0.39	1.80
MCW118	47	ABG/KNE	29	F	41	0	0	44	0.20	0.22	0.20	0.15	0.27	1.33	2.12	2.20	1.24	3.15
MCW119	45	ABG/KNE	71	M	81	4	11	54	0.20	0.24	0.28	0.34	0.42	7.47	7.27	5.88	8.24	3.86
MCW120	24	3PT	51	M	66	3	8	22	0.40	0.36	0.28	0.26	0.22	2.50	2.50	2.29	2.45	2.29
MCW121	25	3PT	67	M	66	0	0	16	0.26	0.23	0.18	0.03	0.09	2.04	1.81	1.70	0.57	1.13
MCW122	24	3PT	81	F	60	2	4	15	0.22	0.24	0.20	0.04	0.13	1.19	1.38	1.21	0.71	1.23
MCW123	24	3PT	67	F	68	2	1	16	0.26	0.22	0.15	0.02	0.16	1.74	1.61	1.17	0.42	1.47
MCW124	32	ABG/KNE	76	M	80	0	0	18	0.16	0.19	0.19	0.24	0.20	3.68	3.21	2.07	3.64	2.68
MCW125	44	ABG/KNE	75	F	85	3	10	46	0.23	0.26	0.27	0.32	0.31	1.67	2.33	2.36	3.71	3.41
MCW126	35	ABG/KNE	64	F	54	3	6	27	0.18	0.18	0.15	0.27	0.37	1.64	1.92	1.29	4.75	5.08
MCW127	34	ABG/KNE	81	M	62	2	3	21	0.12	0.11	0.11	0.14	0.18	1.50	1.30	1.25	1.41	2.42
MCW128	30	3PT/ABG	67	F	46	2	3	23	0.34	0.34	0.26	0.04	0.19	2.27	2.36	2.00	0.38	1.99
MCW129	33	ABG/LAP	59	M	78	3	8	NA	0.15	0.17	0.17	0.19	0.10	1.96	2.24	2.13	4.60	3.38
MCW130	33	ABG/3PT	56	M	63	2	4	NA	0.14	0.19	0.11	0.08	0.18	1.12	1.70	1.28	0.89	1.87

DESIGN AND EVALUATION OF AN INSTRUMENTED ABDOMEN FOR THE NHTSA ADVANCED DUMMY

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ABSTRACT

A dummy abdomen consisting of two sections was designed as a part of an effort to upgrade the biofidelity and measurement capabilities of current generation frontal crash test dummies. The abdomen was designed to mimic the dynamic stiffness of the human abdomen under steering wheel, belt and airbag impacts in an automotive environment. Instrumentation capable of measuring the deformation of the dummy abdomen was also designed and integrated into the abdomen. This presentation will discuss the features of an abdomen and instrumentation system. In addition, tests conducted to evaluate the performance of the system will be described. Results of these tests will be presented. A number of design changes were instituted based on the results from static and dynamic tests. These design changes will be described.

INTRODUCTION

Recently, Rouhana [1989] described the design of an abdominal injury assessment device. This frangible abdominal insert was fabricated from a styrofoam block and was designed to fit the Hybrid III and TAD-50M dummies. It was used to quantify the effects of belt loading on the lower abdomen. This design exhibited a more "human like" force-deflection characteristic when loaded by belts, and was capable of measuring the maximum abdominal deformation. The abdominal insert is frangible and has to be replaced after each test. The insert was not designed to assess injury potential due to the abdomen being loaded by steering wheels and airbags.

Prior to the development of the frangible insert, attempts have been made to design non-frangible, biofidelic abdominal inserts. Mooney and Collins [1986] reported on the development of a foam loaded airbag insert developed for the Hybrid III dummy. This device was designed to assess injury potential due to steering wheel loading, and to relate abdominal compression to the pressure generated in the airbag. Its pressure-deflection response was dependent on shape of the impactor and the location of impact.

More recently, Ishiyama et al. [1994] have reported on the design of an abdominal insert made of Neoprene - 15. These authors also designed and tested a strain gauge based device to measure time-wise compression of the abdomen as it was loaded by a rod shaped impactor. This device was also designed to assess injury potential due to steering wheel. The time-wise deflection of the abdomen was measured by the strain gauge device in the mid-sagittal plane of the abdomen. The authors reported that their device could not be reused when the steel band housing the strain gauges was deformed plastically. Redesign was needed to solve the problem of bending fracture of the steel band. They also pointed out the need to obtain test data to better characterize the impact response of the human abdomen.

As a part of the current dummy design effort funded by the NHTSA, GESAC staff in consultation with NHTSA staff decided to refine the design of dummy abdomen. The goal of the effort was to design a biofidelic, non-frangible device capable of providing time-wise deformation and velocity of deformation data

as the abdomen was loaded by belts, steering wheels, and airbags.

DESIGN OF THE ABDOMEN

As a part of the design procedure, a survey of prior literature was conducted to identify the response characteristics of the abdomen when loaded by steering wheels, belts and airbags at various velocities. The results of this survey are discussed in detail in Rangarajan, et al. [1995] and will be summarized below.

Response of Abdomen to Belt Impacts

Miller [1989] conducted belt loading experiments on anaesthetized pigs to develop response corridors for belt impacts. In addition, Rouhana, et al. [1989] conducted belt loading experiments on porcine cadavers. These data were then self normalized (normalized to account for variation in zoomorphy of test subjects) by Rouhana et al., scaled to human scale and reported by them. The authors report that at the 0.05 level of significance, there were no differences between:

1. Mean porcine cadaver stiffness and mean live anaesthetized porcine stiffness.
2. Mean porcine cadaver stiffness and mean human cadaver stiffness.
3. Mean scaled porcine cadaver stiffness and mean human cadaver stiffness.

However, porcine cadaver data were obtained using standard safety belt material while human cadaver data were obtained using a rigid bar as the loading surface. In addition, impact velocities in the human cadaver study were higher than those in the porcine study. Bearing in mind that there was a paucity of data to define belt loading behavior of human cadavers, the authors defined target stiffness of the abdomen to be 23.0 N/mm.

Response of the abdomen to rod impacts

Cadaver impact tests conducted by Cavanaugh [1986] and Nusholtz [1986] were analyzed in order to obtain response characteristics of the abdomen when impacted by rods and steering wheels.

Cavanaugh conducted impact tests on seated cadavers. A one inch diameter horizontal bar was used to load the abdomen at about the L3 level. Tests were conducted at several impact velocities with impactors with two different masses. Cavanaugh segregated the response of the abdomen into two groups based on impact velocity. Impact velocities in the low speed tests varied from 4.87 m/s to 7.24 m/s with an average of 6.1 m/s. It is possible that in tests conducted by Cavanaugh, the impacting rod engaged only the soft part of the abdomen and the involvement of the rib cage in generating the response was minimal. Therefore, a response corridor for the soft abdomen was obtained from the low speed impact tests conducted by Cavanaugh. This is shown in Fig. 1.

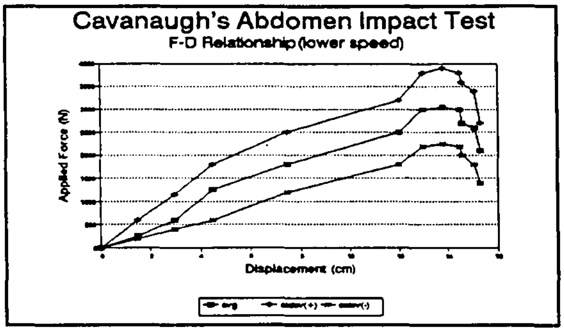

Figure 1. Mean response and corridors for Cavanaugh's low-speed tests.

The average stiffness as seen from Fig.1 is approximately 21 kN/m. This is quite similar to the stiffness of 23 kN/m reported by Rouhana, et al. from their analysis of porcine cadaver and anesthetized porcine data.

Response of the abdomen to steering wheel impacts

Nusholtz et al. [1985] conducted frontal impact tests using unembalmed, re-pressurized human cadavers. Steering wheels were mounted on an impactor weighing 25 lbs and they impacted cadavers seated on tables around the L3 level. The average stiffness was calculated to be approximately 55 kN/m. The average stiffness during the first 4 cm penetration was about 45 kN/m while the stiffness for penetrations greater than 4 cm was about 70 kN/m. This increase in stiffness for higher penetrations probably arises from engagement of steering wheel rim with lower rib structure. Therefore, a response corridor for the abdomen including its interaction with the rib cage was developed from Nusholtz's data which is shown in Fig. 2.

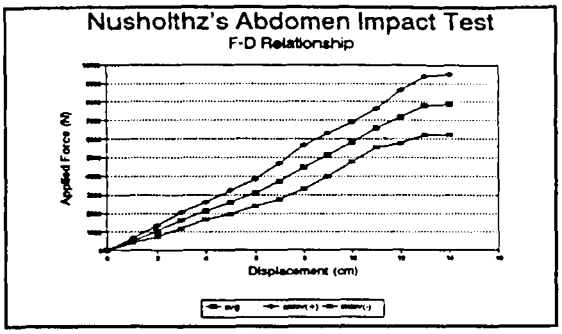

Figure 2. Mean response and corridors for Nusholtz's tests.

Prior to embarking on the design effort a set of design criteria were developed to guide design efforts. These criteria are similar to those proposed by Rouhana et al. [1989] to guide the development of the frangible abdomen. They are as follows:

1. The density of the response element should be such that human like mass and mass distribution are achieved in the design.
2. The design should incorporate elements to measure loads from deploying airbags on the abdomen in addition to belt and steering wheel loads.
3. The force-deflection characteristics of the abdomen must fall into established corridors.
4. The structural integrity of the abdomen must be maintained under loading that can be generated during submarining.
5. Restitution properties of the abdomen should be well tabulated. It should be matched with the restitution properties of the dummy thorax.
6. Batches of material used to design the abdomen should exhibit minimum variability in material properties. The material should be easily machinable or moldable.
7. The abdomen should not generate response when the dummy bends under impact loads. Response should be generated only when the response element is loaded directly.
8. The design should incorporate elements to give indications when the lap belts leave the Anterior Superior Iliac Spine (ASIS).
9. Initially, the abdomen should be designed to fit into the prototype TAD-50M pelvis. This abdomen will be redesigned to fit the final design of the pelvis.
10. The new pelvis-abdomen design should exhibit biofidelic behavior when submarining.

Design of the two-segment abdomen

The rod shaped horizontal impactor used by Cavanaugh probably loaded the soft part of the abdomen near the pelvic cavity. Therefore, it seems reasonable to assume that the response corridors shown in Fig. 1 represents response of the soft abdominal tissue. However, the wheel shaped impactor used by Nusholtz, most probably engaged the ribs as it penetrated the soft part of the abdomen. Thus, it seems reasonable to assume that the corridor shown in Fig. 2 represents the response of a combination of the softer parts of the abdomen and rib cage. This being the case, it was decided that the abdomen should be designed as two separate, upper and lower segments. Figure 3 shows the two abdominal segments integrated with the TAD-50M dummy.

The lower segment closer to the pelvic cavity would respond in a way similar to the response of the soft abdominal tissue. The response of this segment would be defined by the corridor shown in Fig. 1. This corridor will adequately represent the force-deflection response of the lower abdomen at loading rates up to about 7 m/s.

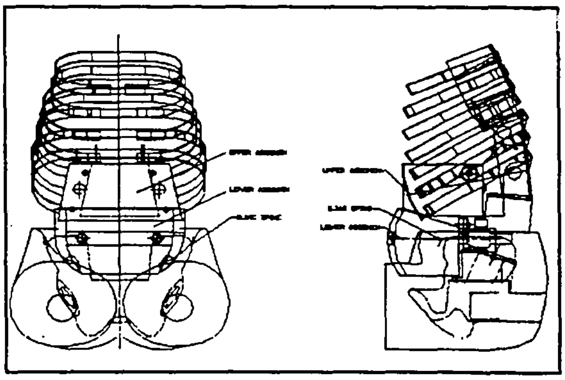

Figure 3. Front and side views showing two abdominal segments integrated in the dummy (TAD-50M).

The upper abdominal segment was attached to the rib cage and its response was influenced by the response of the rib cage. Therefore, the response corridor shown in Fig. 2 would define the response of the upper abdomen. It is believed that the response corridor shown will adequately represent the force-

deflection response of the abdomen/rib cage system in the velocity range of 4 to 13 m/s.

<u>Preliminary design of lower abdominal bag</u> - The lower segment was made of two layers of foam inside a stiff kevlar bag. The foams are commercially available and were chosen using lumped mass modelling techniques and static testing so that the combination provided the desired stiffness. Figures 4 through 6 show the plan, side and frontal views of the lower bag. These figures illustrate the salient features of the design.

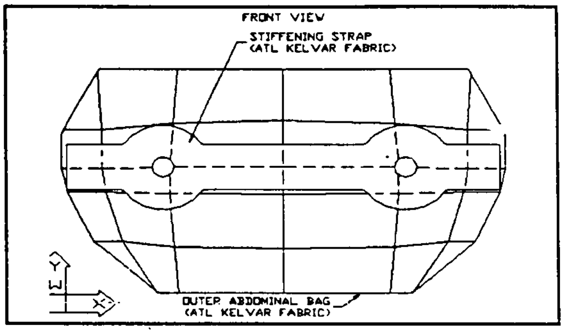

Figure 4. Front view of lower abdomen showing stiffener.

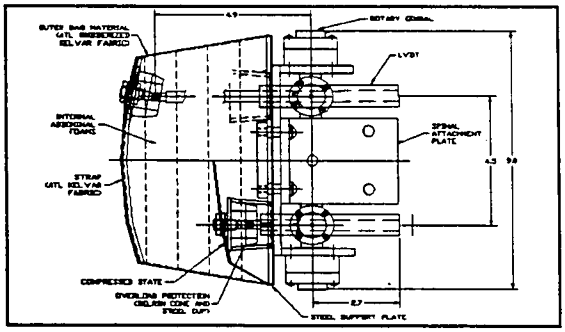

Figure 5. Plan view of lower abdomen.

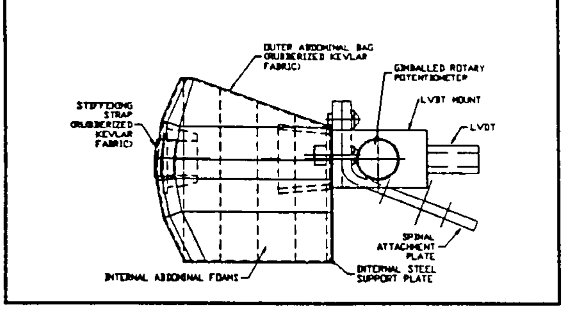

Figure 6. Side view of lower abdomen.

The lower abdomen had a 2" thick base layer foam of L-200 Minicel. A front layer of 3" thickness of the 6# Polyester Urethane was added to the base layer and cut as needed to conform to the desired contour. The foam layers were not glued together. The foam assembly was sealed in a kevlar bag. The lower abdomen incorporated a zipper in the cover material to allow access to the foam and instrumentation inside. The zipper was located in such a way that it crossed the entire bottom side of the lower abdomen bladder and extended approximately 2.5" up each side. The zipper was centered across the lower side of the abdomen so that it extended evenly up each side. The zipper was located with its centerline at a distance of 0.75" from the back edge of the rear support.

A strong glue was used to bond the zipper edges to the abdominal bladder material. The fabric was then sewn together with Kevlar thread. A layer of bladder or gasket material was sewn onto the inside of the upper abdomen bag along one track of the zipper. This acted as a gasket to minimize air leakage through the zipper in the upper abdomen.

The lower abdomen bag was attached to the dummy around the lumbar spine region and sat in the pelvic cavity. The lower bag was instrumented with two linear potentiometers which were attached to the front of the bag. The back of each potentiometer was attached to a double gimbal system. The double gimbal system was instrumented with two rotary potentiometers. Thus, 3-D displacement of the points at which the linear potentiometer is attached to the bag front can be measured as a function of time. The total weight of the abdomen together with the instrumentation system was 2.6 kg.

<u>Design of the upper abdominal bag</u> - Figures 7 through 9 show the plan, side and rear views, respectively of the upper abdomen and illustrate important design features. The abdominal bag was constructed out of Kevlar fabric. Foamex polyurethane open cell foam was used to fill the bag.

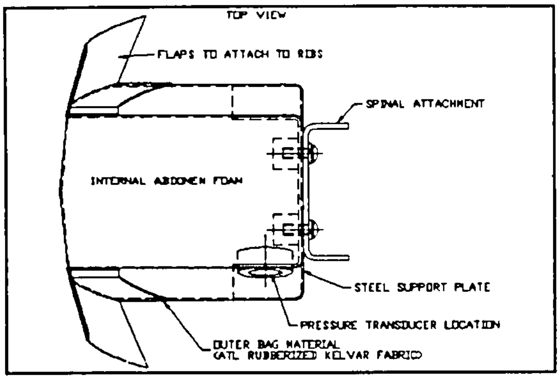

Figure 7. Plan view of the upper abdomen.

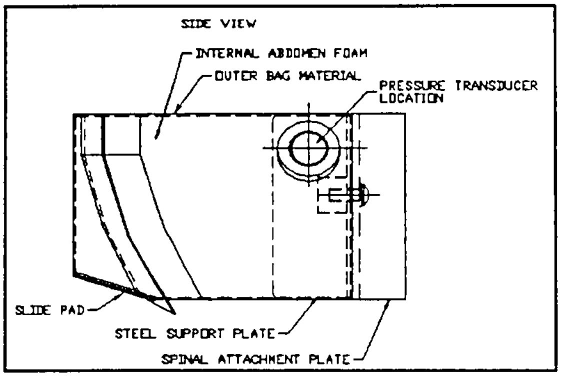

Figure 8. Side view of the upper abdomen.

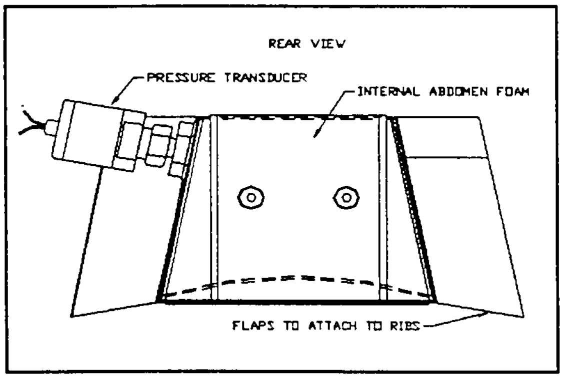

Figure 9. Rear view of upper abdomen.

The abdomen assemblies required a foam thickness of slightly greater than 5" and the foam was only available in 4" thickness. So, the foam was layered in two pieces. The upper abdomen included a constant thickness back piece of 1.5" to 2", which rests flush against the internal bracket. A second piece of foam was then shaped to fill the remaining area. In addition, the back piece of foam was cut 0.25" oversize so that the pieces would compress together slightly upon assembly and hold themselves in place.

Like the lower abdomen assembly, the upper abdomen design also incorporated a zipper for ease of access to the foam and instrumentation. Details of the procedure used to attach the zipper to the bag were similar to those used to attach the zippers to the lower abdomen and have been discussed above. The important difference between the lower and upper abdomen design was that the upper abdominal segment was designed to perform like a sealed, foam loaded airbag and thus efforts were made to ensure that the bag did not leak air. The upper segment instrumented with a pressure transducer was attached to the lower ribs in the front and the lower thoracic spine in the rear. The weight of the upper abdomen together with the pressure transducer was 1.2 kg.

Since the upper abdomen was attached to the ribs and was expected to move with the ribs, the aim was to record pressure in the bag and also the compression of the ribs using the lower DGSPs during tests. The Double Gimballed String Potentiometers (DGSP) were a part of the TAD-50M design.

Test and Evaluation of the Preliminary Design

Static Testing - Both upper and lower abdomens were assembled into the dummy and tested under quasi-static conditions on an Instron machine. Static testing was conducted to ensure proper functioning of the newly designed components. The assemblies were also loaded with various shaped load application heads to examine the effect of their shape on the performance of the abdominal system. Table 1 provides information about the load application heads used in static testing.

Table 1. Shape of Application Heads Used in Static Testing

Indentor Number	Size	Indentor Shape
1A	2" Diameter	Circular Indentor
1B	2" x 6"	Side of Cylinder
2	2" x 6"	Rectangular Indentor
3	1" x 14"	Bar Loading

The test articles were loaded to their maximum compression to evaluate the performance of the overload stops and the instrumentation. Tests were also

repeated to assess durability and repeatability of the design. The stroke of the Instron machine was compared with the compression recorded by the linear potentiometers in the lower abdomen. No problems were noticed during static testing. A series of dynamic tests were then conducted on the test articles. These tests are described below.

In an effort to confirm that the design did not cause spurious chest compression under bending loads, the dummy was seated in a chair and a load applied in the posterior-anterior direction. The signals from the thoracic DGSPs were monitored. Under static conditions, minimal chest compression in response to spinal bending was noted.

Dynamic Testing - Dynamic testing was performed on both the upper and lower abdomen assemblies using a linear impactor. In preparation for the impact, the dummy was seated on a table with the legs extended straight in front and its back unsupported. The arms of the dummy were placed in the raised position. The dummy was positioned at right angles to the impactor head and an upright posture was maintained throughout the testing.

The impactor head was attached to a load cell and accelerometer was attached to the load cell. Another accelerometer was attached to the spine of the dummy on the same plane as the impactor. High speed film and video were used to film the test sequence.

Three different types of impact tests were conducted. In the steering wheel tests, the upper abdomen was loaded by an impactor shaped like the lower half of a steering wheel. The impactor was constructed from tubular steel and had a diameter of approximately 2.54 cm (1"). The wheel was inclined at an angle of 45 degrees. The mass of the impactor was approximately 32 kg. This impactor was similar to the one used by Nusholtz. The location of impact was centered on the upper abdomen. Tests were conducted at 4, 6.5, and 10.8 m/s.

The lower abdomen was loaded using a solid Aluminum rod 30 cm long with a diameter of 2.54 cm. The mass of the impactor was 32 kg. This impactor was similar to the one used by Cavanaugh. The location of impact was approximately at L3 and was centered on the Linear potentiometers of the lower abdomen. Tests were conducted at 4.9, 6, and 7.2 m/s.

The lower abdomen was also loaded with a belt stretched between the arms of a yoke. The seat belt was pre-tensioned slightly to minimize slack in the belt. The mass of the impactor was 32 kg. The location of impact was centered on the linear potentiometers of the lower abdomen. Tests were conducted at 1, 3, and 6 m/s.

A list of all dynamic tests is provided in Table 2.

Table 2. Dynamic Test Conditions

Test Number	Impactor	Target (U / L)	Velocity (m/s)	Film (Y/N)	VCR (Y/N)
5B	SW	U2	6.5	Y	Y
6A	SW	U2	6.5	Y	Y
7A	SW	U2	8.8	Y	Y
7B	SW	U2	9.4	Y	Y
7C	SW	U2	10	N	Y
7D	SW	U2	12.1	Y	Y
8A *1	SW	U2	6.7	Y	N
8B	SW	U2	3.9	N	N
18A	SW	U1	4.0	Y	N
19A	SW	U1	6.5	Y	N
20A	SW	U1	10	Y	N
2A	Rod	L2	4.9	N	Y
3A	Rod	L2	6.0	Y	Y
4A	Rod	L2	7.2	Y	Y
4B	Rod	L2	7.2	Y	Y
9A	Rod	L2	4.0	N	Y
14A	Rod	L1	4.9	Y	N
15A	Rod	L1	4.0	Y	N
16A	Rod	L1	6.0	Y	N
17A	Rod	L1	7.2	Y	Y
10B *2	Belt	L2	3.0	N	N
11A	Belt	L2	6.0	Y	Y
12A *3	Belt	L1	3.3	Y	N
12B	Belt	L1	3.3	N	N
13A	Belt	L1	6.0	Y	N

Notes:
U - Upper abdomen ; L - Lower abdomen
*1 This test was a low hit on the upper abdomen assembly to determine possible problems caused by the gaps between the abdomen assemblies.
*2 Belt Load Cell added to instrumentation for this

test. belt tension increased.
*3 Left Abdominal LVDT malfunction.

In addition, sled tests were conducted to evaluate the dynamic response and robustness of the design.

Test Results and Discussion

This series of tests proved the efficacy of the design and testing approach. Results from the test series indicated that the modelling approach was sound and yielded valuable design guidance. Finally, the models could be used to improve the design post-test, and to overcome some of the shortcomings identified during testing.

Figure 10 shows the response of the second version of the lower abdomen to belt impacts at 3 m/s and 6 m/s. During the 3 m/s impacts, the tension in the belt varied from "very snug" to "not snug" in order to identify the effects of belt tension on the test results. Belt tension was not measured in these tests. In general, it is seen that the response of the foams used in this abdomen was stiffer than the target stiffness. Belt stretch was not measured in these tests.

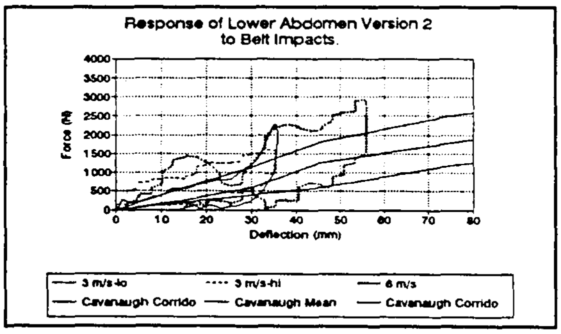

Figure 10. Force-deflection response of lower abdomen to belt impact also showing Cavanaugh low speed corridor.

Figures 11 shows the response of lower abdomen 2 to rod impacts at 4 m/s, 6 m/s and 7.2 m/s while Fig. 12 shows its response to rod impacts at 4.0 m/s and 7.2 m/s respectively. Tests at impact speeds of 4 m/s and 7.2 m/s were repeated after adjusting the linear impactor's stroke to achieve different levels of abdominal compression. Rapid stiffening of the foam in the 4 m/s tests when compression reaches about 60 mm can be attributed to the foam bottoming out.

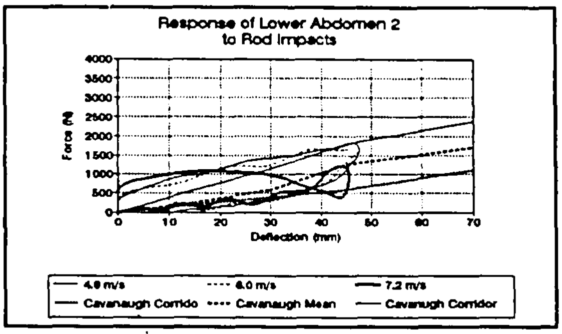

Figure 11. Force-deflection response of abdomen to rod impact also showing Cavanaugh low speed corridor.

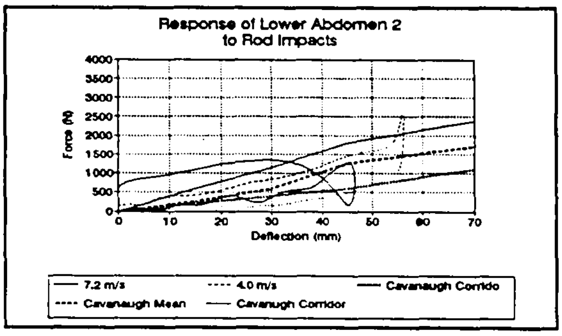

Figure 12. Force-deflection response of abdomen to rod impact also showing Cavanaugh low speed corridor.

The upper abdomen was tested using an impactor shaped like a steering wheel. Pressure-time history from the pressure transducer in the abdomen, force-time history from the impactor load cell and also compression-time history from the left lower DGSP of the TAD-50M were recorded. It is important to point out that the DGSP started responding after the abdomen had been compressed about 25 mm when the lower ribs started moving with the abdomen. It is also important to point out that prior tests conducted on the TAD-50M seemed to suggest that the DGSP could not provide accurate compression information above loading rates of approximately 6-8 m/s.

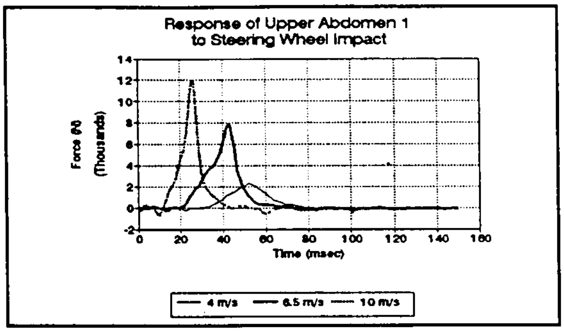

Figure 13. Response of upper abdomen to steering wheel impact force vs time plot.

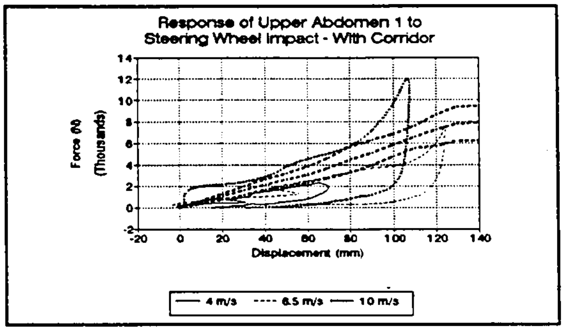

Figure 14. Response of upper abdomen to steering wheel impact with Nuscholtz corridor.

The response of the upper abdomen 1 to steering wheel impact is illustrated in Figs. 13 and 14. These figures show the force - time response of the upper abdomen / lower rib system. The force response of the system was combined with the compression recorded by the left lower DGSP on the TAD-50M to develop the force - deflection response of the system. Figures 12 and 13 also show the Nusholtz corridor which was the performance target for this system. Even though the system appears a bit stiffer than the target, it is to be remembered that the DGSP deflection probably started after the abdomen was compressed about 25 mm. The data plotted in Fig. 13 and 14 were obtained from instantaneous recordings of the DGSP compression and the impactor load cell signals.

Sled tests were also conducted to evaluate the response of the abdominal segments to belt loading on sleds. There was a need to determine if the design would allow the belts to be caught in the crevice between the two abdominal segments during impact tests. Sled tests were conducted at 30 mph. Two tests were conducted with the dummy sitting on a hard seat. In the first test, the dummy was sitting in "normal" seated posture and was restrained by a 3-point belt. In the second tests, the dummy was seated on the same seat but in a slumped posture to promote submarining. Problems with the data acquisition system at the laboratory prevented recording and analysis of dummy response data. Photographic evidence suggests that the dummy behaved normally during impact. However, the lap belt was caught in the crevice between the two abdominal segments when the dummy submarined.

Discussion of Test Results and Design Revisions

A preliminary design of a two-segment dummy abdomen was fabricated and tested. Linear impactor and sled tests were conducted. Rod and steering wheel shaped impactors and a belt stretched between a yoke were used in impact tests. The lower abdomen was instrumented with a linear potentiometer attached to a gimbal system. The upper abdomen was instrumented with pressure transducers.

The design of the abdominal segments was revised based on test results. In this section, test results will be summarized and the revised design will be described.

Design of upper abdomen

Tests of the sealed, foam filled bag used to generate the response of the upper abdomen revealed that its response could vary with impact location. Also, tests revealed that correlating the pressure in the bag with compression would be a difficult task. It was decided not to pursue this concept any further in the near term.

It was also decided to redesign the upper abdomen as a foam filled bag similar in concept to the lower abdomen. However, the foam used to fill the upper abdomen would have to be stiffer than the foam used to fill the lower abdomen in order to meet the Nusholtz corridor. Since the abdomen was not designed as a sealed bag, it was decided that it could be designed as a cordura fabric bag filled with foam. This would make it easier to manufacture the abdomen and also reduce the cost of manufacture.

The design tested had no provision for measuring abdominal compression. It was also decided that in the next design, the upper abdomen would be

instrumented with a high-tension string pot and that an accelerometer be attached to the front of the bag. The accelerometer would be attached to pick up the response of the abdomen to airbag slap. As in the preliminary design, the upper abdomen was to be rigidly attached to the lower rib cage so that compression of the upper abdomen could also be tracked by lower rib displacement measurement system. Figures 15 through 17 show the front, side and top views of the current upper abdomen design together with details of the instrumentation system in place currently. This revised design has been integrated into the advanced dummy and tests are in progress to evaluate the performance of the design.

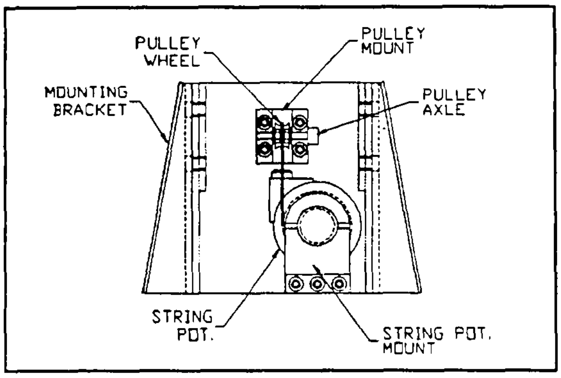

Figure 15. F·ont view of current upper abdomen.

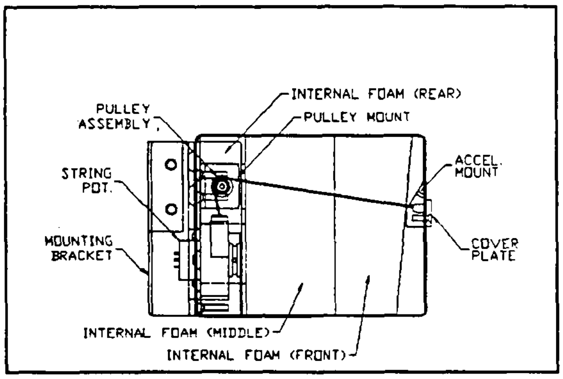

Figure 16. Side view of current upper abdomen.

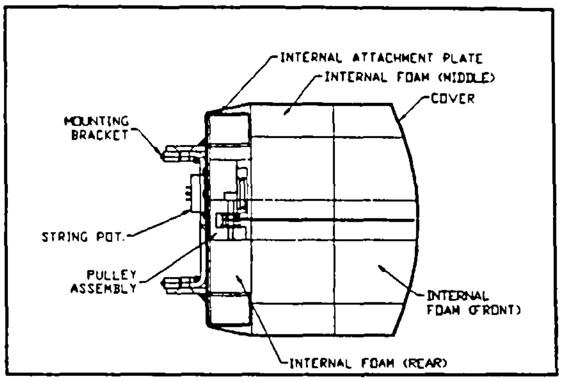

Figure 17. Top view of current upper abdomen.

Design of the lower abdomen - In general, the response of the lower abdominal segments was reasonably close to the target corridors. However, test results showed a need to increase the compression capability of the abdomen. A compression capability of 4 inches was selected as a design goal. This necessitated redesign of the abdominal instrumentation system. The linear potentiometers in the abdomen were replaced with DGSPs. This bag like the upper abdominal bag was to be made of cordura fabric in order to reduce manufacturing time and cost.

Figures 18 and 19 show the top and side view of the current lower abdomen design together with details of the instrumentation system in place currently. The lower abdominal bag has been redesigned, fabricated and integrated into the advanced dummy. A rigorous testing program has been designed to evaluate the performance of this design.

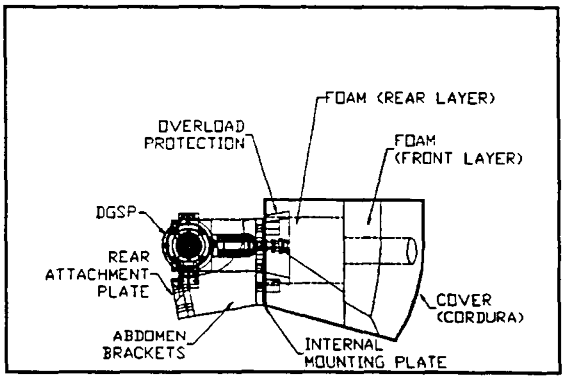

Figure 18. Side view of current lower abdomen.

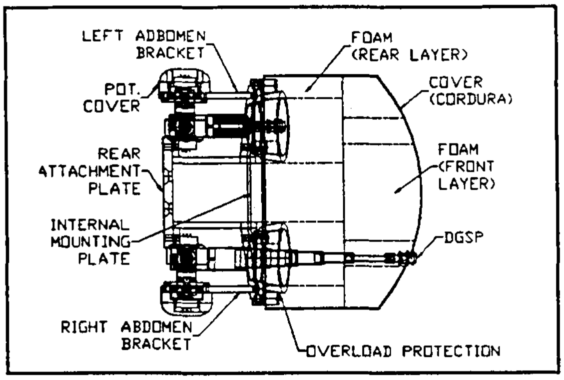

Figure 19. Top view of current lower abdomen.

Design of outer skin - Limited sled tests pointed out the need to shield the gap between the upper and lower abdominal segments from belt intrusion. It was decided to prevent belt intrusion by incorporating two features in the revised design. First, a shaped piece of non-structural foam was inserted into a pouch sewn on top of the lower abdomen bag. Second, an outer skin made of stiff material was designed to cover both abdominal segments. Some details of the shaped foam and the outer skin design are shown in Fig. 20. These concepts will be tested in the near future.

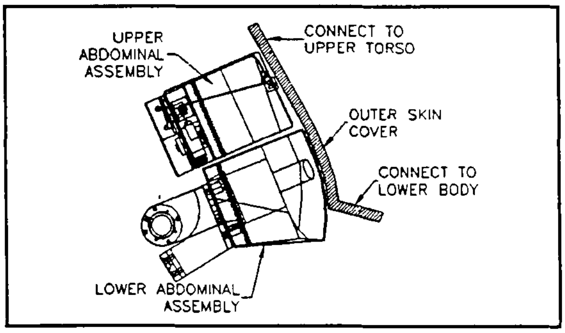

Figure 20. Outer skin covering for abdomen segments.

ACKNOWLEDGEMENT

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REFERENCES

1. Cavanaugh, J.M., G.W. Nyquist, S.J. Goldberg, and A.I. King. 1986. Lower Abdominal Impact Tolerance. Proceedings of the Thirtieth Stapp Car Crash Conference.

2. Ishiyama, S, K.Tsukada, H. Nishigaki, Y. Ikeda, S. Sakuma, F. Matsuoka, Y. Kanno and S. Hayashi. 1994. Development of an Abdominal Deformation Measuring System for Hybrid III Dummy. Proceedings of the thirty-eighth Stapp Car Crash Conference. .265-280.

3. Miller, M.A. 1989. The Biomechanical Response of the Lower Abdomen to Belt Restraint Loading. Journal of Trauma, Vol 29(11).

4. Mooney, M.T. and J.A. Collins. 1986. Abdominal Penetration Measurement Insert for the Hybrid III Dummy. SAE Technical Paper 860653.

5. Nusholtz, G.S., P.S. Kaiker, D.F. Huelke, and B.R. Suggitt. 1985. Thoraco-Abdominal Response to Steering Wheel Impacts. Proceedings of Twenty-Ninth Stapp Car Crash Conference. 221-267.

6. Rouhana, S.W. 1993. Biomechanics of Abdominal Trauma. In Accidental Injury - Biomechanics and Prevention. Ed. Nahum, A.M. and J.W. Melvin. Springer-Verlag. 391-428.

7. Rangarajan, N., T. Shams and Y. Zhao. Design Requirements for Advanced Dummy Abdomen. 1995. Report Submitted to NHTSA/DOT. Contract No. DTNH22-94-C-07010.

8. Rouhana, S.W., D.C. Viano, E.A. Jedrzecjak and J.D. McCleary. 1989. Assessing Submarining and Abdominal Injury Risk in the Hybrid III Family of Dummies. Proceedings of the 33rd Stapp Car Crash Conference. 257-278.

9. Stalnaker, R.L. and M.S. Ulman. 1985. Abdominal Trauma - Review, Response, and Criteria. Proceedings of the Twenty-Ninth Stapp Car Crash Conference. 1-16.

Evaluation of TAD-50M Dummy Prototype Performance in HYGE Sled Tests

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ABSTRACT

This paper describes the results of laboratory evaluation of the thoracic assessment device (leased out by NHTSA under the cooperation research) developed for the advanced anthropomorphic test device and prototyped for the 50th percentile male dummy (TAD-50M) in a HYGE test under relatively severe impact conditions. The advanced thorax has been integrated with the HY-III head, neck, pelvis, and upper and lower extremities. The evaluation program consisted of eight sled tests; five at 30 mph and three at 35 mph, including airbag only, the 3-point seat belt and the 3-point seat belt with airbag systems using a white body of a compact car. The evaluation of the TAD-50M, judged by the comparison with HY-III, in terms of response characteristics found under this study are as follows.

1) HIC of the TAD-50M tends to be smaller than that of the HY-III, due to the difference in spine structure (Thoracic Spine Articulation) which would affect the dummy behavior.
2) Differences in deflection among individual sterna and lower ribs, and between right and left sides, can be measured by using the new thoracic displacement measurement devices. Owing to the above, various types of occupant restraint systems can be evaluated more precisely by using the new thoracic structure.
3) The practical applicability of TAD-50M as a human surrogate would be improved if the difference in shoulder behavior and head behavior of the TAD-50M from those of the HY-III could provide so-called "biofidelity".

INTRODUCTION

Research and Development on advanced dummies was initiated in the USA in the early 1980's, for further enhancement/improvement of HY-III dummies. Similar studies have also started in Europe as well, with active discussions going on in frameworks of ISO, SAE and EEVC regarding performance requirements of impact test dummies which should have characteristics that approximate those of humans. For the development of TAD dummy being pursued under a joint international cooperation with the initiative taken by NHTSA, JARI/JAMA has also decided to participate actively in the R & D work for "easier-to-use advanced dummies" with objectives listed below.

(1) Identification of problems related with the HY-III dummy
(2) Collection of basic data to ensure conformity with dummy design requirements
(3) Timely feedback of improvement measures, etc. based on the data of (2) above to the advanced dummies
(4) Contribution to the development of "easier-to-use dummies".

This paper provides the comparison of impact response between the HY-III and the TAD dummies using the TAD thoracic assessment device prototyped (S/N 002) and leased out by NHTSA, which we incorporated in the HY-III dummy and tested under relatively severe HYGE sled test conditions, as a step forward to attain the objectives mentioned above. Comments on future R & D activities required in relation

to the practical applicability, handling ease, etc. of the TAD dummy, and laboratory evaluation results of the TAD thoracic assessment device are also given in this paper.

DESCRIPTION OF PROTOTYPE

Details of the development of the TAD dummy were already reported in the papers of Schnider, et al. (1992) and Haffner, et al. (1994), while the structure and vital characteristic points of the thoracic assembly used in the tests will be described in the following.

Improved Shoulder - An Improved shoulder mechanism has been designed for the TAD with clavicles that articulate at the top of sternum and translate both forward and rearward due to belt and inertial loading, similar to the pivoting of the human clavicles about the sternoclavicular articulations. Within the clavicles construction, removable nylon shear pins aid in the initial placement of the clavicle. These pins then break under minimal loading to allow uninhibited movement of the clavicle (Fig.1).

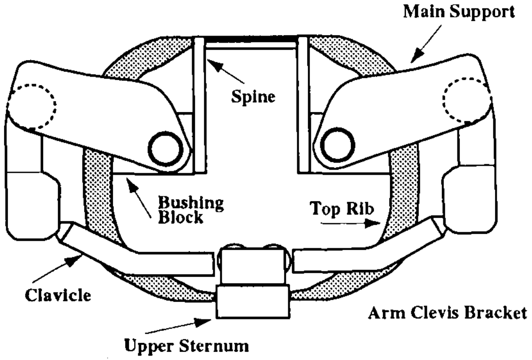

Figure 1. TAD Shoulder and Clavicle

Chest - The TAD thoracic ribcage is more similar to the human shape and structure than the HY-III. The same applies to the shapes of ribs and spines.

Ribs - The number of ribs is increased to seven from six of the HY-III, with the ribs extended to the lateral abdomen (including a representation of the lower ribcage in the liver and spleen area), showing an improved shape closer to that of humans (Fig. 2).

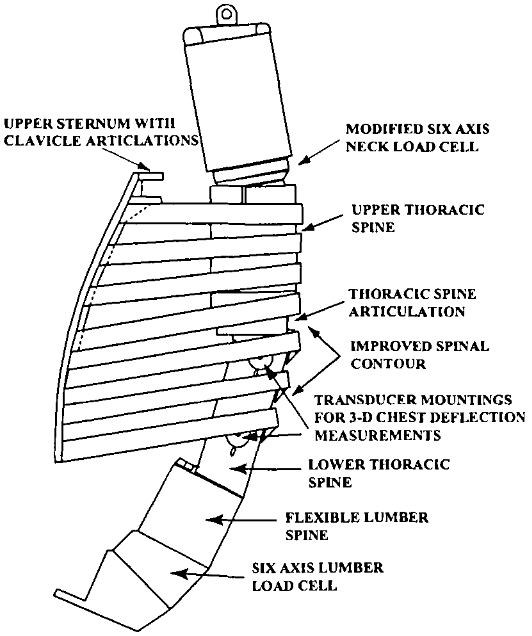

Figure 2. TAD Thorax Structure

Chest Deflection Measuring Instrument - The TAD is equipped with new instrumentation of three-dimensional displacement measurement assembly called a "Double Gimballed Stringpot (DGSP)" (see Fig. 3).

The chest deflection was measured at four points through 12 channels, with 3 channels consisting of a pair capable of measuring both the rotation (biaxial; vertical-horizontal angle) and the displacement (uniaxial; longitudinal length). The four DGSPs were installed at the spines, which were capable of measuring the displacements at the four points of ribs (the third rib corresponding approximately to the level of the fourth/fifth rib innerspace and the sixth rib corresponding to the level of the eighth rib in humans) three-dimensionally.

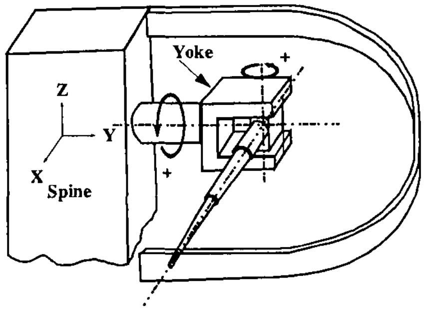

Figure 3. TAD Double Gimballed Stringpot Assembly (DGSP)

Spines - The curved profile of spines from the neck to the pelvis is closer to that in humans. Deformation type links with a similar structure to that of the lumbar are used for the thoracic structure also (Fig. 2).

Abdomen - The frangible abdomen of the TAD-50M was developed as a customized version of the HY-III abdomen specifically designed by Rouhana, et al. (1989, 1990). The abdomen is apt to be compressed intensely by the seat belt, and injuries caused by submarine phenomenon are the main targets of assessment.

Table 1. Sled Test Matrix

Restraint Sys.	Speed	Test No.	Driver	Passenger
Airbag	30 mph	No.1 DTPH A30-1	TAD	HY-III
		No.2 DTPH A30-2	TAD	HY-III
		No.3 DHPT A30	HY-III	TAD
3 P Seat Belt		No.4 DHPT B30	HY-III	TAD
		No.5 DTPH B30	TAD	HY-III
Airbag + 3 P Seat Belt	35 mph	No.7 DHPT AB35-2	HY-III	TAD
		No.8 DTPH AB35	TAD	HY-III
		No.9 DTPH AB35-2	TAD	HY-III

SCOPE OF TEST PROGRAM

The TAD prototype thoracic assembly was incorporated in the existing HY-III dummy and installed on a white body of a Japanese compact passenger car (1500 cc) in HYGE sled tests for evaluation. The TAD dummy and the HY-III dummy were mounted on the driver seat and the front passenger seat, respectively. The dummy restrained conditions were divided into the state with an airbag only and the state with a three-point seat belt only. At the sled velocity of 35 mph, however, the combination of an airbag and a three-point seat belt was also used (see Table 1). Measured items were the acceleration, displacement, load, moment, etc. at each region of dummy, airbag deployed timing, sled acceleration, etc. The pre- and post-series dummy calibrations were conducted at TRC in Ohio prior to leasing from NHTSA and after it was returned to NHTSA from JARI. As for the change in chest conditions per test, component damages and functional changes were checked by visual observation or three-dimensional measurements.

RESULTS

The experiments conducted under this study have covered different occupant restrained conditions ; 1) with an airbag alone and 2) a three-point seat belt alone at the velocity of 30 mph in HYGE sled tests, and 3) the combination of an airbag + a three-point seat belt at the velocity of 35 mph in addition to 1) and 2) above. The responses and dynamics of the TAD and HY-III dummies under those conditions were compared and analyzed for the evaluation of characteristics of the TAD prototype thoracic assembly. The practical applicability of the TAD dummy and issues to be dealt with in the future will be described in the following. Items analyzed in the above are divided into four ; 1) HIC and neck moments, 2) chest deflection, 3) chest acceleration and 4) trajectories. The results of analysis will be discussed for each item per type of occupant restraint system. The outline of the HYGE sled test data of both dummies is shown in Tables 2.1 and 2.2.

1) HIC and Neck Moment

HIC - Fig. 4 show HIC values of TAD and HY-III dummy heads, divided by different types of occupant restraint systems, and a comparison of HIC values between HY-III and TAD dummies. The HIC of TAD dummy tends to show a smaller value than that of HY-III dummy in every test using airbag only, 3-point seat belt only and 3-point seat belt with airbag, which is approximately 0.75 times that of the HY-III dummy. One of the factors would be the differences in spine structure between those dummies. That is, the spines of HY-III dummy is in a rigid structure while the spine of TAD dummy consists of two connected rigid structures, to which the Thoracic Spine Articulation is added (see Fig. 2). Therefore, rigidity between the head/neck and chest of the TAD dummy is lower than that of the HY-III dummy, which presumably resulted in relatively low HIC values of TAD dummy.

Neck Moment - Figs. 5.1 and 5.2 show comparison of time histories of neck moment between the TAD and HY-

Table 2.1. Summary of HYGE Sled Tests (Driver Side)

Configuration	48 kph Tests Air Bag			48 kph Tests 3 Point Belt		56 kph Tests 3 Point Belt with Air Bag		
Test Number	No. 1	No. 2	No. 3	No. 4	No. 5	No. 7	No. 8	No. 9
	DTPH A30-1	DTPH A30-2	DHPT A30	DHPT B30	DTPH B30	DHPT AB35-2	DTPH AB35	DTPH AB35-2
Dummy	TAD	TAD	HY-III	HY-III	TAD	HY-III	TAD	TAD
HIC	371	437	516	1554	1194	1200	741	791
Max Head Result (G)	46	51	54	100	133	83	73	71
Max Chest Result (G)	68	58	48	66	70	80	85	85
Lap Belt Force (N)	-	-	-	9499	7891	10589	8951	8953
Shoulder Belt Force (N)	-	-	-	12229	12257	12061	10935	11123
Chest Pot (mm), HY-III			-50	-47		-49		
Max. Deflections (mm), TAD								
Right Sternum X	-70	-57			-56		-59	-57
Left Sternum X	-57	-53			-28		-39	-44
Right Lower Cage X	-18	-35			-61		-61	-73
Left Lower Cage X	-7	-20			17		17	11
Right Sternum Y	7	3			10		10	-15
Left Sternum Y	10	9			14		16	17
Right Lower Cage Y	14	11			7		-8	-5
Left Lower Cage Y	-5	3			7		9	9
Right Sternum Z	15	7			4		-7	7
Left Sternum Z	18	11			4		-9	7
Right Lower Cage Z	20	8			15		9	13
Left Lower Cage Z	24	13			21		15	16

Table 2.2. Summary of HYGE Sled Tests (Passenger Side)

Configuration	48 kph Tests Air Bag			48 kph Tests 3 Point Belt	56 kph Tests 3 Point Belt with Air Bag		
Test Number	No. 1	No. 2	No. 3	No. 4	No. 7	No. 8	No. 9
	DTPH A30-1	DTPH A30-2	DHPT A30	DHPT B30	DHPT AB35-2	DTPH AB35	DTPH AB35-2
Dummy	HY-III	HY-III	TAD	TAD	TAD	HY-III	HY-III
HIC	432	391	300	904	876	1014	1052
Max Head Result (G)	63	66	57	73	76	74	79
Max Chest Result (G)	54	60	78	70	88	81	85
Lap Belt Force (N)	-	-	-	7025	8315	11010	11998
Shoulder Belt Force (N)	-	-	-	11623	11910	11825	12399
Chest Pot (mm), HY-III	-18	-13				-50	-51
Max. Deflections (mm), TAD							
Right Sternum X			-17	-39	-31		
Left Sternum X			NG	-52	-60		
Right Lower Cage X			7	20	16		
Left Lower Cage X			8	-71	-51		
Right Sternum Y			10	-15	-23		
Left Sternum Y			NG	-7	-19		
Right Lower Cage Y			8	28	-15		
Left Lower Cage Y			9	12	-19		
Right Sternum Z			48	4	10		
Left Sternum Z			NG	10	7		
Right Lower Cage Z			54	24	23		
Left Lower Cage Z			60	23	6		

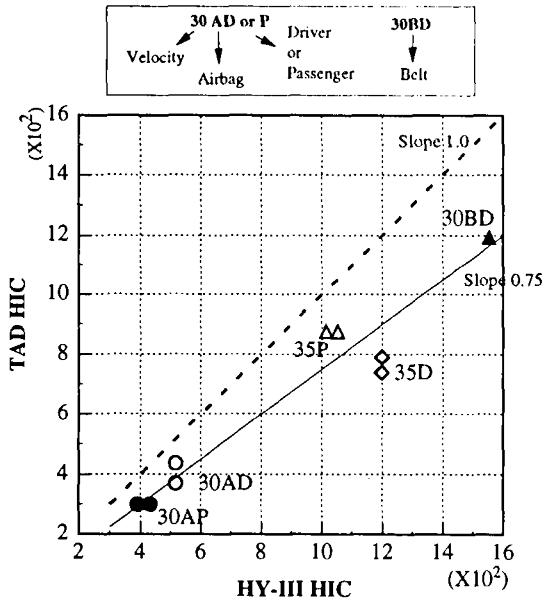

Figure 4. HIC Correlation between TAD and HY-III

III dummies according to different types of occupant restraint systems. In the comparison of neck moment between the TAD and HY-III dummies, the values are higher for the TAD dummy in every type of occupant restraint system. This is presumably due to the difference in the location where the head is initially fitted to the neck. That is, the head-neck fitting location of the HY-III dummy is such that the fitting angle can be adjusted according to various seating postures that may be taken by the occupant, while the fitting angle is fixed in the TAD dummy.

2) Chest Deflection

Chest deflections of both dummies cannot be compared directly, as there are more measuring points for the TAD dummy than the HY-III dummy, with the difference in location of measuring points between them. This can be done, however, by averaging the right and left chest deflections of the TAD dummy and comparing the mean value with the chest deflection of the HY-III dummy at its sternum (chestpot).

__Airbag Only__ - Fig. 6 shows the comparison between the chest deflections of the HY-III dummy at its sternum and the corresponding chest defelection of the TAD dummy (mean value of the right and left sternal

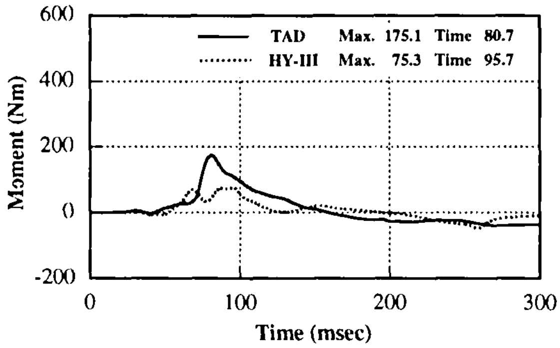

Figure 5.1. Comparison of Upper Neck Moment between TAD-50M and HY-III (30AD)

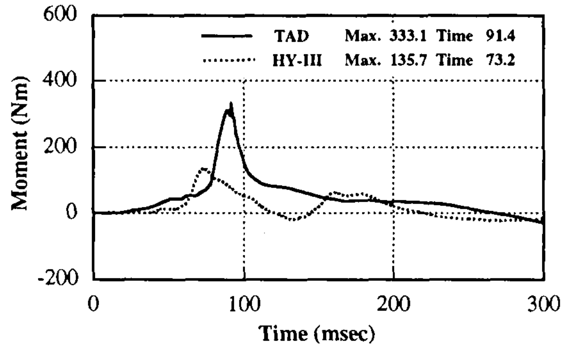

Figure 5.2. Comparison of Upper Neck Moment between TAD-50M and HY-III (30AP)

displacements) shown individually for the driver side and front passenger side. The displacements of the TAD dummy at the driver side are greater than those of HY-III dummy. This is presumably due to the fact that the chest of the TAD dummy is made softer so that the chest

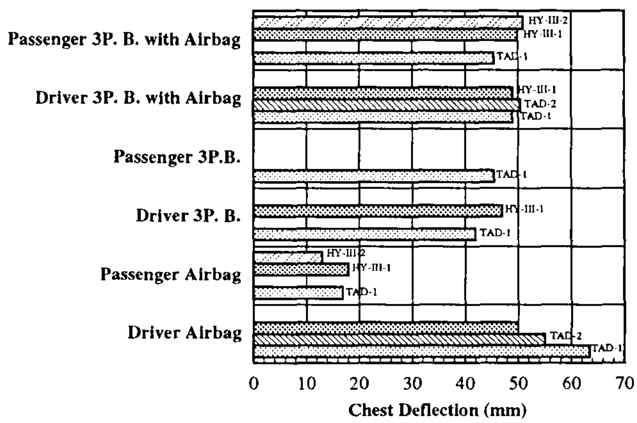

Figure 6. Comparison of Chest Deflection between TAD and HY-III by Three Different Restraint Systems (All Tests)

Driver

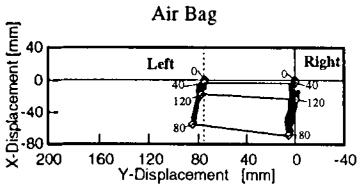

Fig. 7.1 Test No.1 Chest Deflection (A30-1: Driver) Sternal Sensor (Top View)

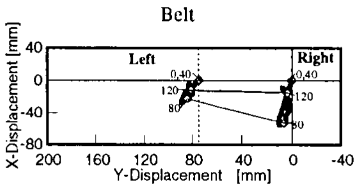

Fig. 7.5 Test No.5 Chest Deflection (B30: Driver) Sternal Sensor (Top View)

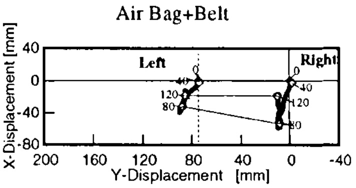

Fig. 7.7 Test No.8 Chest Deflection (AB35-1: Driver) Sternal Sensor (Top View)

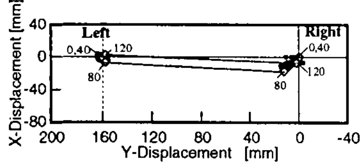

Fig. 7.2 Test No.1 Chest Deflection (A30-1: Driver) Lower Sensor (Top View)

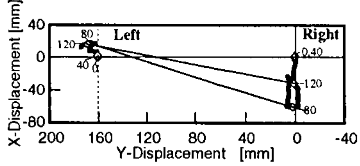

Fig. 7.6 Test No.5 Chest Deflection (B30: Driver) Lower Sensor (Top View)

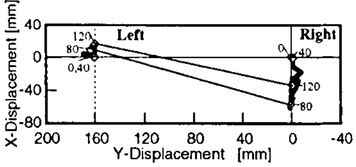

Fig. 7.8 Test No.8 Chest Deflection (AB35-1: Driver) Lower Sensor (Top View)

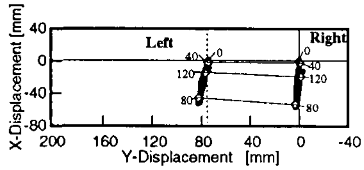

Fig.7.3 Test No.2 Chest Deflection (A30-2: Driver) Sternal Sensor (Top View)

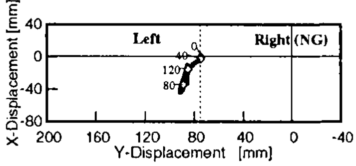

Fig. 7.9 Test No.9 Chest Deflection (AB35-2: Driver) Sternal Sensor (Top View)

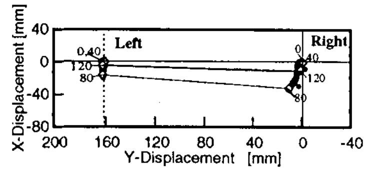

Fig. 7.4 Test No.2 Chest Deflection (A30-2: Driver) Lower Sensor (Top View)

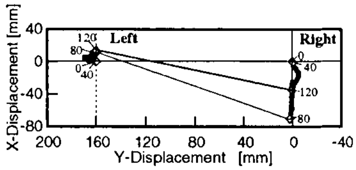

Fig. 7.10 Test No.9 Chest Deflection (AB35-2: Driver) Lower Sensor (Top View)

Passenger

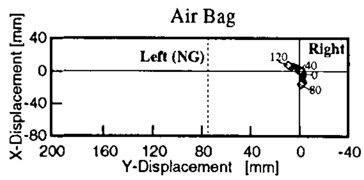

Fig. 7.11 Test No.3 Chest Deflection (A30-2: Passenger) Sternal Sensor (Top View)

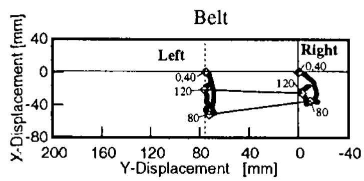

Fig. 7.13 Test No.4 Chest Deflection (B30: Passenger) Sternal Sensor (Top View)

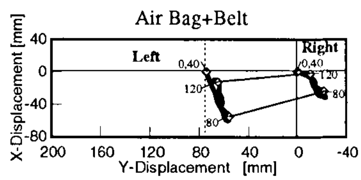

Fig. 7.15 Test No.7 Chest Deflection (AB35-2: Passenger) Sternal Sensor (Top View).

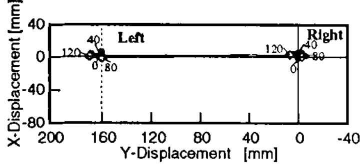

Fig. 7.12 Test No.3 Chest Deflection (A30-2: Passenger) Lower Sensor (Top View)

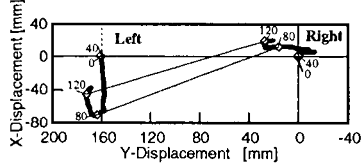

Fig. 7.14 Test No.4 Chest Deflection (B30: Passenger) Lower Sensor (Top View)

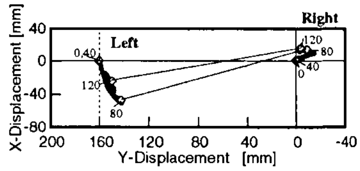

Fig. 7.16 Test No.7 Chest Deflection (AB35-2: Passenger) Lower Sensor (Top View)

load-deflection characteristics would approximate those of humans. As for the front passenger side, on the other hand, a clear tendency could not be determined due to the absence of sufficient comparative data, but the displacements of the TAD dummy tend to become greater as in the case of the driver side. In the TAD dummy, the upper right and left sternal displacements are greater than those of the lower right and left ribs (see Figs. 7.1-7.4, and 7.11-7.12). This is probably because the TAD dummy is more sensitive to loads that act partially, as the ribs are more loosely connected with each other, compared with the ribs of the HY-III dummy, which are connected rigidly with metallic sternum.

<u>3-point Seat Belt Only</u> - Comparing the chest pot sternal displacement of HY-III dummy and the corresponding chest displacement of the TAD dummy (mean value of the right and left sternal displacements) in the same manner as in "Airbag Only", it is found that the displacements tend to become smaller for the TAD dummy (see Fig. 6). It is also found by comparing the chest displacements of the TAD dummy between the right and left sides that the chest on the belt inner side deformed markedly (see Figs. 7.5, 7.6, 7.13 and 7.14). This is a tendency found on both the upper and lower sides. It is presumed that such phenomenon occurred as the shoulder belt slipped to the neck side along the clavicle, as reported already in a paper of Bohlen et. al. (1995) with the vehicle tests that used the TAD dummy. That is, the belt slipped and deviated from the center of the chest around the height of chest displacement measurement (on the upper side), which resulted in one-sided deformation of the chest, and the smaller mean value of the right and left chest displacements for the TAD dummy in comparison to the HY-III dummy.

<u>3-point Seat Belt with Airbag</u> - Roughly the same tendencies as in "3-point Seat Belt Only" were observed (Figs. 7.7-7.10, 7.15 and 7.16).

3) Chest Acceleration

<u>Airbag Only</u> - Figs. 8.1 (driver side) and 8.2 (front passenger side) show the comparison of chest acceleration-time histories between the TAD and HY-III dummies. It is found from the figure that chest acceleration tends to be higher for the TAD dummy. Figs. 9.1 (driver side) and 9.2 (front passenger side) show the relationship between the chest displacement and the chest acceleration, where the chest acceleration at the spine unit against the sled is integrated twice to see the process of the chest kinetic energy absorption by the occupant restraint system, etc. That is, the figures show the above-mentioned relationship in the form of chest acceleration - displacement curves. According to these curves, the rise of chest acceleration is generally less steep for the TAD dummy at both the driver side and the front passenger side, but the acceleration rises more sharply

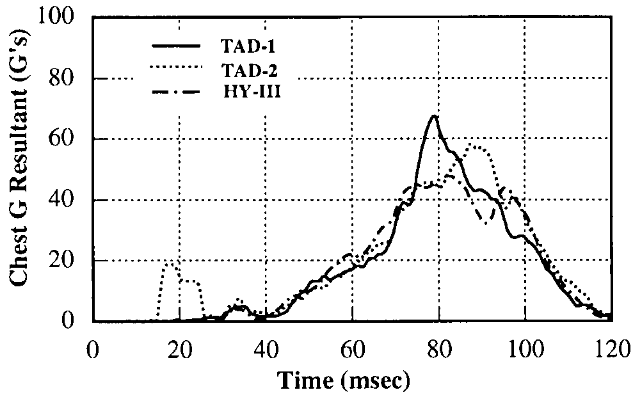

Figure 8.1. Comparison of Chest Acceleration-Time Histories between TAd and HY-III (Driver, Airbag Only; 30mph)

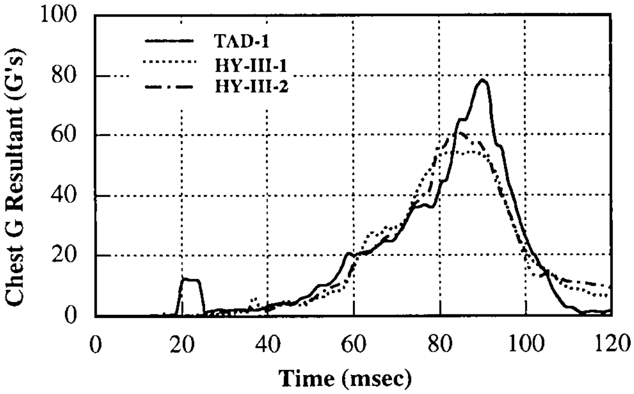

Figure 8.2. Comparison of Chest Acceleration-Time Histories between TAD and HY-III (Passenger, Airbag Only; 30 mph)

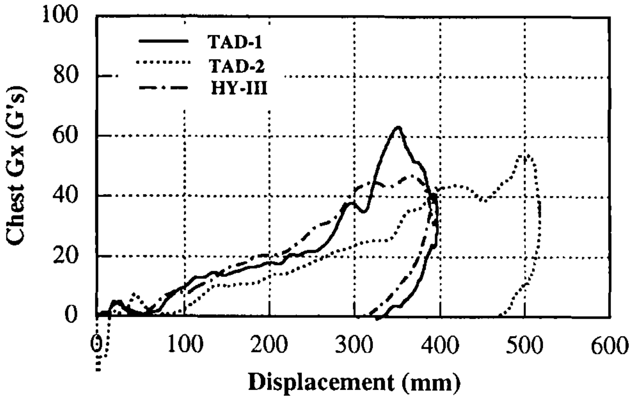

Figure 9.1. Relationship between Chest Displacement (Twice Integrated; Chest vs. Sled) and Chest Acceleration (Driver, Airbag Only; 30 mph)

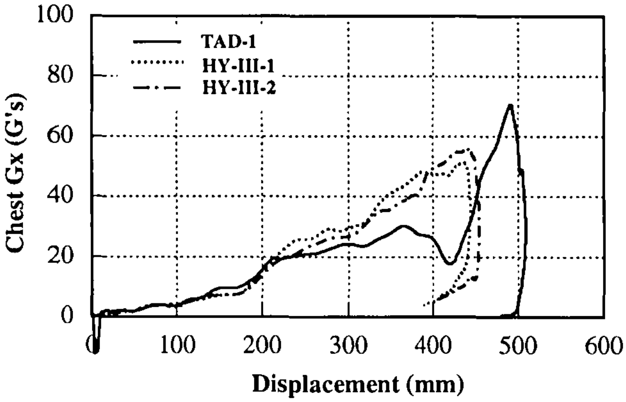

Figure 9.2. Relationship between Chest Displacement (Twice Integrated; Chest vs. Sled) and Chest Acceleration (Passenger, Airbag Only; 30 mph)

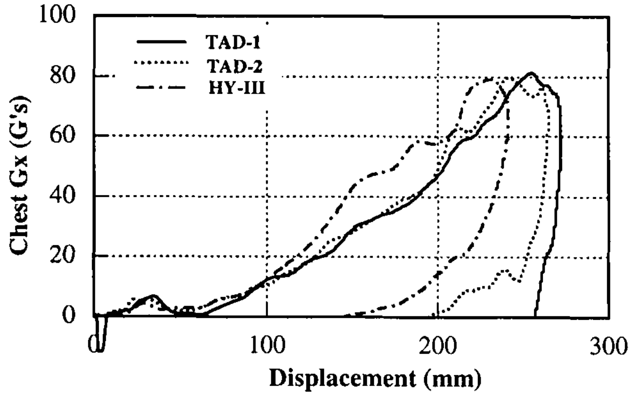

Figure 10.1. Relationship between Chest Displacement (Twice Integrated; Chest vs. Sled) and Chest Acceleration (Driver, 3 Pt. B. with Airbag; 35 mph)

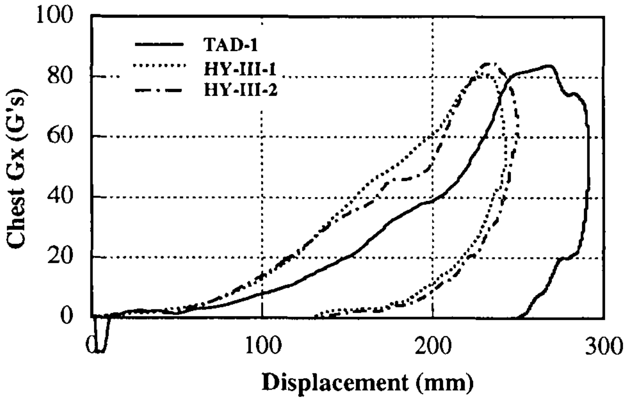

Figure 10.2. Relationship between Chest Displacement (Twice Integrated; Chest vs. Sled) and Chest Acceleration (Passenger, 3 Pt. B. with Airbag; 35 mph)

for the TAD dummy where the deformation becomes maximum. This is attributable to the sharp increase of the load on the chest according to the increase of the displacement, as the energy absorption is smaller for the TAD dummy where the chest displacement range is small. The less steep rise of acceleration for the TAD dummy is probably due to the effect of the chest deflection characteristics, but the specific mechanism of the sharp increase of load that works on the chest cannot be determined.

3-point Seat Belt Only; and 3-point Seat Belt with Airbag - Figs. 10.1 and 10.2 show the chest acceleration - displacement where 3-point seat belt with airbag is used (the chest acceleration against the sled is integrated twice). It is found from these figures that no significant difference in chest acceleration is found between the TAD and HY-III dummies where 3-point seat belt with airbag is used. The same tendency is also found where 3-point seat belt only is used. However, the TAD dummy shows less steep rise of chest acceleration than the HY-III dummy where the characteristics of restraint system are the same, as shown in the chest acceleration - displacement curves. This is probably due to the difference in chest energy absorption characteristics. As a result, the chest deflectional displacement becomes greater for the TAD dummy.

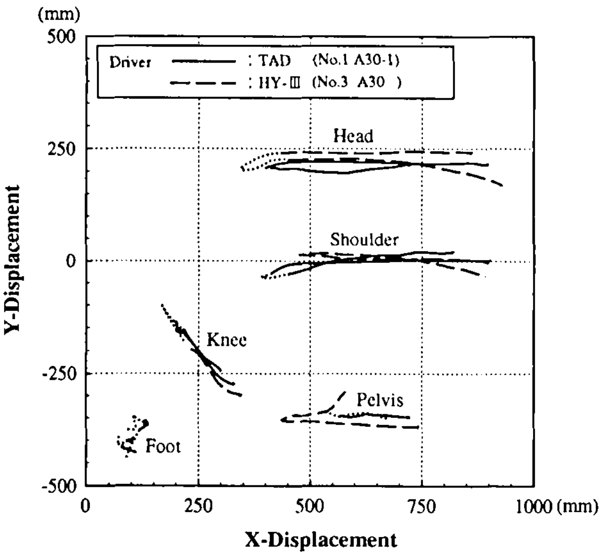

Figure 11.1. Comparison of Trajectories between TAD and HY-III (Driver, Airbag Only; 30 mph)

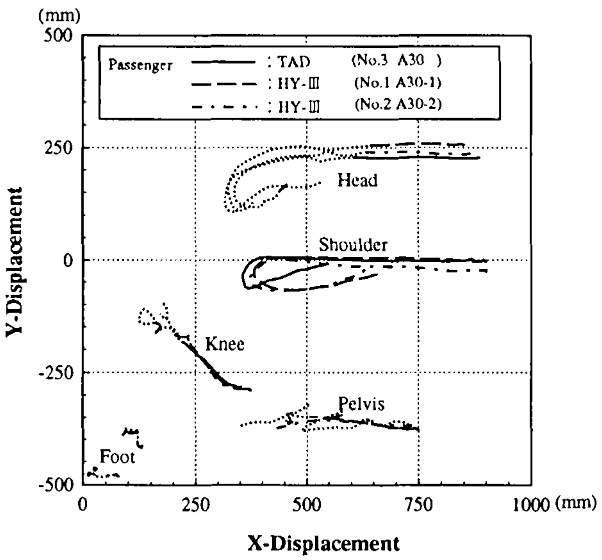

Figure 11.2. Comparison of Trajectories between TAD and HY-III (Passenger, Airbag Only; 30 mph)

4) Dummy Trajectories

__Airbag Only__ - Fig. 11.1 shows the comparison of trajectories at the driver side of the TAD and HY-III dummies, while Fig. 11.2 shows the comparison at their front passenger side. The trajectory of TAD dummy shoulder at the driver side is about 75 mm greater than that of the HY-III dummy. For the front passenger side, the trajectory of the TAD dummy is slightly greater than that of HY-III dummies. This is presumably due to the increase of chest displacement in the TAD dummy as the chest rib deflection response, reported in a paper of Neathery from the Kroell et al. data base, is reduced to approximate that of humans. It is also because the shoulder tends to move forward according to the increased chest displacement, as the clavicle unit is linked with the chest. At the driver side in particular where the airbag capacity is smaller than that at the front passenger side, the chest of the dummy is apt to receive the concentrated reaction force of the airbag, and the phenomenon (of chest displacement) becomes more significant (than at the front passenger side).

__3-point Seat Belt Only__ - Fig. 12 shows the comparison of trajectories at the driver side of the TAD and HY-III dummies. As in the case of "Airbag Only", the trajectory of the TAD dummy shoulder is about 50 mm greater than that of the HY-III dummy. This is presumably due to the increase of chest displacement in the TAD dummy as the chest rib deflection stiffness is made lower than that of the HY-III dummy to approximate that of humans. It is also because the load of shoulder belt works beltwise on the ribs which increases the travel shoulder, as the

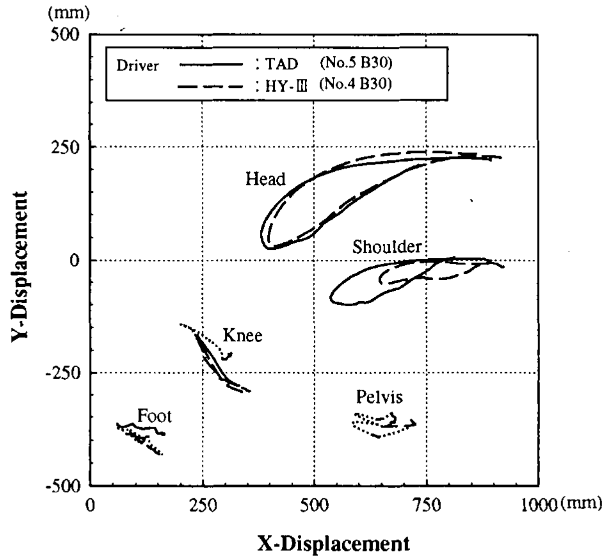

Figure 12. Comparison of Trajectories between TAD and HY-III (Driver, 3-Point Seat Belt Only; 30 mph)

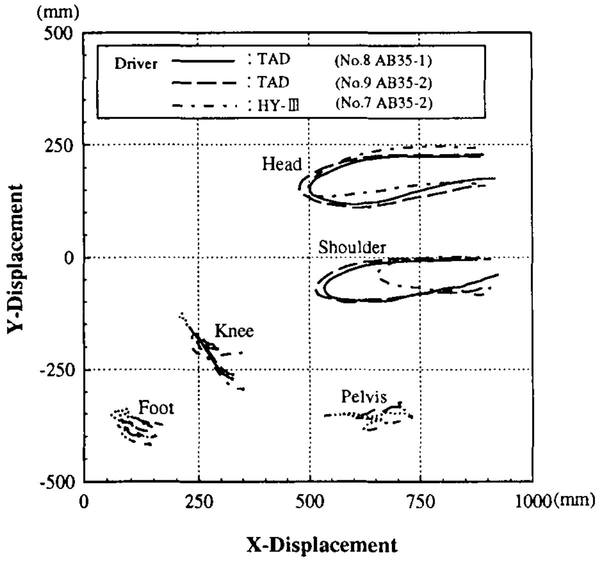

Figure 13.1. Comparison of Trajectories between TAD and HY-III (Driver, 3-Point Seat Belt; 35 mph)

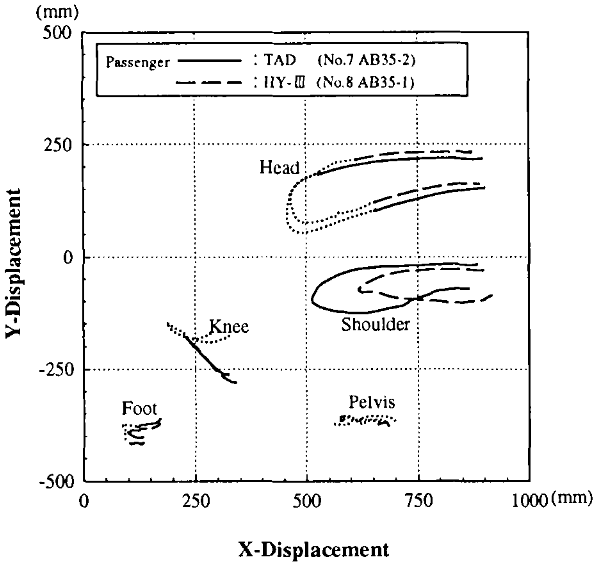

Figure 13.2. Comparison of Trajectories between TAD and HY-III (Passenger, Airbag Only; 30 mph)

Note : The Dotted lines represent displacements that were not directly visible due to certain obstructions such as inflated airbag (for the head), side panel of the car (for the foot), etc.

clavicle unit is linked with the chest (see Fig. 1). Moreover, the tendency of forward inclination of the portion above the thoracic spine is increased by the thoracic spine articulation installed anew (see Fig. 2), which in turn increased the head motion. The head acceleration and HIC of the TAD dummy are reduced in the process.

__3-point Seat Belt with Airbag__ - Fig. 13.1 shows the comparison of trajectories at the driver side of the TAD and HY-III dummies while Fig. 13.2 shows the comparison at their front passenger side, where 3-point seat belt with airbag is used. The trajectory of TAD dummy shoulder at both the driver side and the front passenger side is about 100 mm greater than that of the HY-III dummy. This is presumably due to the lowering of chest deflection stiffness of the TAD dummy, and the increased motion of shoulder as the clavicle unit is linked with the chest, and the shoulder belt load works beltwise on the ribs.

FUTURE TASKS FOR TAD THORACIC ASSESSMENT DEVICE

It is difficult to identify the cause(s) of the difference in chest impact response between the TAD and HY-III dummies by means of the test data obtained under this study alone. It will be necessary to clarify the following points for the identification of the cause(s) of the difference.

__Tasks for Improvement of Practical Applicability__

(a) The TAD dummy tends to show lower HIC values while the neck moment tends to become higher than the HY-III dummy. It is necessary to determine whether such tendencies are caused by the addition of Thoracic Spine Articulation Structure and/or the difference in location of neck fitting.

(b) It is presumed that the lower HIC values of the TAD dummy are caused by the addition of Thoracic Spine Articulation Structure, but HIC should be also affected by the difference in material. Verification of the above is necessary.

(c) Movability of shoulder joints or the shape of shoulder

edge influences responses of a dummy, such as head acceleration, chest acceleration, etc. It will be, therefore, necessary to find the extent of simulation of human shoulder motions by the TAD dummy shoulder link mechanism (shoulder longitudinal and inner spinning motions).

(d) Some unclear points remain unsolved on the phenomenon of higher chest acceleration. It will be necessary to find whether the phenomenon is caused by the structure and mechanism of the TAD dummy.

(e) The information on chest displacement is increased in the TAD dummy. Nevertheless, correlation between such information and actual injury is not necessarily clarified. It will be necessary to study the correlation between a partial displacement of a rib and its injury.

<u>Tasks Related with Structure, Shape, Durability and Handling Ease</u>

The durability and response of each part and the assembly have not been studied sufficiently this time, as the number of tests conducted under this study is rather small. However, the following comments can be made on the structure, shape, durability and handling ease of the TAD dummy chest assembly, through the series of tests conducted so far.

(a) Due to the insufficient movability of idler pulley in DGSP, a tension wire was ruptured. The structure of DGSP is also so intricate that the handling ease in assembling the parts is poor. Structural improvements including the durability and handling ease will be necessary.

(b) As the rib damping material was partially peeled due to the deflection/torsion, it will be necessary to select a proper composite material to reduce the frequency of repair.

(c) A three-dimensional measuring equipment is required for the initial angle setting of DGSP. It will be necessary to devise a proper measuring mechanism that would not require such a three-dimensional measuring equipment.

(d) A thorax design taking account of measuring cable wiring will be necessary, as the space is small due to the DGSP installed in the thorax.

CONCLUSIONS

With these tests performed from October 1994 to February 1995, the impact response of TAD dummy subject to R & D under the international joint cooperation has been compared with that of the HY-III dummy, by testing the thoracic assessment device prototyped and leased out by NHTSA. The practical applicability and functions of the TAD dummy as an evaluation tool have been evaluated under various conditions assuming occupant protection evaluation tests for mass production vehicles in Japan. Findings obtained by the evaluation are as follows.

(a) HIC of the TAD dummy tends to show smaller values than the HY-III dummy, due to the difference in spine structure (caused by the addition of Thoracic Spine Articulation to the TAD dummy). At the same time, the difference in spine structure appears to have influenced their behaviors as dummies.

(b) With an airbag installed, the TAD dummy tends to show a greater chest deflection and chest acceleration. In case where a three-point seat belt is installed, on the other hand, the HY-III dummy tends to show a greater chest deflection. With both an airbag and a seat belt installed, no significant difference is found between the TAD and HY-III dummies. However, it is found that the TAD thorax is in fact designed to be more sensitive to local loading than HY-III dummy. Although the experiments were conducted only twice we can deduce that the repeatability of the chest response of the TAD dummy is roughly the same as that of the HY-III dummy.

(c) Differences in deflection between the sternum and lower rib and between the right and left sides can be measured by using the TAD Thoracic Structure. Hence it may be concluded that various types of occupant restraint systems can be evaluated more precisely with the TAD Thoracic Structure.

(d) Assuming that the difference in shoulder behavior between the TAD and HY-III dummies and the difference in head motion caused by the seat belt restraint system are characteristic differences to maintain the biofidelity at a higher level, it may be considered that the practical applicability of the TAD

dummy is already higher than that of the HY-III dummy.

(e) At the same time, issues to deal with to ensure the practical applicability and functions of the TAD dummy as an evaluation tool have been found. This is an area that requires further studies.

We intend to conduct further tests and analysis, concerning not only lower extremities but also head/ face, neck, abdomen and pelvis of the TAD dummy being developed under the joint cooperation with the initiative of NHTSA. We also intend to make use of the outcomes of such efforts for the "harmonization" of next generation dummies not only of Japan and the U.S.A but also of all countries concerned including Europe.

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REFERENCES

SAE Task Group on Frontal Impact Dummy Enhancements, of the Mechanical Human Simulation Subcommittee of the Human Biomechanics and Simulation Standards Committee

"Recommended Requirements for Frontal Impact Dummies", EEVC WG12 Document 10, 1994, 10.4

Schneider, L.W., Haffner, M.P., Eppinger, R.H., Salloum, M.I., Beebe, M.S., Rouhuna, S.W., King, A.I., Hardy, W.N. and Neathery, R.F. (1992) Development of an Advanced ATD Thorax System for Improved Injury Assessment in Frontal Crash Environment, 36th STAPP Conference (1992)

Haffner, H., Kleinberger, M., Eppinger, R., Hennessey, B., Pritz, H., Beebe, M., Hagedorn, A., Klinich, K., Ore, L., Tanner, B., and Kuppa, S., Progress in the Development of New Frontal Dummy Components for the NHTSA Advanced Frontal Protection Program, 14th ESV Conference (1994)

Rouhana, S.W., Viano D.C., Jedrzejczak, E.A., and McCleary, J.D. Assessing submarining and abdominal injury risk in the Hybrid III family of dummies. 33rd STAPP Conference (1989)

Rouhana, S.W., Jedrzejczak, E.A., and McCleary, J.D. Assessing submarining and abdominal injury risk in the Hybrid III family of dummies: Part II - Development of the small female Frangible Abdomen. 34th STAPP Conference (1990)

Bohlen, J.L., and Keller J.R., Advanced Thorax Dummy (TAD-50M) Versus Hybrid III: A Characteristic Comparison in Frontal Barrier Testing. 1995 SAE Paper No. 950666

Neathery, R.F., Analysis of Chest Impact Response Data and Scaled Performance Recommendations, 18th STAPP Conference, 1974

Kroell, C.K., Schneider, D.C., and Nahum, A.M., Impact Tolerance and Response to the Human Thorax II, 18th STAPP Conference, 1974

PERFORMANCE OF TAD-50M IN VEHICLE-BARRIER TESTS AND COMPARISON WITH HYBRID III

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ABSTRACT

Four rigid barrier, frontal vehicle tests at 48 and 56 kph using the TAD-50M dummy were performed. Restraint conditions included a 3-point belt only, an airbag only, and a combination bag and 3-point belt system. TAD-50M responses, including the head, chest, and pelvic accelerations, belt and femur loads and chest deflections have been analyzed and compared with the Hybrid III. Some user convenience issues related to the use of the TAD-50M in a test environment are also discussed.

The data from the four DGSP transducers on the TAD have been analyzed to study the differences in response of the TAD-50M thorax to loading from belt and airbag. The TAD-50M produced symmetric A-P deflections under airbag loading and asymmetric A-P deflections under belt loads. For airbag tests, maximum deflections reached 70 mm, while for 3-point belt tests, maximum deflections reached 50 mm. Some lateral deflection was observed for all restraint cases, especially for the belt only restraint case at the higher impact speed. In addition, vertical deflection was also observed for the bag restraint tests. Deflection rates were generally higher for the bag restraint tests.

INTRODUCTION

The basic features of the new advanced thoracic system in the TAD-50M have been given by Schneider [1992] and the results of the initial testing of the ATD have been described by Schneider [1992] and Hagedorn [1992]. Additional testing has been carried out on the new ATD and the results of these tests have been reported by Bohlen [1995] and Ono, et.al. [1996]. This paper describes additional analysis of the data collected from the four frontal barrier crash tests reported in Bohlen. This analysis is primarily directed at evaluating the response of the new thorax to different restraint conditions.

The features of the new thoracic system that relate to the response of the system to external impact are:

- Ribcage with more human-like geometry. The ribcage consists of seven, slanted ribs, with the ribs increasing in breadth when seen from top to bottom.
- An articulation, which divides the thoracic spine into an upper and lower section, providing additional flexibility.
- An improved shoulder mechanism that allows for greater mobility of the clavicles in the anterior/posterior direction under belt and inertial loading.
- A chest deflection measurement system, that provides 3-dimensional deflection data at four separate locations on the anterior chest. In addition, angular velocities in the sagittal plane can be measured on two spine segments and on the pelvis.

As part of a joint program between Honda R&D North America, Inc. and the National Highway Traffic Safety Administration (NHTSA), a series of four full vehicle to rigid barrier frontal crash tests were conducted using the TAD-50M ATDs in both driver and passenger positions. The main objective of the barrier tests was to evaluate the response of the chest to airbag and belt loading. Two similar tests were also conducted using Hybrid III dummies in the driver and passenger positions. This was to provide a benchmark for comparison with the TAD-50M results.

DESCRIPTION OF TESTS

The four tests using TAD-50M consisted of two test conditions, where each condition was repeated twice. This allowed an assessment of the repeatability of the TAD under barrier testing. Two TAD dummies were used, one in the driver position and one in the

passenger position. The two test conditions were replicated using Hybrid III dummies in the driver and passenger locations. All tests were conducted at the Transportation Research Center, Inc. in Ohio using modified 1992 four door Honda Accords. The tests and their conditions are summarized in the following table:

Table 1. Description of Tests

Test	NHTSA Test #	Test Speed	Occupant	Restraint
TAD#1	2039	48 kph	TAD.driver TAD.passenger	Airbag 3pt belt
TAD#2	2040	48 kph	TAD.driver TAD.passenger	Airbag 3pt belt
TAD#3	2041	56 kph	TAD.driver TAD.passenger	Airbag+3pt 3pt belt
TAD#4	2042	56 kph	TAD.driver TAD.passenger	Airbag+3pt 3pt belt
Hyb3#1		48 kph	Hybrid 3.driver Hybrid 3.passeng	Airbag 3pt belt
Hyb3#2		56 kph	Hybrid 3.driver Hybrid 3.passeng	Airbag+3pt 3pt belt

Data from a number of transducers were collected. Accelerations were measured at the head, chest and pelvis, and 3-dimensional deflections were measured at four locations on the chest. Angular velocity sensors were placed at the upper spine, lower spine and pelvis. Force and moments were measured at the top of the neck, femur, and when instrumentation was available, also at the tibia and ankles. Shoulder and lap belt loads were measured for the 3-point restraints. Airbag pressure was also measured. It should be mentioned that in each test one of the dummies was equipped with the Advanced Lower Extremity system (ALEX).

Data Analysis Procedure- The data from the various transducers were processed using the following typical procedure:

1. Remove bias from signal and filter signal.
2. For deflection measurements, process signal using the DEFLECT algorithm developed by UMTRI for generating X, Y, Z deflections from the radial and angular curves obtained from the displacement transducers. Initial orientations of each of the transducers were obtained and used as input. The X, Y, Z deflections are measured in the lower spine coordinate system, as described by Schneider [1992].
3. For deflection measurements, differentiate curve to estimate deflection rate (in A-P direction) and calculate V•C
4. Truncate the curve data, and extract signal between 0. - 150. msec at 1 msec intervals and convert curve data into ASCII text files.

Vehicle Accelerations- From the vehicle acceleration plots (Figures 1 & 2), it is seen that the 48 kph tests show a maximum in the range 27 - 28 G and the 56 kph tests show a maximum in the range 30 - 37 G (accelerations were measured at the floor tunnel). It is seen that there is a small increase in the peaks for the 56 kph tests and the pulses are stretched out further by about 10 msec. For the 56 kph tests, the peak actually hovers around 30 G for a period between 60 - 70 msec, rather than having a pronounced peak. It is observed that for the 48 kph tests, the pulses for the TAD and the Hybrid III match very well, while at 56 kph, the peak acceleration in the Hybrid III test is about 4 G greater than the TAD test. This somewhat more severe pulse, should be borne in mind when comparing the results.

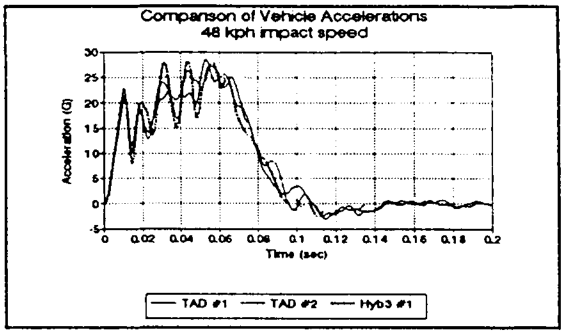

Figure 1. Comparison of vehicle accelerations for 48 kph tests.

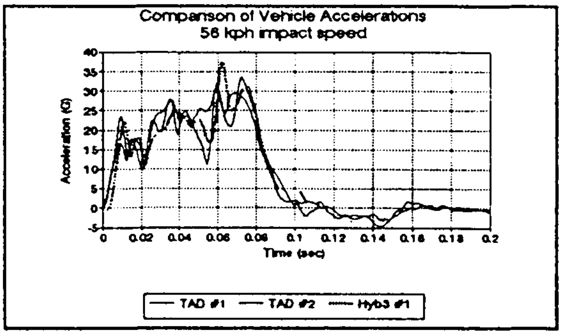

Figure 2. Comparison of vehicle accelerations for 56 kph tests.

The following maximum accelerations are noted:

Table 2. Peak Vehicle Accelerations

Test	Test Speed	Max	Time
TAD #1	48 kph	-28.5 G	53 msec
TAD #2	48 kph	-27.3 G	54 msec
TAD #3	56 kph	-33.9 G	72 msec
TAD #4	56 kph	-29.9 G	59 msec
Hyb 3 #1	48 kph	-28.3 G	44 msec
Hyb 3 #2	56 kph	-37.6 G	62 msec

Initial Positioning - Because of the articulation of the spine, the TAD sits somewhat differently than the Hybrid III. It has been pointed out by Bohlen [1995] that the TAD torso is inclined at a greater angle than the Hybrid III and the knees are about 40 mm closer to the instrument panel/dash panel than the Hybrid III and that the anterior chest was about 10 mm closer to the steering wheel. The head/neck angle could not be adjusted in the TAD, but this angle can be set in the new advanced frontal dummy under development.

RESULTS

The principal injury parameters, the maximum forces measured at the femur, and the maximum loads generated by the lap and shoulder belts for both the TAD and Hybrid III tests are provided in Table 3. The comparison of chest deflections are provided in Table 4.

Table 3. Principal Injury Parameters and Forces for TAD and Hybrid III Tests

Test No	Clsspd (kph)	Occloc	Restrnt	HIC	Clip3m (G)	L. Femur (N)	R. Femur (N)	Lap Belt (N)	Shld Belt (N)
TAD #1	48.8	Driv	Airbag	361	50.9	5745	5719		
TAD #2	48.8	Driv	Airbag	209	54.2	*	*		
Hyb3 #1	48.8	Driv	Airbag	332	54.4	7144	8280		
TAD #1	48.8	Pass	3pt	469	53.2	3392	1591	7393	9280
TAD #2	48.8	Pass	3pt	411	50.9	2421	2336	7700	9248
Hyb3 #1	48.8	Pass	3pt	499	46.8	1971	628		
TAD #3	56.5	Driv	Bag+3pt	612	59.7	2574	4664	6350	8738
TAD #4	56.5	Driv	Bag+3pt	588	59.2	3054	5788	6672	9517
Hyb3 #2	56.5	Driv	Bag+3pt	645	56.5	2615	4510	9009	9192
TAD #3	56.5	Pass	3pt	634	47.8	4533	3939	6594	9296
TAD #4	56.5	Pass	3pt	712	52.5	3630	4010	7686	9782
Hyb3 #2	56.5	Pass	3pt	613	48.8	3054	1718	8908	9960

* channel failure; no data collected

Table 4. Maximum Chest Deflections (mm)

		TAD				Hybrid III			
		Driv	Pass	Driv	Pass	Driv	Pass	Driv	Pass
DIR	POS	Bag (48)	3pt (48)	Bag+3pt	3pt (56)	Bag (48)	3pt (48)	Bag+3pt	3pt (56)
X	RU	-62.8	-12.4	-56.3	-12.2	-53.6	-39.1	-47.2	-36.8
	LU	-69.1	-53.8	-44.3	-53.5				
	RL	-58.5	14.8	-48.4	13.0				
	LL	-51.4	-32.4	8.8	-29.4				
Y	RU	-5.5	-23.0	10.2	-25.1				
	LU	11.2	-28.1	15.8	-30.4				
	RL	9.7	-15.3	13.9	-15.0				
	LL	17.5	-32.9	12.5	-35.2				
Z	RU	14.0	-10.2	-16.8	-15.0				
	LU	20.7	-15.8	-13.5	-20.2				
	RL	1.8	21.8	-14.6	19.2				
	LL	20.1	1.7	-9.1	0.5				

NOTE: DGSP Positions: RU = right upper; LU = left upper; RL = right lower; LL = left lower

It is noticed that:

- Lower HIC is obtained for the TAD for the passenger in the 48 kph tests, and for the driver in the 56 kph tests. TAD displayed a higher HIC for the passenger in the 56 kph tests. There does not appear to be any significant difference in HIC between the TAD and the Hybrid III, when compared to the variation in HIC between similar TAD tests.
- Chest acceleration is usually greater for the TAD, though only by a small amount and the differences are again of the same order of magnitude as the variations within similar test conditions.
- Greater chest deflections are obtained with TAD for all restraint conditions. The single Hybrid III deflection is compared to the two upper X-deflections from the TAD, since they are similarly located. The difference is greatest for the airbag only condition. With the 3-point belt restraint, the TAD shows an asymmetric deflection, and the larger of the two upper deflections is greater than the Hybrid III deflection measured utilizing the center potentiometer.
- Femur forces are less in TAD for the airbag case, but greater for the 3-point belt and slightly greater (using the average of the two TAD tests) in the 3-point plus airbag case.
- Shoulder belt forces are not significantly different for the TAD and Hybrid III. But the lap belt forces are significantly lower for the TAD (compared to the variation seen between similar tests), and mainly due to the earlier knee impact for the TAD.

These results have been presented previously by Bohlen [1995] and similar results have been obtained by Ono and co-workers [1996].

Chest Accelerations - Figure 3 shows the resultant chest accelerations for the driver position, and Figure 4 shows them for the passenger position. For the driver position, it is seen that the location of the peak chest acceleration, when only an airbag is used, occurs about 20 msec later than when the both bag and belt restraints are present. It should be noted that the airbag with the 3-point belt configuration produces the highest peak accelerations,. with 5 - 7 G above the other configurations.

The timing of the peak when both bag and belt are present is consistent with the 3-point only situation seen in Figure 4. In this figure, it is seen that all the accelerations are clustered together, indicating that they have about the same shape and timing. When the repeated tests are compared, the repeatability of the TAD is seen to be quite good.

As mentioned above, the TAD usually produced slightly higher accelerations than Hybrid III, seen in Figure 5 and 6. There is no significant difference in the airbag case, but a visible difference for the 3-point case. Also a secondary peak is observed in the TAD tests, which is strongest for the belted cases. This may be due to a chin-chest contact, though a definitive answer will require a closer analysis of the high-speed film.

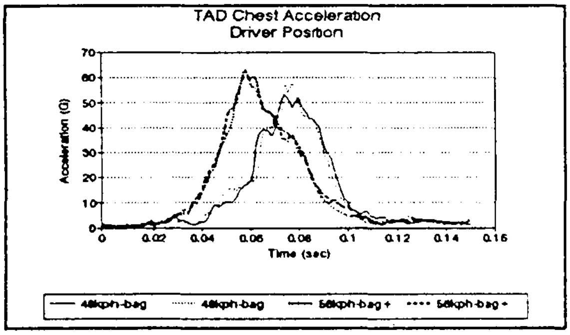

Figure 3. Chest accelerations at driver position.

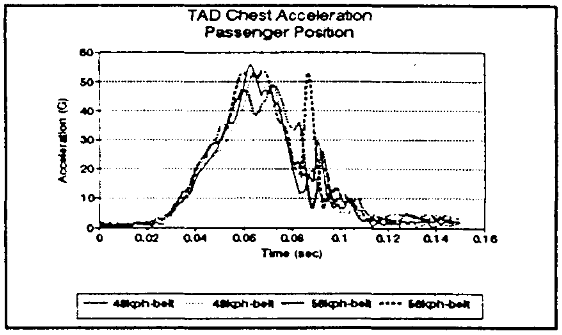

Figure 4. Chest Accelerations at passenger position.

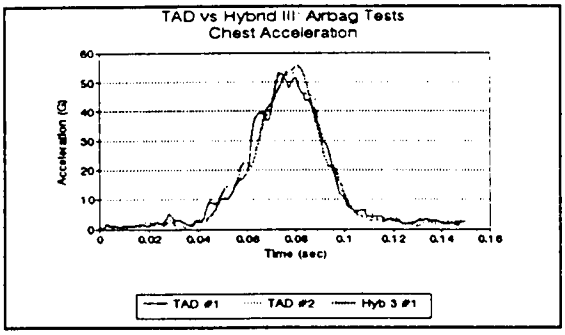

Figure 5. Chest accelerations for 48 kph with airbag.

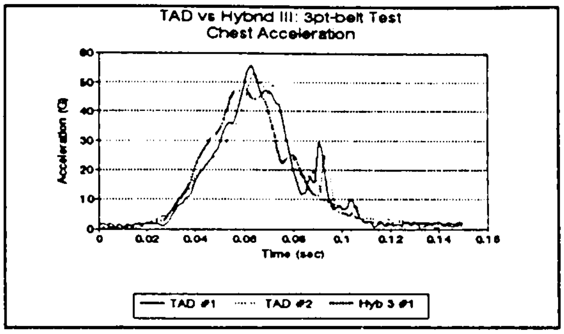

Figure 6. Chest accelerations for 48 kph with 3-pt belt

Belt Loads - When the belt loads are examined, it appears there is no strong division between the curves produced by the belt only cases and those with both airbag and belt. The lap belt loads are usually higher when only the 3-point belt is used than when it is used with the airbag. This would be expected from a simple consideration of the distribution of forces, since the total restraint force is shared between the bag and the belts. From the graphs, this appears to be the case only for the lower speed (48 kph) case, where the load is between 7100 - 7600 N. But the right passenger lap belt from TAD Test #3 (belt only) has a peak comparable with the lap belt loads from the belt/bag configuration (about 6700 N). This lower lap belt load is probably due to greater femur engagement at the higher speed. The Hybrid III lap belts loads for both 3pt and airbag and 3pt cases are almost 30% greater than the TAD. This is probably due to the greater engagement of the femur, in the case of the TAD, especially in the higher speed case.

The shoulder belt loads are more evenly clustered, at both 48 and 56 kph, with the peak around 9000 N at about 70 msec. This would indicate that there is no significant difference in the shoulder belt loads, regardless of whether an airbag is present or not. The belt unloads more slowly for the 56 kph test (leads to greater change of momentum, and hence greater change of velocity). The shoulder belt loads are comparable for both Hybrid III and TAD. For the 3pt belt case, the belt tends to unload more slowly in the Hybrid III, while for the airbag and 3pt belt case, there is good agreement for both magnitude and time dependence.

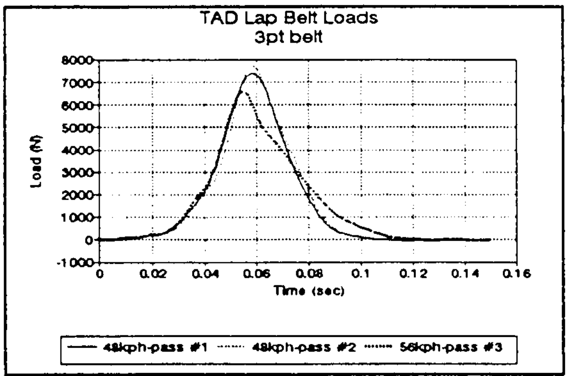

Figure 7. Lap belt loads for 3-pt belt tests.

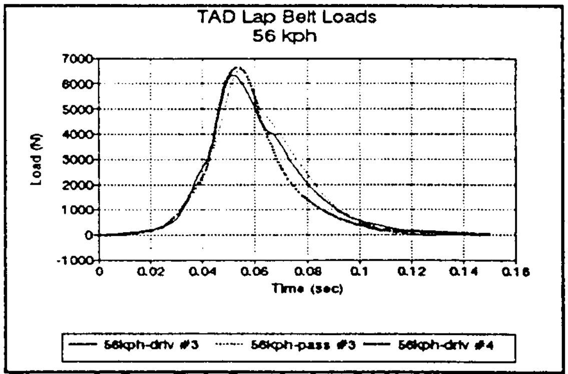

Figure 8: Lap Belt Loads for 56 kph tests.

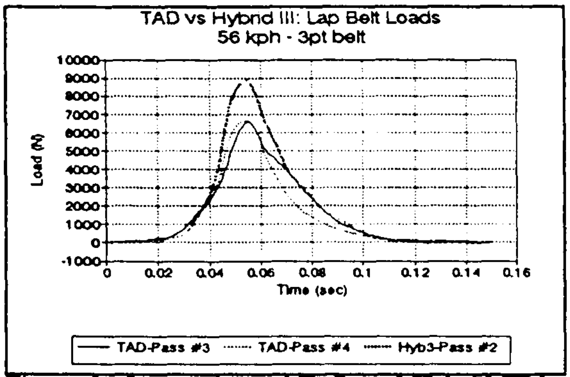

Figure 9. Comparison of TAD and Hybrid III lap belt lap loads for 3-pt belts.

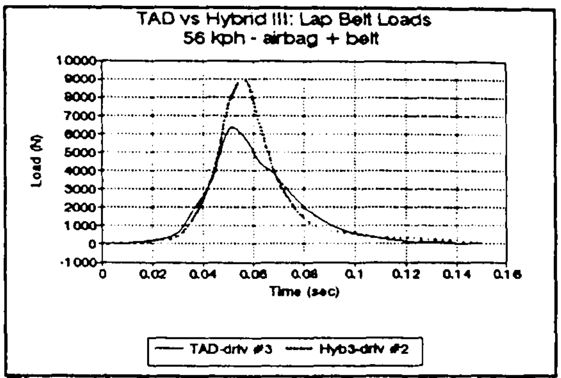

Figure 10. Comparison of TAD and Hybrid III belt loads for airbag+3-pt restraints.

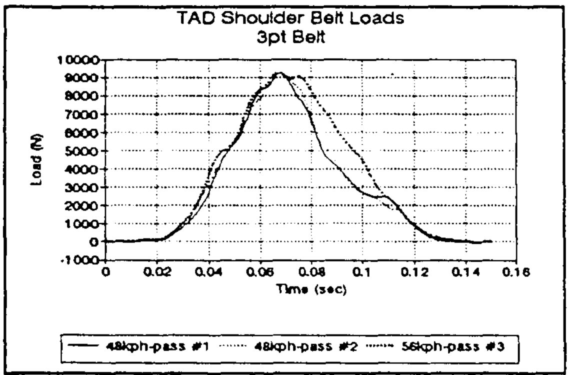

Figure 11. TAD shoulder belt loads for 3-pt belts.

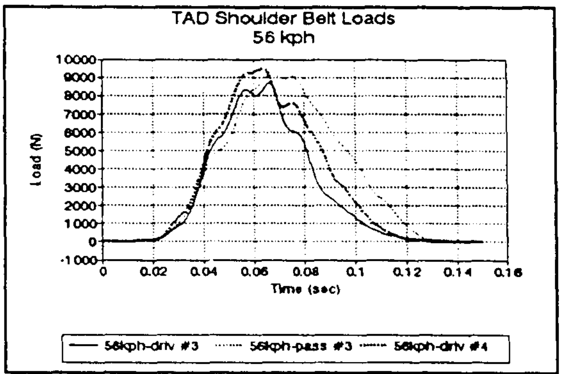

Figure 12. TAD shoulder belt for 56 kph tests.

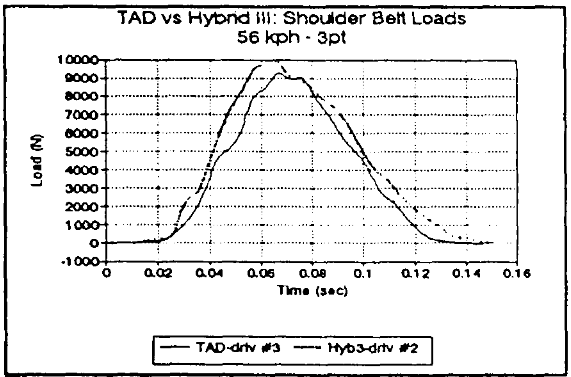

Figure 13. Comparison of TAD and Hybrid III shoulder belt loads for 3-pt belts.

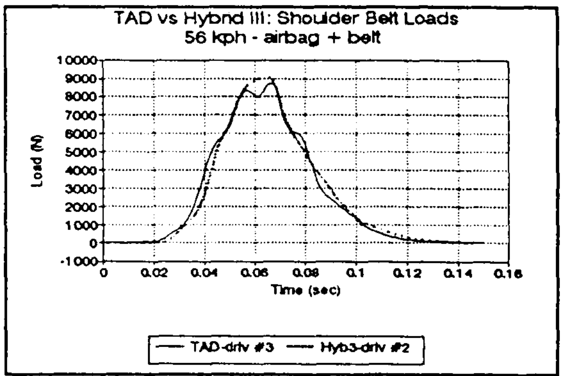

Figure 14. Comparison of TAD and Hybrid III shoulder belt loads for airbag+3-pt.

Bag Pressure - The bag pressure time histories shows the usual initial spike from the bag deployment and the secondary peak from the occupant impact. The peak during this contact phase is about 40 - 50 kPa (6-7 psig). The maximum value is attained for TAD Test #2, i.e. for the airbag only case at 48 kph, which would be consistent with the fact that the airbag is wholly responsible for restraining the occupant motion. There were no comparable bag pressure data for the Hybrid III tests.

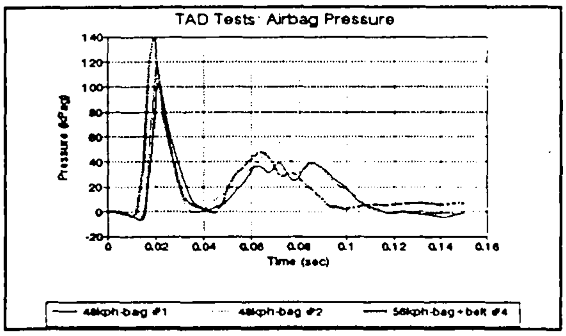

Figure 15. Airbag manifold pressure.

Chest Displacements - The TAD deflection measurement system provides the ability to examine the local deflections in three dimensions at four separate locations on the chest. Since the Hybrid III has only a single central chest potentiometer for measuring deflection in the A-P direction, it is difficult to properly compare the results for chest deflections for the two dummies. The comparisons are easier for the cases with an airbag, since the distributed loads tend to deflect both left and right DGSPs by about the same proportion. It is seen from Figure 14 that both the left and right side deflections are greater than the Hybrid III indicating a greater compliance to distributed loading. The deflections for the 3-point belt in Figure 17, show the Hybrid III deflections falling between the two string pot deflections which would be expected in an asymmetric loading situation. For the combined restraint case, the asymmetry is less, and the Hybrid III deflection is close to the deflection on the less deflected side.

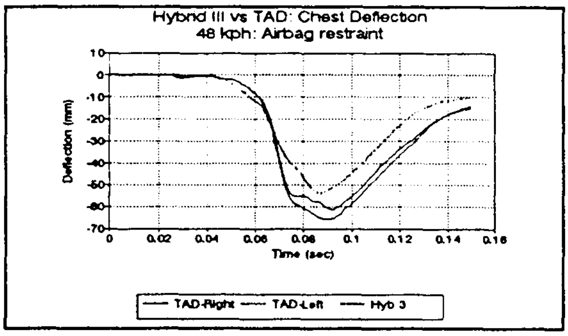

Figure 16. Chest deflection for 48 kph airbag.

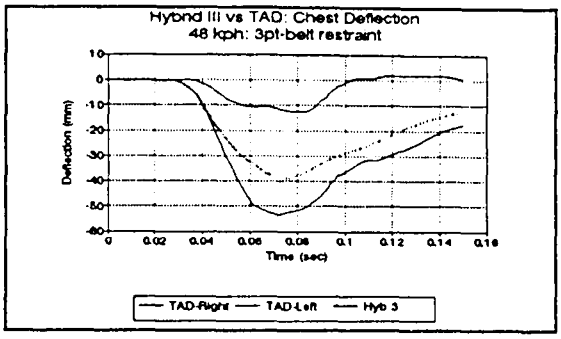

Figure 17. Chest deflection for 48 kph 3-pt belt.

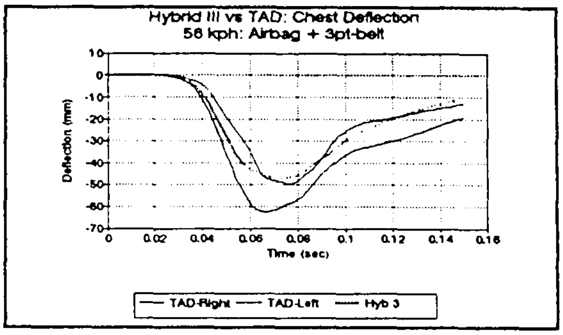

Figure 18. Chest deflection for 56 kph airbag+3pt belt.

The deflection output available from TAD was deflections for a representative test. Both tests for the same condition are plotted and indicate that the measurements are repeatable, though there was some variance at the lower right location for the Y and Z deflections.

The asymmetry of the deflection pattern is seen when the X and Y deflections are plotted together. It should be remembered that these deflections are measured in a coordinate system aligned with the lower thoracic spine. The small black rectangles represent the location of the end of the joysticks at 5 msec intervals.

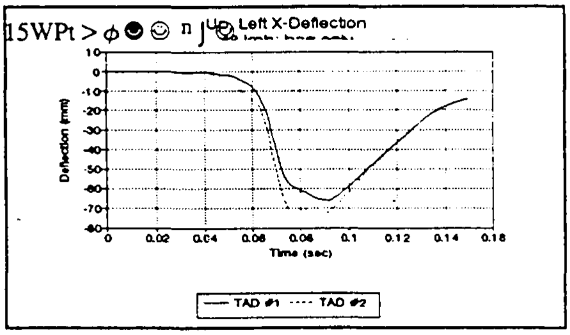

Figure 19. Upper Left X-defl; 48 kph-bag.

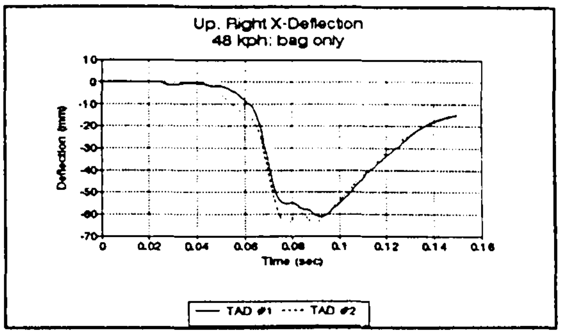

Figure 20. Upper Right X-defl; 48 kph-bag.

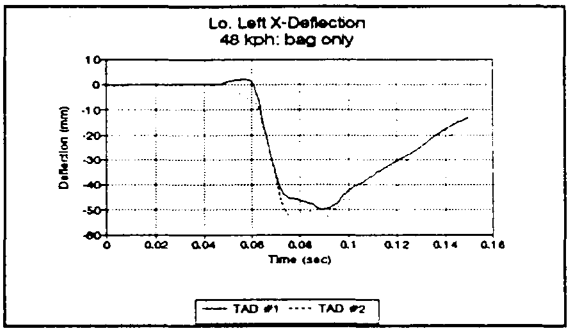

Figure 22. Lower Left X-Defl; 48 kph-bag.

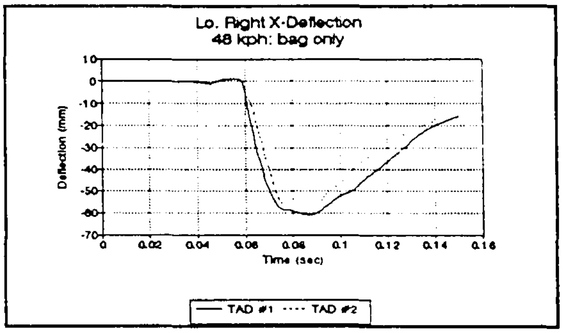

Figure 22. Lower Right X-defl; 48 kph-bag.

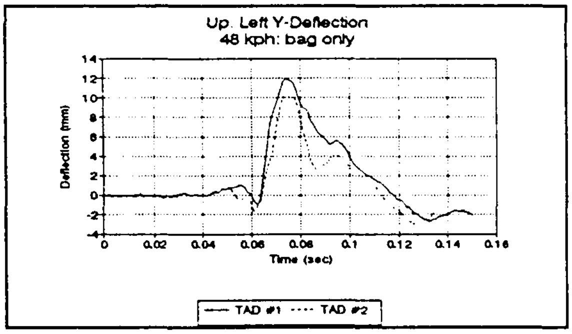

Figure 23. Upper Left Y-defl; 48 kph-bag.

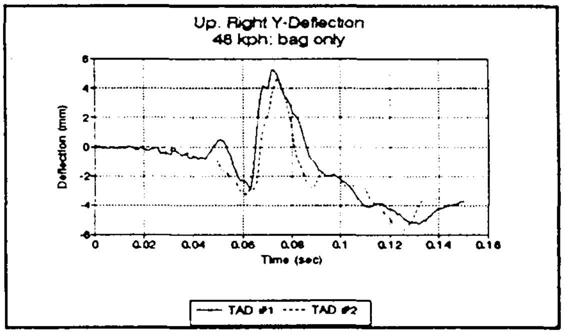

Figure 22. Upper Right Y-defl; 48 kph-bag.

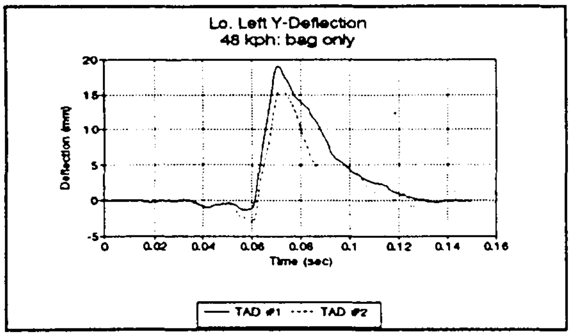

Figure 25: Lower Left Y-defl; 48 kph-bag.

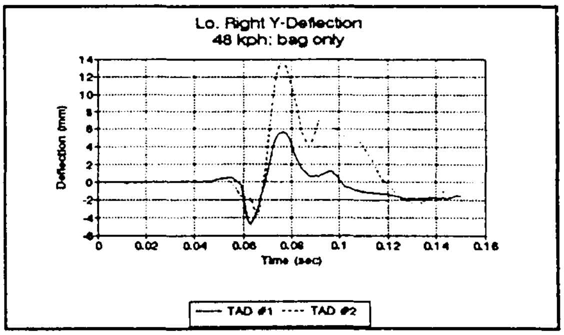

Figure 26. Lower Right Y-defl; 48 kph-bag.

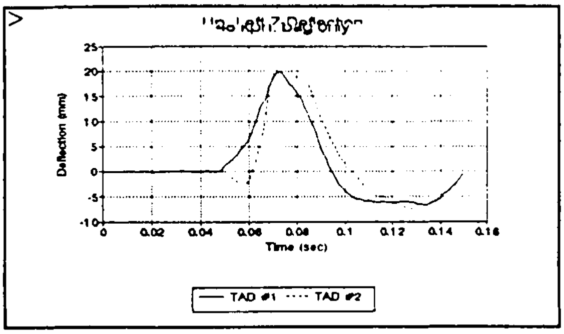

Figure 27. Upper Left Z-defl; 48 kph-bag.

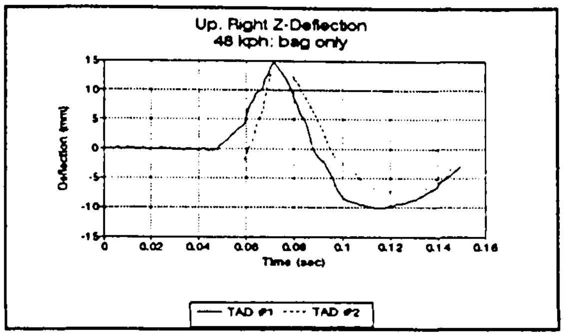

Figure 28. Upper Right Z-defl; 48 kph-bag.

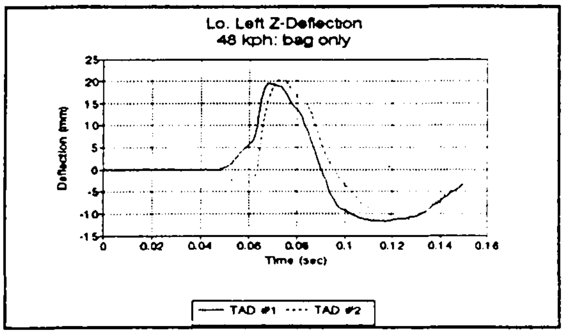

Figure 29. Lower Left Z-defl; 48 kph-bag.

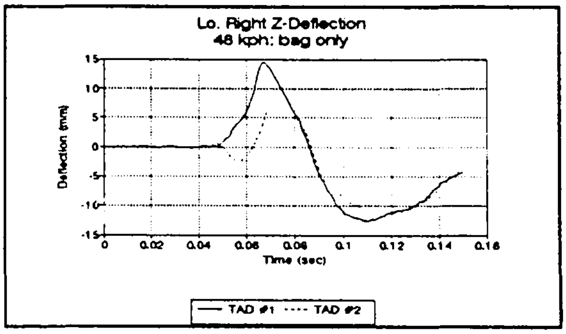

Figure 30. Lower Right Z-defl; 48 kph-bag.

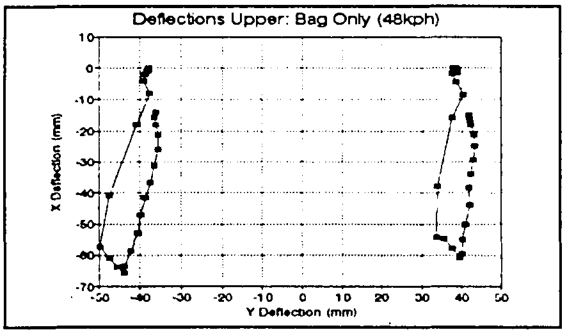

Figure 31: Upper chest X-Y deflections; 48 kph-bag.

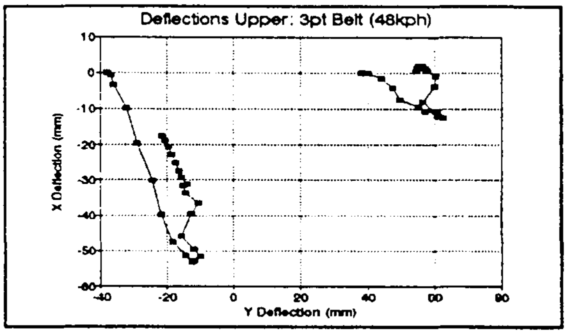

Figure 32. Upper chest X-Y deflections; 48 kph 3pt-belt.

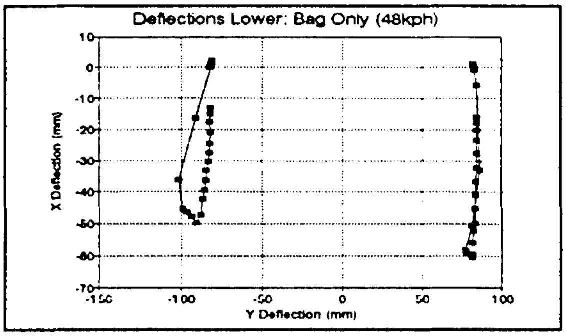

Figure 33. Lower chest X-Y deflections; 48 kph-bag.

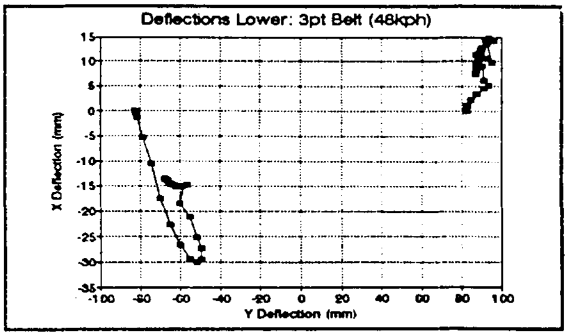

Figure 34. Lower chest X-Y deflections; 48 kph-3-pt belt.

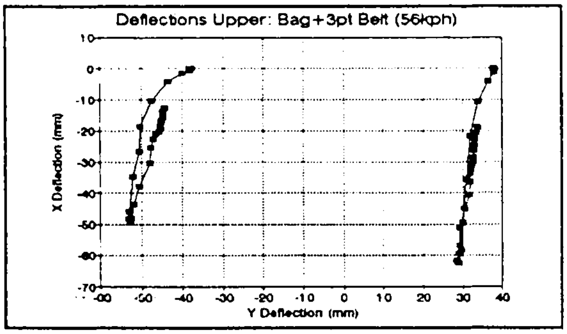

Figure 35. Upper chest X-Y deflections; 56 kph-bag+3pt.

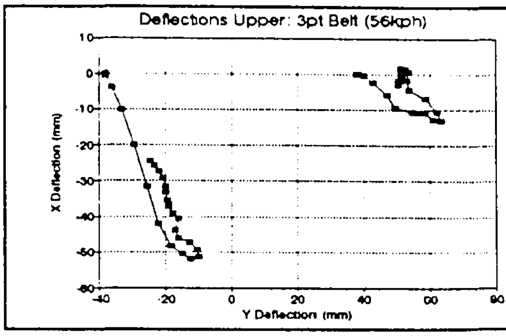

Figure 36. Upper chest X-Y deflections; 56 kph-3-pt belt.

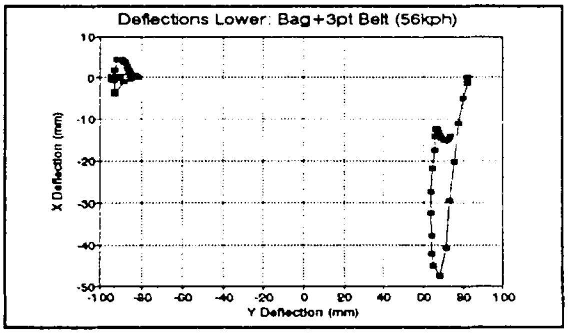

Figure 37. Lower chest X-Y deflections; 56 kph-bag+ 3pt.

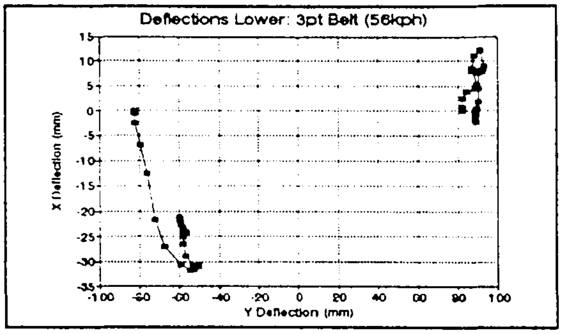

Figure 38. Lower chest X-Y deflections; 56 kph-3-pt belt.

The following results are noted for the displacements obtained from the 4 chest transducers in each dummy:

1. The airbag and airbag/belt restraint produces a more symmetrical distribution for the left and right transducers in X or A-P direction. The upper displacements are more symmetrical than the lower displacements. The belt only restraint shows a large asymmetry with the left side showing a much larger deflection (about 4 times greater on left side than right side). One peculiarity of the 3-point belt deflections is that the asymmetry at both the upper and lower locations is all on one side and at the passenger position, this is on the left side. It has been noted by Bohlen [1995] in the previous analysis of the data that this was probably due to the belt slipping across the shoulder and lodging close to the neck base and applying greater force along the left side of the dummy. The effect may be further accentuated by possible roping of the belt, where the belt curls up, making it narrower and producing a more localized force application, though the high speed film has to be analyzed more carefully to fully confirm the effect. Similar response has been indicated by Ono [1996] during a series of sled tests under similar restraint conditions. There is also some asymmetry for the bag and 3pt belt combination, with the upper and lower deflections showing greater deflections on the same side.

2. The magnitude of the deflection in the A-P direction is greater for the airbag cases than in the belt only cases. The maximum displacement for the cases with the airbag is about 50 - 70 mm, while the maximum displacement for the belt only cases is about 50 mm. The deflection is highest for the two airbag only cases, where the displacement of the upper transducers reaches about 70 mm.

3. There is some noticeable lateral deflection for all the tests. The belt only tests do show a much larger deflection than the bag tests, with the high speed test (56 kph) showing a deflection to the right of about 30 - 35 mm (for

the left side transducers).

4. There appears to be an upward displacement (I-S direction) of about 12 - 20 mm, for the bag only cases. The belt only cases show an oscillation in the vertical displacement. The upper transducers usually show a downward displacement and the lower transducers show an upward displacement. This would indicate that the front of the upper and lower ribs are being pushed toward each other along the vertical direction. For the high speed (56 mph) case, the upper left transducer shows about a 23 mm displacement downwards. It also appears that the transducers do not return to their equilibrium position (zero) in the Z direction within 150 msec. It is difficult at this time to compare these results directly with cadaver results, since three dimensional measurements are not currently feasible with cadavers.

5. The X-Y deflections at the lower chest, for the bag only cases, shows an average deflection in the A-P direction of about 50 mm. The left side shows some Y deflection (about 12 mm), while the right side has a smaller amount.

The deflections, at the lower ribcage, for the bag + 3pt belt cases show much higher asymmetry than the upper chest deflections. The deflections for the belt cases show a high asymmetry. The right side deflections in the X direction are actually positive, showing a larger degree of rotation of the lower chest region than the upper chest. There is a similar but less pronounced effect for the bag + 3pt belt case, where the lower left side shows a small positive deflection.

6. As also seen in the chest accelerations, the time at which maximum deflection is reached is usually later for the bag restraints than for the belted restraints. The width of the signal, on average, is somewhat narrower for the bag cases than the belt cases.

7. The deflection rates shown in Figures 39 - 42 show that the highest rate is found for the airbag only case. The rate of deflection is quite high and is about 4.8 m/s or 190 in/sec. The rates of deflection for the other cases appear to be in the expected range averaging about 2.5 m/sec or 100 in/sec. The high rate of deflection for the bag only case, appears to be consistent with the higher accelerations and the later peak times in this configuration. The chest develops higher speeds before the airbag fully engages it leading to the related effects. It is also seen, that the deflection rates for Hybrid III is significantly lower, again indicating the softer ribcage in the TAD.

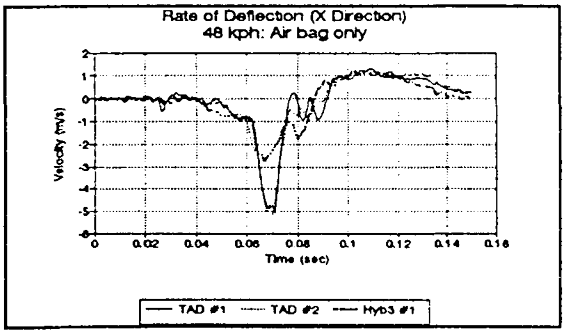

Figure 39. Rate of deflection for 48 kph -bag test.

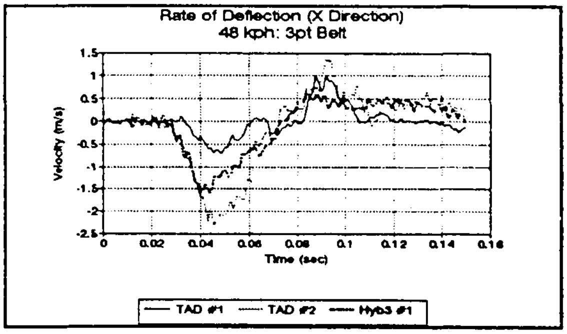

Figure 40. Rate of deflection for 48 kph-3pt belt.

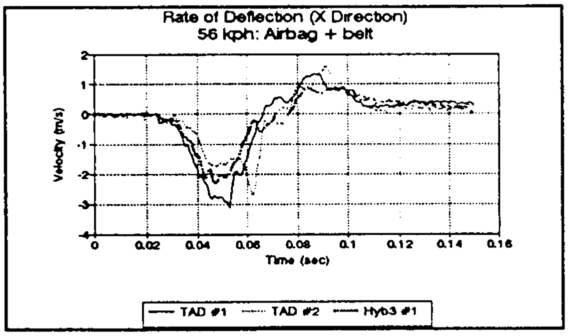

Figure 41. Rate of deflection for 56 kph-airbag+ 3pt belt test.

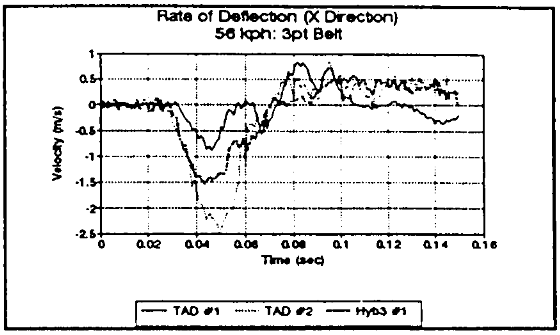

Figure 42. Rate of deflection for 56 kph-3pt belt test.

Head Motion - As seen from the summary above and the analysis of the tests published earlier by Bohlen (1995), the magnitude of the head accelerations are slightly reduced in the tests using the TAD dummy. As an example, Figures 43 and 44, show the comparisons for the airbag and 3-point restraint cases for the 48 kph test.

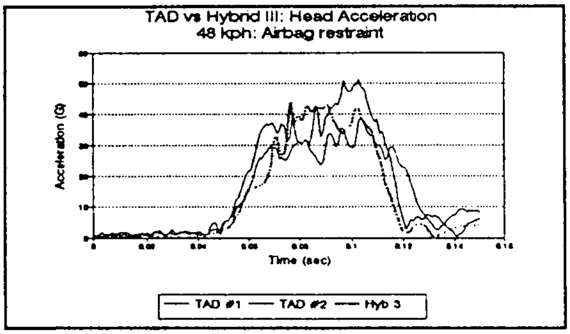

Figure 43. Comparison of head accelerations for 48 kph-airbag.

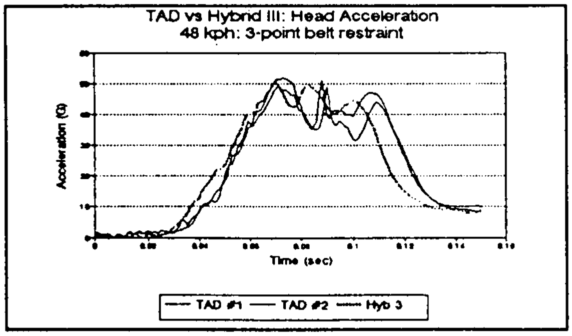

Figure 44. Comparison of head accelerations 48 kph-3pt belt.

It is observed that there are no distinct differences in the head response of the Hybrid III with that of TAD for the airbag case, and there is slight lowering of the acceleration in TAD for the 3-point belt case. This difference in response may be due again to the general behavior observed for the other dynamic variables, i.e. the TAD shows similar behavior to Hybrid III under the distributed loading of airbags but somewhat different response under the strip loading of belts.

A further analysis can be performed by comparing the displacements of the head C.G. under the different restraint conditions. Figures 45 to 47 show these comparisons for the motion in the X-Z plane for the three restraint conditions. The motions were estimated by digitizing the head C.G. positions from the high speed films. All three situations show the trajectories of the head following a similar path. These are also similar to results obtained by Ono, though his group found a somewhat greater displacement for TAD in the airbag case.

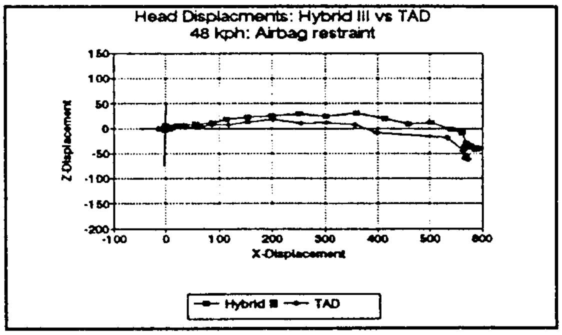

Figure 45. Comparison of head displacement for 48 kph-airbag restraint airbag.

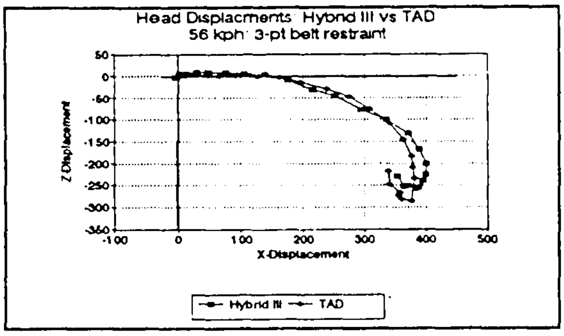

Figure 46. Comparison of head displacement for 56 kph-3 pt belt.

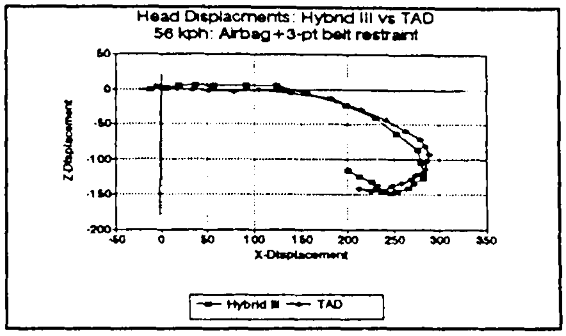

Figure 47. Comparison of head displacement for 56 kph airbag+3pt.

Spinal Rotations - A total of three angular velocity MHD measurement sensors were attached to the upper thoracic spine (above the spine articulation), the lower thoracic spine (below the spine articulation) and the pelvis. When the sensors performed correctly, they provided a simple way of estimating the orientation of the spine segments in the sagittal plane. It was found that the sensors sometimes did not function properly, resulting in loss of data or generation of spurious data. A different angular velocity measurement system is being placed in the new advanced frontal dummy being developed under the auspices of NHTSA. The typical output from the sensors and the change in angle computed from the integrated signal are shown in Figures 48-53.

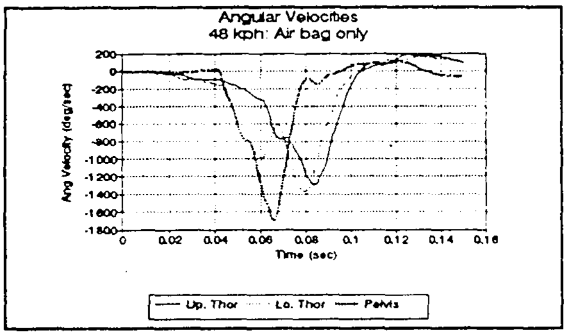

Figure 48. Angular velocities; 48 kph-airbag.

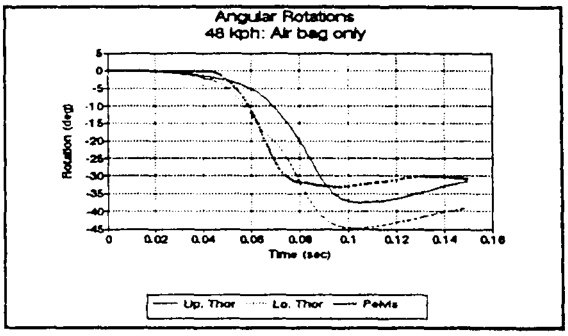

Figure 49. Angular rotations; 48 kph-airbag.

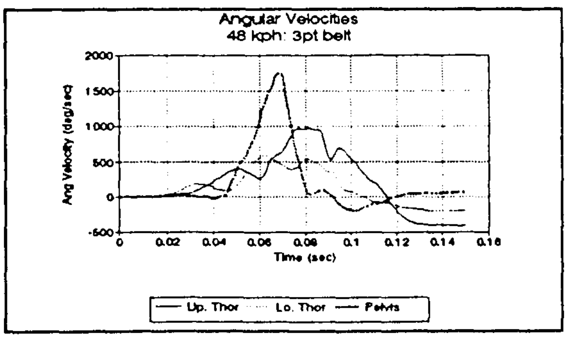

Figure 50. Angular velocities; 48 kph-3pt belt.

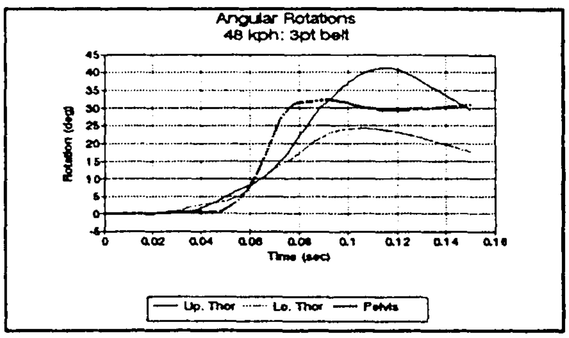

Figure 51. Angular rotations; 48 kph-3pt belt

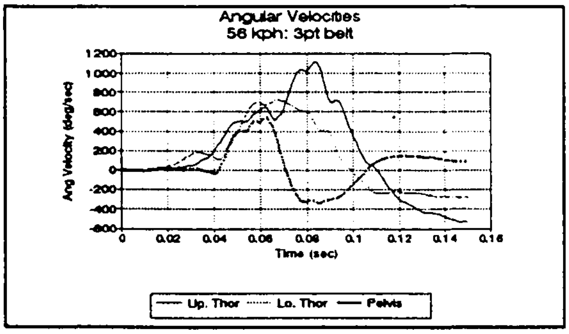

Figure 52. Angular velocities; 56 kph-3pt belts.

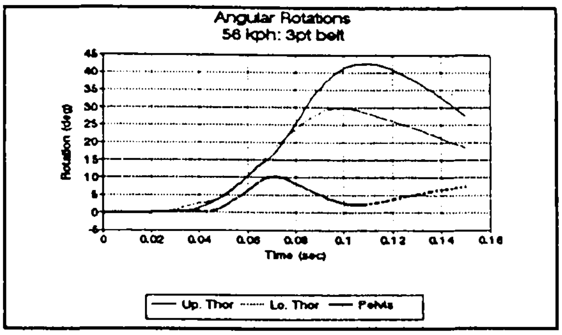

Figure 53. Angular rotations; 56 kph-3pt belts.

Figure 54 shows a reconstruction of the motion using the angular rotation data for the 48 kph 3-pt belt case. The solid line shows the initial position, which was assumed at a normal seating posture, and the little squares indicate the location of the thoracic and pelvic joints. Only the rotational motion is being displayed, by keeping the bottom of the pelvis stationary.

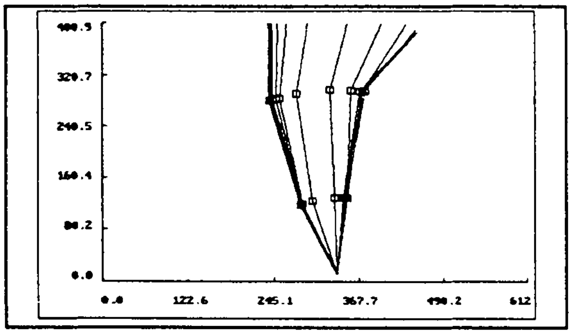

Figure 54. Rotation of spinal segments for 48kph-3pt belt.

CONCLUSIONS

The results from the four barrier tests and their comparison with results from equivalent Hybrid III tests show the following:

1. There is a reduction in HIC in TAD, but the overall motion of the head, both regarding acceleration and displacement are quite similar in the two dummies.
2. There is a slight increase in the chest resultant acceleration in TAD, though again the overall size and shape of the curves are quite similar.
3. There is greater chest deflection in TAD for all restraint conditions, and the TAD instrumentation can assess the asymmetry arising from localized loading of belts.
4. Lap belt loads are significantly reduced in TAD, while the femur forces are generally increased. This is likely due to the difference in seating positions of the two dummies.
5. The greatest difference in the response of the two dummies arise in the case of 3-point belts.
6. The TAD dummy appears to show good repeatability, though each test condition was repeated only twice.

The differences seen between the response of the TAD and Hybrid III, are probably related, apart from differences in the input crash pulse, to the greater flexibility of the spine and ribcage in the TAD and the altered seating position due to the angulation in the thoracic spine. The latter results in a difference in initial seating position, which allows the knees of the TAD to be positioned much closer to the instrument/dash panel. This permits the femur to take a greater proportion of the crash energy as opposed to the lap belt. The difference seen in the 3-point situation arises from the weaker regional coupling in the TAD ribcage as seen in static compression tests described by Schneider [1994]. Also the slippage of the shoulder belt over the clavicle to the base of the neck produces a more pronounced asymmetry on both the upper and lower ribcage on one side, as opposed to the Hybrid III.

The limited results on the repeatability of the dummy (test repeated twice) indicate that the dummy performs in a predictable manner test to test. From the aspect of durability, the TAD has now been subjected to a variety of test environments, and appears to have maintained its response characteristics as seen from pre- and post-test calibration results. There have been problems in some debonding of the damping material

from the steel ribs under repeated tests, and in the accessibility of some of the components. Several of these issues are being addressed in the new frontal dummy now under development.

ACKNOWLEDGEMENTS

The TAD-50M thorax system was developed under contract to the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA). The tests used in these analyses were performed at the Transportation Research Center, Inc (TRC) in conjunction with the NHTSA Vehicle Research and Test Center (VRTC). The digitization of the high speed film was performed at Honda R&D, North America.

REFERENCES

1. Schneider, L., Haffner, M., etal., (1992) "Development of an advanced ATD thorax system for improved injury assessment in frontal crash environments," Proc. 36th Stapp Car Crash Conference, pp 129-155, SAE, Warrendale, PA.
2. Hagedorn, A., Haffner, M., and Schneider, L., (1992) "Performance of an advanced ATD thorax system in frontal crash environments," Proc. 1992 International IRCOBI Conference on the Biomechanics fo Impacts., IRCOBI, Brussels, Belgium.
3. Bohlen, J., and Keller, J., (1995) "Advanced Thorax Dummy (TAD-50M) Versus Hybrid III: A Characteristics Comparison in Frontal Barrier Testing." SAE Paper No. 950666.
4. Ono, K., Hayano, K., Ito, M., and Matsuoka, F., (1996) "Evaluation of TAD-50M Dummy Prototype Performance in HYGE Sled Tests," 15th International Technical Conference on ESV, Melbourne.
5. Schneider, L., Ricci, L., Salloum, M., etal, (1994) "Design and development of an advanced ATD thorax system for frontal crash environments. Volume I: Primary concept development." Final Report on NHTSA Contract No. DTNH22-83-C-07005. U.S. Department of Transportation. National Highway Traffic Safety Administration. Washington D.C.

THE BIOMECHANICS OF THE CERVICAL SPINAL CORD IN ROLLOVER CRASHES

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ABSTRACT

A series of physical models of the human head and neck were constructed to study the biomechanics of the cervical spinal cord during a simulated rollover crash. These models incorporate anatomically similar surrogates for the skull, vertebrae, spinal cord and brain. The spinal cord and brain surrogates have embedded within them a grid of dots to allow visualisation of the deformation patterns within the tissues during the experiment. The mechanical properties of each element of the physical models were matched to those of the human. The kinematics of the head and spine were validated carefully against the cadaver experiments of Pintar et al [1] and the human volunteer experiments of Margulies et al[2].

This model was dynamically loaded in axial compression while high speed film was taken. Individual frames from this film were acquired into a personal computer for analysis. The spatial and temporal patterns of strain in the spinal cord were calculated by digitising the grid points in the spinal cord on each frame and comparing their coordinates with the previous frames. The largest strains were seen in the regions near subluxations from simulated ligament disruptions. The strain rates were calculated, and were sufficiently high in some regions that functional failure of the axons in the spinal cord would be expected in neural tissues undergoing these loads. The location and magnitude of strain and strain rate correlate with regions of cord damage in pathology data from these types of injuries.

INTRODUCTION

Although much work has been done in the biomechanics of spinal injuries, the majority of this work has been focused on the vertebral and ligamentous injury rather than the neural injury. Little has been done to investigate the effects of the injury to the vertebral column on the spinal cord itself. Recent work Bilston et al [3] and Pintar et al [4, 5] has begun to address these problems by the incorporation of a spinal cord surrogate model in simulations of neck injury to measure strain and pressure changes, respectively. The need for a better understanding of the detailed mechanics of spinal cord injuries motivates this study. The aim was to investigate the mechanics of the spinal cord in the most common injury mode leading to neural damage from motor vehicle accidents, namely axial compression of the neck which occurs during vehicle rollovers.

METHODS

Model Construction

A series of inanimate physical models of the adult skull and cervical spine, which are anatomically similar to the human were constructed. Physical modelling techniques have previously been used to study the mechanisms of traumatic brain and spinal cord injury [6-9]. The model construction has been described in more detail by Bilston et al [3]. In brief, these models incorporate a plastic reproduction skull and vertebrae, simulated spinal ligaments and musculature made of elastic, and a silicone gel brain and spinal cord whose mechanical properties are matched to those of the human brain and spinal cord respectively. Prior to assembly, the skull was sectioned approximately 3cm left of the midsagittal plane, and 0.5cm sections of the left lamina of each vertebra were removed to allow visualisation and measurement of the deformation of an embedded grid within the surrogate brain and spinal cord in the models during the simulated injury. The removal of these sections was done in such a way that the articulations of the intervertebral joints and the atlanto-occipital joints were not affected. Black circular markers were placed on the surface of the vertebral elements to allow measurement of

the individual vertebral motions during each experiment. A schematic of the model is shown below (Figure 1).

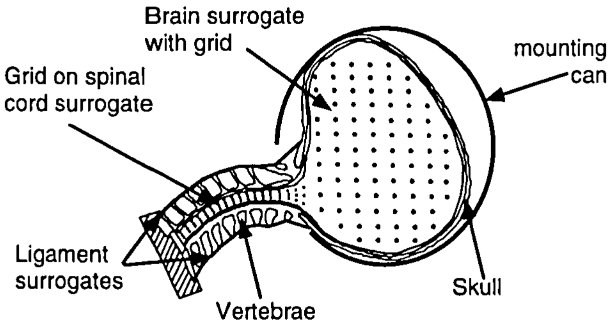


Figure 1. Schematic of the physical model showing the grid embedded in the spinal cord surrogate.

In order to evaluate the effects of a flexion-compression and extension-compression mode of buckling, one model was mounted so that the impact simulated an occipital contact, and the other a crown of the head impact.

Model Validation

It was then necessary to validate the motion of each element of the model against human motions in order to ensure that the model was an accurate rendition of the human head and neck. Two types of validation were performed. The first compared the motions of the individual model vertebra and the axial motions of the spinal cord within the canal to those for normal human volunteers in flexion and extension motions as measured by Margulies et al and further analysed by Bilston [2, 9]. The model was placed on a flat surface, and manually flexed and extended quasistatically. The motion was recorded using a video camera and video cassette recorder. Individual frames were digitised from the videotape using a frame grabber(DT55, Data Translation) in a personal computer. The position of markers on the vertebrae were located, their coordinates digitised on screen and saved to a file using an image analysis program (NIH Image, NIH, Bethesda, MD). The displacement and rotation of each vertebra was calculated relative to the T1 vertebra throughout the motion. The position of grid dots in the spinal cord adjacent to the vertebrae were also digitised, and the relative axial motion calculated.

The second validation process compared the vertebral motions from the model to those from a cineradiographic study using cadaver necks by Pintar et al, and Yoganandan et al [1, 10]. For this validation, a series of frames were grabbed from the film of the model motions during the injury simulation and stored as digital images on a personal computer. Similar to the quasistatic validation, the position of markers on the vertebrae were located, their coordinates digitised on screen and saved to a file. The displacement and rotation of each vertebra was calculated relative to the T1 vertebra throughout the motion.

Injury Simulations

The models were mounted in a materials testing device (Shimadzu, Japan). They were dynamically compressed by 25-35mm at a rate of $1.5ms^{-1}$. Force and displacement data were recorded and stored on a digital oscilloscope (Thurlby DSA254, Thurlby Instruments, UK) at a sampling rate of 10kHz. This data was then downloaded to a personal computer for analysis. The deformations of the surrogate brain and spinal cord throughout the experiments were recorded by high speed photography (Stalex WS-3 camera & Kodak Ektachrome 7297 film) at 1000 frames per second. The films were then processed and transferred to high resolution (SVHS) videotape for further analysis. After the experiments were concluded, the testing device's load cell and LVDT (used to measure force and displacement) were calibrated using standard weights and vernier calipers respectively.

Data Analysis

Individual frames from the videotape were digitised onto the personal computer using a frame grabber board, and saved as digital images. Custom image processing routines were developed, using the MATLAB programming environment (The Mathworks, MA, USA), to digitise the coordinates of the gridpoints embedded in the model spinal cord from the images. The coordinates of the vertebral markers were also digitised from each frame. From these coordinates, the axial strain and average strain rate in the surrogate spinal cord were calculated. This method gives a digitising accuracy of approximately 0.25 pixels, which corresponds to a strain error of approximately ±3%. The strain and strain rate was compared with existing functional tolerance criteria for neural and vascular tissues to tensile loading to determine the likely location and degree of cervical cord injury.

The force and displacement data were read into a spreadsheet, and plotted.

RESULTS

Model Validation

The rotations of the vertebrae relative to T1 during both flexion and extension motions were found to increase along the length of the cervical spine, as shown in Table 1

for flexion and extension motions. In all cases, the rotations were very similar to the motions of normal humans, as measured by Bilston [9], being within the reported range at all times, except that in the extension motion, the rotations for C5-C7 were slightly above the human range. This was deemed to be unlikely to significantly affect the response of the model during axial compression, unless large rotations of the lower cervical spine were seen. The angles also increased with increasing head angle, as shown in Figure 2.

Axial motion of the model spinal cord within the canal was measured during the same flexion and extension experiments. In flexion both the patterns and magnitudes of displacement were very similar to human motions, with increasing displacement with head angle. In the physical model, the cord moved down relative to C3 6mm, near C4 the amount was 4mm, near C5 and C6 the cord moved about 3.5mm. In the Margulies et al study, these amounts were the same as the first subject's motions within 1mm, and very similar to the second subject's motions. In extension, the model cord at C3 level moved caudally approximately 5mm and the C5 region moved caudally approximately 2mm. The C7 region did not move. This is similar to the motions seen for the first subject in the Margulies et al study, (C3=3-8mm, C5=1.5-3.5 mm, C7= 0.5-2.5mm) although another subject had different patterns with each extension motion, some with larger caudal displacements at the lower vertebral levels. This is summarised in Table 2.

Table 1.
Comparison Between the Vertebral Motions in Flexion and Extension for the Current Model and Adult Humans, from Bilston [9]

	Current Model		Human Volunteer	
Vertebral Level	Flexion (°)	Extension (°)	Flexion (°)	Extension (°)
C2	39.6	48.1	40-53	26-48
C3	26.7	30.9	32-47	20-33
C4	26.2	28.4	22.5-33	18-30
C5	22.3	21.6	10-23	12-20
C6	13.6	23.1	2.5-14	3-19
C7	4.8	11.4	-3-+9	-4-+7

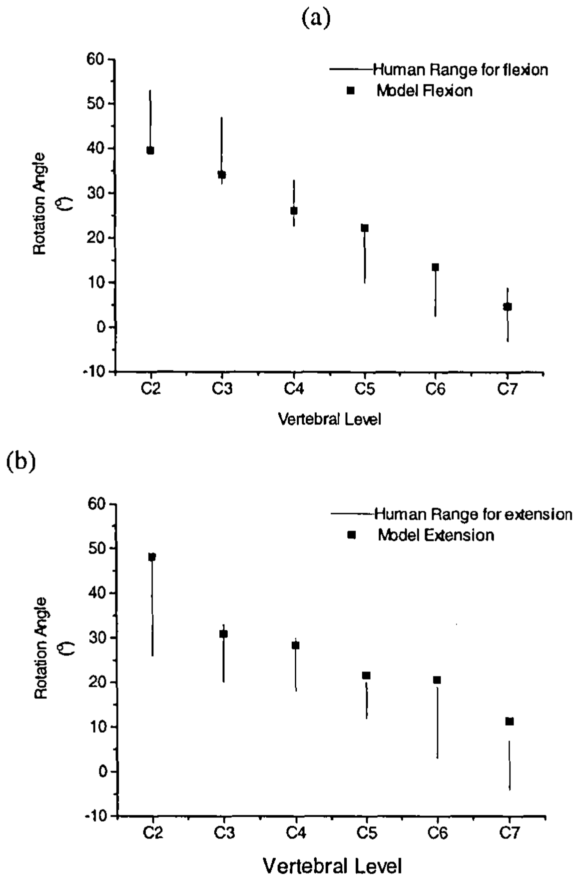


Figure 2. Variation of the vertebral angles with head angle during (a) flexion and (b) extension motions.

Table 2.
Comparison of the Axial Motion of the Spinal Cord during Flexion and Extension for the Current Model and Adult Humans, from Margulies et al [2]

	Current Model		Human Volunteer	
Vertebral Level	Flexion (mm)	Extension (mm)	Flexion (mm)	Extension (mm)
C2/C3	-5.5	-6	-6.3 - +4	-3.6 - -8.7
C3/C4	-5	-5	-5.9 - +2	-4.6 - +3
C4/C5	-3	-3	-4 - +3	-4 - +1
C5/C6	-2.5	-5	-3 - 3.6	-5 - +0.6
C6/C7	-3.5	0	-2.5 - +4	-5 - -1.3
C7/T1	-	-	1.6 -6.6	-3 - -2

Validation of the vertebral motions during axial compression was also performed. The displacement of each vertebra during the injury simulation was calculated and compared to those measured by Pintar et al [1] in their cadaver neck study. The results are summarised in Table

3. Two specific neck injury modes seen in their study were simulated in the current study, namely their first specimen, which had a compression-flexion failure, with a C1/C2 subluxation, and their second specimen, which had a compression-extension failure, with a subluxation of C4 on C5. The pattern and magnitudes of the displacements were within 5 millimetres for these two modes of injury for these vertebral motions, and most were within 2mm. Thus, the vertebral motions of our model appear to be very similar to those experienced by cadaver necks during axial compression.

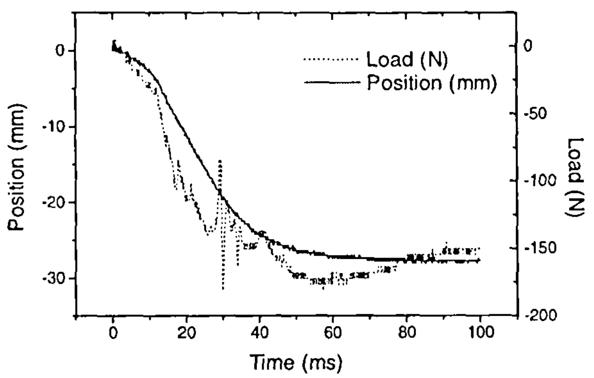
Table 3.
Comparison of the Motion of the Model Cervical Spine in Axial Compression with Data from Yoganandan et al [10] F-C is flexion -compression, and E-C is extension-compression

	Model		Cadaver	
Level	F-C (mm)	E-C (mm)	F-C (mm)	E-C (mm)
C2	11.4	10.4	9.4	12
C3	13.1	7.6	6.4	6.3
C4	3.7	17.6	2.9	12.3
C5	4.5	3.0	6.0	2.5
C6	2.9	2.0	1.4	2.5
C7	2.3	2.6	-	-

Injury Simulations

Force and Displacement Data - The force and displacement data were recorded and plotted. This data showed that the 25-35mm compression occurred over a period of approximately 35-40ms. A sample set of data for a flexion-compression mode and an extension-compression mode are shown in Figure 3. In some experiments, a sudden decrease (or notch) in the measured force was seen part way through the run. This corresponded to the time when dislocation of C4 on C5 happened in the extension-compression mode simulation, or when the C2 dislocation occurred in the flexion-compression simulation. This was seen from the high speed film.

(a)



(b)

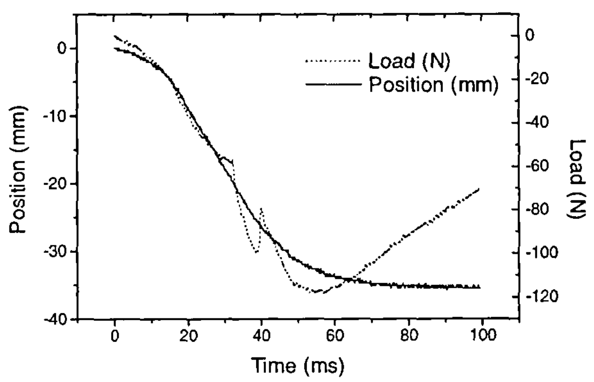


Figure 3. Force and displacement responses of the models in dynamic axial compression. (a) Extension-compression mode, (b) Flexion-compression mode. Force notches in both figures correspond to vertebral dislocations seen on the high speed film.

Spinal Cord Deformation - The model spinal cord showed significant amounts of deformation during the injury simulations. The axial strains and strain rates were calculated throughout the spinal cord during a simulated injury from the high speed film images. The largest strains (up to 40%) and strain rates (up to $6.5s^{-1}$) were, as expected, found in the regions immediately adjacent to vertebral dislocations, when these occurred. That is, in the flexion-compression simulation, the largest strains are adjacent to the C2 dislocation, and in the extension-compression, they are adjacent to the C5 dislocation. The regions of high strain extend for 1-2 vertebral levels above and below the level of the dislocation, however, as seen in Figure 4. The peak values of the strain and strain rates are summarised in Table 4.

(a)

(b)

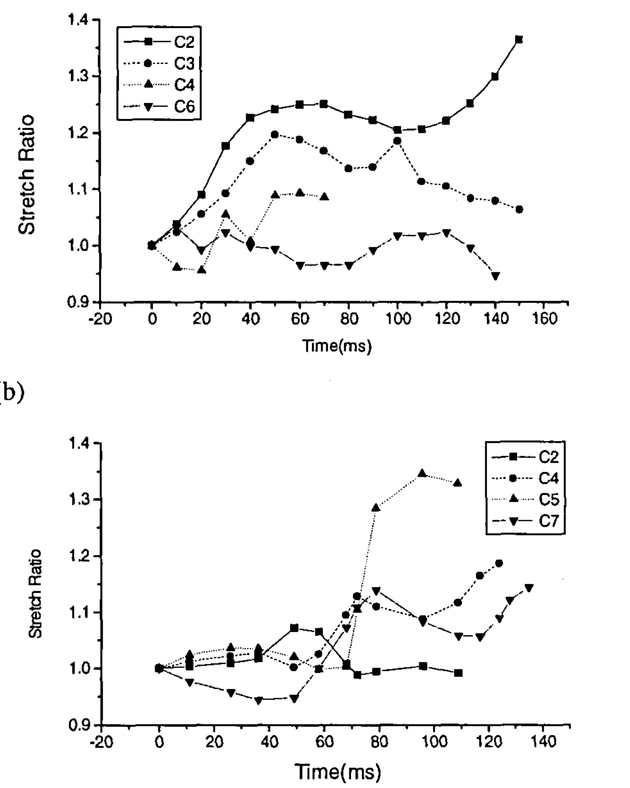


Figure 4. Stretch ratios in the model spinal cord during injury simulations. (a) Flexion-compression mode, (b) Extension-compression mode.

Table 4.
Peak Strain and Strain Rate in the Model Spinal Cord During an Injury Simulation

	Mode	C2/3	C4/5	C6/7
Strain	Extension	40%	23%	7%
Rate	Extension	$6.5s^{-1}$	$4s^{-1}$	$0.5s^{-1}$
Strain	Compression	35%	8%	12%
Rate	Compression	$2s^{-1}$	$1s^{-1}$	$4s^{-1}$

DISCUSSION

In this physical modelling study, several things were observed. First, the largest values of strain and strain rate occurred in the model spinal cord in the region surrounding the simulated dislocations. These strains and strain rates are not confined only to the region immediately next to the dislocation, but tend to be spread over one or two vertebral levels above and below the injury. The values of the strains and strain rates measured in this study can be examined in the light of available data on the mechanical tolerances of axons to dynamic stretch. Work by Galbraith et al [11] on the giant squid axons showed that strains in excess of approximately 15-20% at strain rates greater than $1\text{-}5s^{-1}$ can cause reversible or irreversible injury to the axon, compromising its calcium ion homeostasis, and possibly leading to depolymerisation of its internal structures. From this information, we would expect that the regions immediately surrounding vertebral dislocations would experience some axonal loss from an injury similar to those simulated in this study. This correlates well with the gross cord pathology data reported by Kakulas et al [12-14], which indicates that cord damage is usually centred around a vertebral subluxation when it occurs, with damage spread across two or three vertebral levels around the bony lesion. This also suggests that spinal cord strain and strain rate is a reasonable method of predicting axonal damage in cervical spinal cord injuries.

The methods used in this study are, at best, an approximation of the complex structure and mechanics of the human cervical spine. The model reproduces the kinematics and dynamics of the cervical spine, as demonstrated by the validation studies, but does not reproduce the detail of all the fine ligamentous and meningeal structures. The effects of the ligamenta flava, nerve roots, and dentate ligaments on the cord deformations are not included in this model. It would be expected, however, that the ligamenta flava would tend to increase the local cord strains on contact, rather than ameliorating the deformation. The role of the dentate ligaments and exiting nerve roots, while not simulated by this model, are accounted for in the mechanical properties of the model spinal cord, and its kinematics within the spinal canal, respectively.

The use of physical models to study neural injury is not new, dating to Holbourn's work of the 1940's [6]. They allow the investigation of mechanisms of injury in a direct fashion, provided that the models are suitably validated, kinematically, anatomically, and mechanically. They also provide useful information about mechanical deformation patterns in the central nervous system, as caused by known applied forces and motions. These data can then be used in the construction and validation of finite element simulations, which may be used to further investigate the type of injury under study. The data from this study is currently being used to construct and validate a finite element model of axial compression in the cervical spine to further investigate these disabling injuries. In these models, the effects of such detailed structures as the ligamenta flava, dentate ligaments and nerve roots can also be studied.

Finally, the main aim of basic research, such as this, into the mechanics of spinal injury is to sufficiently understand the injury to be able to design preventative measures to avoid the occurrence of the types of neck

loading which cause long term disability. Such devices might include stiffeners for the vehicle frame to limit intrusion into the passenger space during rollovers, along with better restraint design to prevent the occupant from sliding out of the restraint. It can be seen from this study, that axial neck compressions of as little as 25-35mm can cause severe spinal cord injury, if the forces are sufficiently large to rupture ligamentous structures, allowing subluxations and/or fractures to occur.

CONCLUSIONS

A physical model was constructed to estimate the deformations in the cervical spinal cord under axial compression loading. Two different injury modes were simulated, flexion-compression and extension-compression. Three simulations of each type of failure gave repeatable results from the models. In the flexion-compression models, a dislocation of the atlanto-axial joint was observed, with very large local strains and strain rates in the cord adjacent to that area. In the extension-compression models, a dislocation of the C4-C5 joint was observed, again with large local cord deformations.

A comparison of the measured strains and strain rates with isolated tissue data for axons under tensile loading [11], shows that in both cases, irreversible damage to some of the axons in the regions adjacent to the simulated dislocations might be expected in a live tissue experiencing these loadings. Moreover, the locations of large strain at high strain rates in the model cord correlate well with pathology from human spinal cord injuries, where the regions of worst spinal cord damage are centred around the area adjacent to a vertebral displacement, when this occurs [14, 15].

REFERENCES

1. Pintar, F.A., *et al. Kinematic and Anatomical Analysis of the Human Cervical Spinal Column Under Axial Loading.* in *33rd Stapp Car Crash Conference.* 1989.

2. Margulies, S.S., *et al. In vivo motion of the human cervical spinal cord during flexion and extension.* in *Proceedings of the 1992 IRCOBI conference.* 1992. Verona, Italy.

3. Bilston, L.E., D.F. Meaney, and L.E. Thibault. *The development of a physical model to measure strain in a surrogate spinal cord during hyperflexion and hyperextension.* in *Proceedings of the 1993 IRCOBI conference.* 1993. Eindhoven, The Netherlands.

4. Pintar, F.A., N. Yoganandan, and M. Schlick. *Biodynamics of cervical spinal cord injury.* in *IRCOBI.* 1995. Lyons, France: International Research Council on the Biomechanics of Impact.

5. Pintar, F.A., *et al., Measurement of Dynamic Spinal Cord Pressure,* in *Crashworthiness and Occupant Protection in Transportation Systems.* 1993, ASME, Bioengineering Division. p. 183-188.

6. Holbourn, A.H.S., *Mechanics of head injuries.* Lancet, 1943. **2**: p. 438-441.

7. Margulies, S.S., L.E. Thibault, and T.A. Gennarelli, *Physical Model Simulations of Brain Injury in the Primate.* J Biomechanics, 1990. **23**(8): p. 823-836.

8. Meaney, D.F. and L.E. Thibault. *Physical Model Studies of Cortical Brain Deformation in Response to High Strain Rate Inertial Loading.* in *Proceedings of the 1990 IRCOBI Conference.* 1990. Lyon, France.

9. Bilston, L.E., *The Biomechanics of the Spinal Cord During Traumatic spinal cord injury,* in *Bioengineering.* 1994, University of Pennsylvania.

10. Yoganandan, N., *et al., Strength and Kinematics Response of Dynamic Cervical Spine Injuries.* Spine, 1991. **16**(10 Suppl): p. S511-517.

11. Galbraith, J.A., L.E. Thibault, and D.R. Matteson, *Mechanical and electrical responses of the squid giant axon to simple elongation.* Journal of Biomechanical Engineering, 1993. **115**: p. 13-22.

12. Kakulas, B.A., P.F. Jacobsen, and G.M. Bedbrook, *Acute spinal injuries. A clinico-pathological study.* Proc Veterans Adm Spinal Cord Inj Conf, 1973(19): p. 84-95.

13. Kakulas, B.A., *Pathology of spinal injuries.* Cent Nerv Syst Trauma, 1984. **1**(2): p. 117-29.

14. Davis, D., *et al., The pathological findings in fatal craniospinal injuries.* J Neurosurg, 1971. **34**(5): p. 603-13.

15. Kakulas, B.A., *The clinical neuropathology of spinal cord injury. A guide to the future.* Paraplegia, 1987. **25**(3): p. 212-6.

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A DUMMY NECK FOR LOW SEVERITY REAR IMPACTS

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ABSTRACT

Neck injury in car collisions is rapidly becoming one of the most aggravating traffic safety problems with serious implications for the society. From studies performed in European countries such as Sweden, Germany and the Netherlands, but also in Canada and Japan, it is found that a very large proportion to traffic injuries to the neck are due to rear impacts. In order to reduce these injuries an increasing number of studies are performed to evaluate the effectiveness of head restraints. However, the current available crash test dummies are not biofidelic for low-severity rear impacts. Since 1995, TNO has started the development of a Rear Impact Dummy. In this paper the kinematic performance requirements for a Rear Impact Dummy neck are defined, the Hybrid-III neck response is evaluated, a new neck is designed and, finally, this neck is evaluated using pendulum and sled experiments. This neck is the first step towards the development of a complete Rear Impact Dummy.

INTRODUCTION

Neck injuries in traffic accidents result in human suffering and high societal costs. This is due to a high injury incidence and a large risk of long term impairment. The annual societal costs for neck injuries from rear impacts only in Sweden (8 million citizens) are estimated to 210 MECU [1]* (270 million US$).

* Number in parentheses designate references at the end of the paper.

In British Columbia, Canada, (3 million citizens) these injuries accounted for 68% of the motor vehicle accident insurance claims in 1989 and the annual number of about 32000 claims was estimated to 250 million CND (450 MECU) [2]. A Dutch study by van Kampen [3] showed a 29% increase in the annual number of rear collisions and a 54% increase in the number of neck injuries during the period 1983 to 1991. The fraction of rear impacts resulting from chain collisions increased from about 3% to more than 30% during the same period. The yearly liability insurance claims due to these injuries in the Netherlands have been estimated to 150 MECU, and for all of the Dutch society >300 MECU, with an annual number of claims of about 11000 [4]. In Germany, neck injuries occur in 82% of all car/car crashes involving personal injuries and the costs to the society have been estimated to 700 MECU [5]. A cost estimate for the European society for neck injuries in rear impacts would be in the order of 5-10 billion ECU/year. A figure, which is steadily increasing.

From Japanese insurance data [6], it has been reported that >50% of traffic injuries are to the neck, and 65% of these are due to rear impacts, with an increase of 30% over the last 7 years. German [7] insurance data have recently shown that 50% of all injuries are caused in rear collisions and 90% of the people in this accident type suffer neck injuries. These injuries in rear impacts mostly occur at low impact velocities, typically less than 20 $km.h^{-1}$. In spite of these low velocities, the injuries lead to permanent disability in about 10% of the cases [8]. Women were found to be up to twice as vulnerable as men in rear accidents (e.g. [9]).

The efficacy of current head-rest designs in reducing the number of "whiplash" injuries is not proven. In the UK, Morris [10] studied 106 patients suffering from neck injuries incurred in rear crashes and found increased incidence when cars did not have a head-rest; whereas, Olney and Marsden [11] and Hildingsson [12] found that the presence of a head-rest did not affect clinical outcome. The question of head-rest position was, however, not addressed in any of these studies. Kahane [13] showed that integral head-rests designed to the American regulation FMVSS 202, reduced the overall risk of injury in rear crashes by 17%. In this study, it is claimed that adjustable head-rests reduce the neck injury risks by 10%.

Technical limitations

In a survey of 4983 cars [14], 78% of drivers had incorrectly positioned head-rests. Nygren et al. [15] found 83% of adjustable head-rests in low position during normal driving. In a Dutch study [3], it was found that only about 40% of the male and about 50% of the female occupants had adjusted their head restraints to the correct height. However, it should be noted that a head-restraint that meets, but does not exceed, the minimum height requirement of the European vehicle regulations, only enables correct height adjustment for males shorter than the 25th percentile male and for females shorter than the 90th percentile female of the Dutch population [3]. In other words, current minimum height requirements in Europe are insufficient to protect the larger part of the population.

Recently, TNO has analyzed an inquiry among approximately 5000 Dutch "whiplash" patients. Data from 2355 patients were received back and put in to a database; 609 male patients (26%) and 1746 female patients (74%). In 1978 cases the symptoms were caused by a car-accident (84%) and in 377 cases by another accident (16%), for instance a sport-accident. In 67% of the car-accidents a rear impact (including chain-collisions) caused the whiplash. In 87% of these rear impacts a head-rest was available, however, only 16% of these headrests were placed in the highest position. Of the victims involved in a rear impact, 74% did not 'foresee' the impact. The complaints caused by the rear impact started sometimes immediately or up to 1800 days after the accident, with an average value of 12 days.

Rear Impact Dummies

The Hybrid III-dummy is the most widely used crash test dummy. In the literature, however, the rear impact biofidelity of the Hybrid-III has been discussed by many researches. A lack of rear impact biofidelity is addressed to too high resistance to bending of the neck and the torso at low severity. Unfortunately, in some cases these conclusions are based on frontal human impact analysis and models which were not based on well defined rear impact experiments. Despite these misleads, a severe $+18G_x$ rear impact experiment with the Hybrid-III dummy and a Post Mortem Human Subject (PMHS) [9], and low-severity rear impact experiments with the Hybrid-III dummy and volunteers [16] showed that a new dummy for this impact type is urgently needed to enable reliable assessment of the occupant motion during a low-severity rear impacts.

OBJECTIVE

The objective of this study is to develop a new biofidelic Rear Impact Dummy (RID) neck to be used in combination with the 50th percentile Hybrid-III dummy in order to evaluate head-rests in rear impacts up to 25 $km.h^{-1}$ (16 mph). In this paper, the performance requirements for such a neck are defined, the response Hybrid-III neck is evaluated, a new neck design is described and, finally, the neck is evaluated using pendulum and sled experiments. The development of a RID neck is a first step in developing a Rear Impact Dummy (RID) that can be used to assess the performance of complete car seats in rear impacts.

No attempt has been made here to determine new injury thresholds and to define injury mechanisms since quantative data is very sparse in terms of "whiplash" thresholds [8], [17], [18], [19], [20], [21]. It is, however, believed that the application of an appropriate dummy will further help in establishing injury thresholds and mechanisms.

DESIGN REQUIREMENTS

A human-like neck must not only fulfil requirements of anthropometry and inertia but it should also describe the dynamic human head and neck response. Until today, however, a complete set of performance requirements [22] is not available but minimum requirements for a RID neck are an accurate representation of the human head rotations and neck bending, otherwise the head might impact the head-rest in a different location or even will have no contact with the head-rest or parts of the interior.

In this study these requirement are derived from static and dynamic head-neck responses from literature.

Voluntary Range of Motion

White and Kapandji [23] reported voluntary total head rotations varying from 54.4 to 72.2 degrees for flexion and 39.4 to 93.2 degrees for extension. Schneider et al. [24] determined the voluntary range of motion of 18 young male adults. They found values of 54.4 to 72.4 degrees for flexion (mean 60.5 degrees) and 63.0 to 87.5 degrees for extension (mean 79.0 degrees). The results also indicated that combined rotations in other planes significantly reduces flexion and extension in the sagittal plane.

Mertz and Patrick [25] summarized the data available for male and females for various age groups. They found that the extension range was 51-92 degrees with a mean of 73 degrees and the flexion range 50-90 degrees with a mean of 66 degrees. The female subjects had a greater mean range of motion in the cervical spine 69 degrees for flexion and 81 degrees for extension respectively. The total range of motion decreases with age, i.e. 139 degrees for 15-24 year old group to 116 degrees in the 55-64 old group.

In rear impact conditions McElhaney [17] stated that a potential for suffering a whiplash exist when the head rotation exceeds 60 degrees.

Kinematic Head-neck Response in Extension

Figure 1 shows the maximum head angle relative to the torso as a function of the average sled acceleration. The relationship is based on the results of low velocity volunteer sled experiments conducted by Ono and Kanno [6], [26], the PMHS sled experiment without headrest conducted by Foret-Bruno et al. [9], the sled experiments with PMHSs and a single volunteer conducted Mertz and Patrick [27], the pendulum experiments with volunteers conducted Tisserand [28], the volunteer sled experiments conducted by Szabo et al. [29] and Scott et al. [16], and a $+7G_x$ unembalmed PMHS test program at Heidelberg University [30]. The figure shows a clear relation between the average acceleration and the maximum head rotation, except for the case of the PMHS of the Mertz and Patrick volunteer who tensed his neck muscles, and one of the Heidelberg PMHS (a young PMHS, no injuries at $+7G_x$).

Except for the single Mertz and Patrick volunteer experiment, all volunteers were assumed to be relaxed. It must be noted, that the volunteers in experiments conducted by Szabo et al. and Scott et al. were seated in a non-rigid seat, while in the others used a seat with a rigid back support. This could explain a part of the dispersion as shown in the figure at low G-levels.

The head angles are not corrected for the rotation of the T1 vertebral body, so the head rotation incorporates the influence of the thoracic column

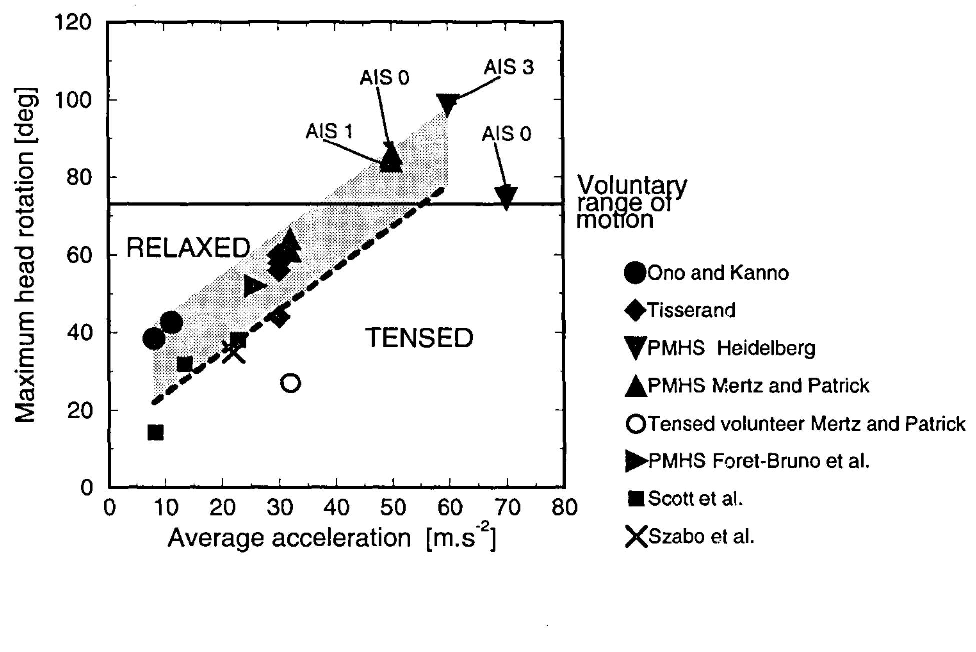

Figure 1 Relation between the average acceleration and the maximum head rotation relative to the torso.

flexibility [22]. This approach is chosen because a neck retrofitting the Hybrid-III dummy should incorporate the flexibility of the human thoracic spine since the dummy's spine is rigid.

Figure 1 suggests that already considerable head rotation can be expected at low and medium G-levels. The relationship between the maximum head rotation and the average acceleration is clearly linear. So far no asymptotic response [31] at high G-levels could be observed due to lack of data, but there are no reasons not to assume an asymptotic response at high G-levels.

Head lag Detailed analyses of the Ono and Kanno volunteer experiments by Happee et al. [26] and the recent performed PMHS experiments [30] indicate that the typical horizontal head motion seen in frontal impacts, the socalled head lag [22], is not observed in these rear impacts. For the PMHS experiments but also for the relaxed Ono and Kanno volunteer, this can be addressed to the low impact severity level and the initial position.

Response Corridors

From the Dutch accident analyses it was shown that most of the victims are unexpectedly subjected to a rear collision and do not have the time for their muscles to react in order to resist the head excursion. Therefore, the performance requirements for a RID dummy neck should be based on relaxed volunteers and PMHS responses. Unfortunately, the response corridors for a rear impact dummy neck cannot be as extensive as defined for frontal impacts [22] due to lack of data. Therefore, only three sets of response corridors can be defined: the moment of force at the occipital condyles joint as a function of the head angle and two head rotation-time history corridors based on the relation between the maximum head rotation versus the average acceleration, see figure 1 , the grey area.

Head Rotation-Time The head rotation-time histories relative to the torso, see figure 2 , are based on the head angle-time histories from the "non-severe" (top figure) and "severe" (bottom figure) Mertz and Patrick PMHS experiments [27] and the pendulum experiments conducted by Tisserand [28] (i.e. impact severity comparable with the "non-severe" experiments of Mertz and Patrick [36]).

Moment of force-head rotation In 1971 Mertz and Patrick [25] stated that the angle between the head and the torso is not a good physical measurement of trauma

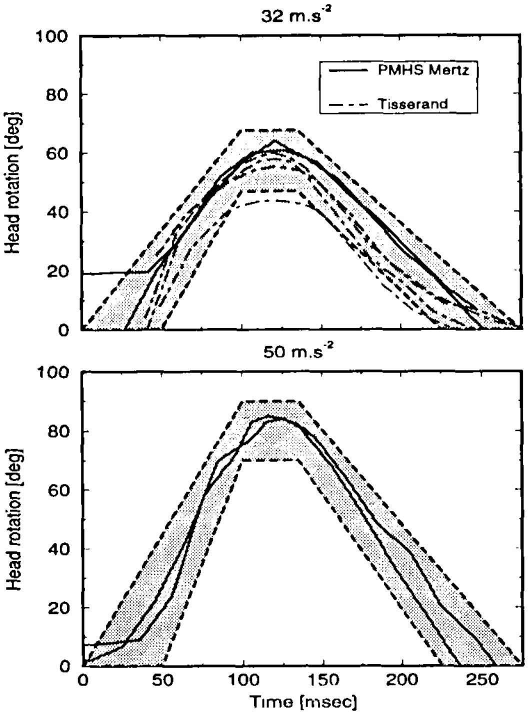

Figure 2 Head rotation-time histories based on the Mertz and Patrick PMHS, and the Tisserand volunteer experiments. Average acceleration 32 (top) and 50 m.s^{-2} (bottom).

for injuries resulting from neck extension or neck flexion. Therefore, they presented head angle-moment of force corridors for neck flexion and extension, see figure 3 , and they suggested tolerance levels for hyperextension. The non-injurious level was defined at 47 N.m with a maximum voluntary head rotation of 75 degrees. The ligamentous damage level was defined at 57 N.m. Of course, size, weight, age, sex and other factors are expected to affect these levels. From these experiments, Kornhauser [20] determined a cervical spine injury threshold based on ΔV. Kornhauser defined the injury threshold for ligamentous damage at 2.2 m.s^{-1}. However, recent work with human volunteers in rear collisions [29],[32],[33] showed that this threshold is rather low, the volunteers can sustain higher ΔV levels without injuries.

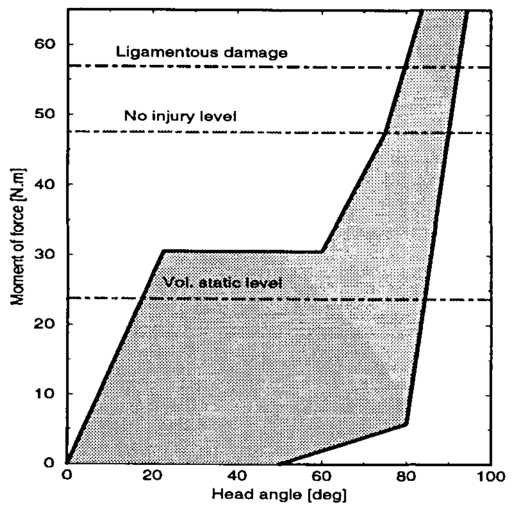

Figure 3 Moment of force at the occipital joint as a function of the head rotation. From Mertz and Patrick [25].

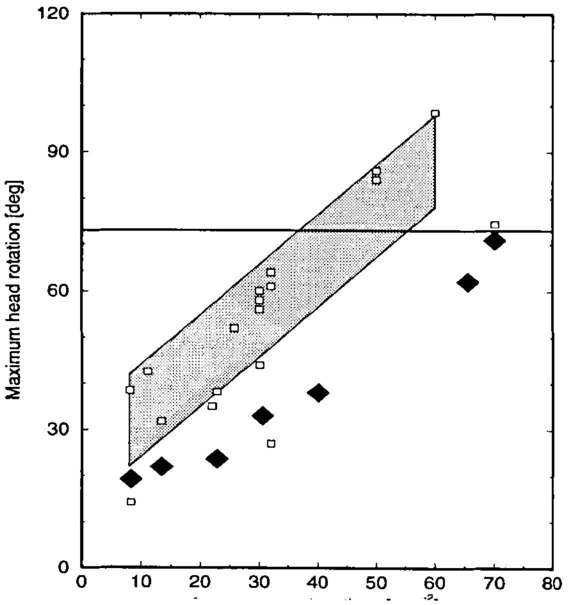

Figure 4 The maximum Hybrid-III head rotations (♦) as a function of the average acceleration. (□ are the volunteer and PMHS responses).

Evaluation of the Hybrid-III

Figure 4 shows the results of sled experiments with a complete 50th percentile Hybrid-III dummy [9],[16]* in equivalent test conditions as the volunteers and PMHSs. The figure indicates that the Hybrid-III neck is too stiff for low severity rear impacts since tne maximum head angles are too low if the car-occupant is relaxed i.e. unaware of the impact.

The use of a RID neck will be in the range between average accelerations 15-50 $m.s^{-2}$ (ΔV between 2-7 $m.s^{-1}$) [34].

NECK DESIGN

A first step was made by Chalmers University, by developing a special prototype Rear Impact Dummy (RID) neck for low-severity rear collisions [35], called the Chalmers RID-neck, which retrofits the current Hybrid-III (50th percentile). The response of the Chalmers RID-neck was validated using data from literature [36].

The TNO Crash-Safety Research Centre, after consulting Chalmers University, has updated the Chalmers RID-neck design and further evaluated its biofidelity and comparative behaviour with the Hybrid-III neck. These development efforts have resulted in a new neck design: the TNO Rear Impact Dummy-neck, TRID-neck. This section gives a short description of the TRID-neck development and design.

TRID-I

The first prototype neck design, the socalled TRID-I neck, closely resembles the Chalmers RID-neck and is a 2-dimensional anatomically based representation of the human cervical spine. As the Chalmers RID-neck, the TRID-I neck consists of nine articulating segments. These segments are connected to each other by means of hinge joints, allowing only flexion-extension motion (in the sagittal plane). All segments have the same height because of simplicity of the design. In between the segments, deformable elements are placed that provide the correct stiffness

* And from dummy sled-tests conducted at Heidelberg University.

and initial position of the neck and allow extension (and flexion) over the full anatomical range of motion.

The anatomical range of motion is based on voluntary motion, which for the cervical area amounts 40 degrees in flexion and 75 degrees in extension. To account for some thoracic spine flexibility, 3 degrees both in flexion and extension is added to represent the flexion/extension motion in the two upper thoracic vertebrae. This results in an anatomical range of motion of the total system of 43 degrees in flexion and 78 degrees in extension. The TRID-I neck allows for 48 degrees in flexion and 83 degrees in extension. This increase of 5 degrees in both directions is added to avoid unrealistic bottoming out effects at the end of the anatomical range of motion. No attention is paid to the fact that muscle activity could reduce the range of motion of the human cervical spine segments [37] nor was the neck optimized to obtain full frontal biofidelity.

The lordosis of the cervical spine of adults is not accounted for, which simplifies the design because all hinges can be aligned vertically if no pre-compression of the intervertebral elements is present. In the automotive seating posture, the neck is flexed 14 degrees, see figure 5 . In the TRID-I neck, this is achieved by equally adjusting the height of all inter-vertebral elements.

An evaluation of this neck design showed poor repeatability and reproducibility due to permanent deformation of the intervertebral elements (foam). Also, the outer shape of the Chalmers RID-neck and the TRID-I neck allows two unrealistic interferences. First, the chin of the Hybrid-III head can contact the neck in rebound. Second, the gaps between the vertebral segments could "grab" head rest fibre or a possible airbag.

TRID-II

A MADYMO model was used to optimize the TRID-I neck design. Below, the most important design changes with respect to the Chalmers RID-neck and the TRID-I neck are explained. The resulting design (the TRID-II design) is presented at the end of this section.

Whereas the Chalmers RID-neck and the TRID-I neck include 9 segments, the human neck has only 7 segments: cervical vertebrae 1 though 7. The rationale behind the original design is that the Hybrid-III neck length (144 mm) is divided by the average cervical vertebrae length (16 mm) from anthropometry studies. This in fact implies that the Hybrid-III neck length is somewhat larger than the actual 50th percentile adult human neck. For a correct neck response in rear impact, however, it is believed that it is more appropriate to represent the number of cervical segments (i.e. vertebrae) rather than to correct the neck length. The TRID-II neck, therefore, includes 7 segments, representing C1 through C7.

Between the rigid vertebral segments, the TRID-II neck incorporates compressible elements, representing the intervertebral bodies. The stability and correct initial position of the TRID-II neck are accomplished by pre-

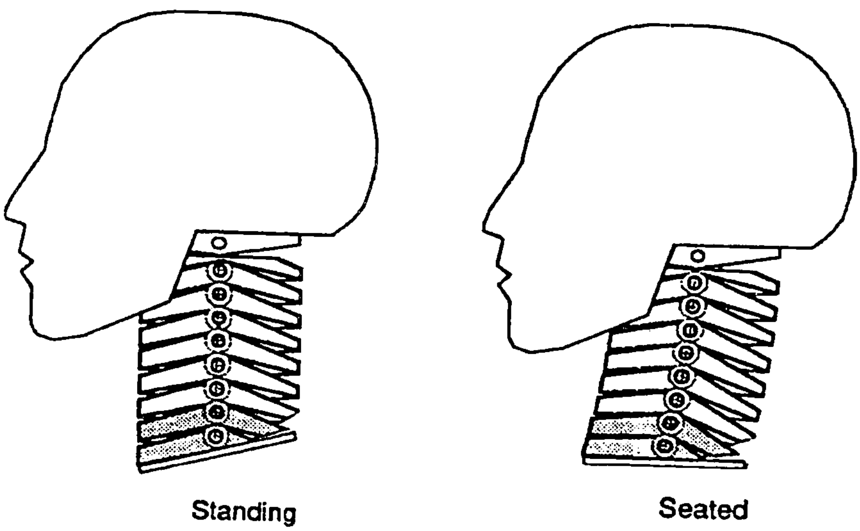

Figure 5 Schematic drawing of the TRID-I neck and head assembly in standing and seating (14 degrees flexed) posture. From [35].

compression of these intervertebral elements, similar to that of the Chalmers RID-neck and the TRID-I neck. Nor in the Chalmers RID-neck, nor in the TRID-I neck provisions are made to prevent bottoming-out of the intervertebral elements. With these two necks, the intervertebral elements can be fully compressed, which is known to cause microscopic permanent deformation and hence could result in poor repeatability and reproducibility. To prevent the intervertebral elements to bottom-out at the end of range of motion, small rubber buffers are included in the TRID-II neck. The rubber buffers included in the TRID-II neck also prevent unrealistic hard contact between the vertebral segments.

The TRID-II neck has been designed such that it closely matches the outer shape of the Hybrid-III neck and that possible interference with head rest fibre or an airbag is kept to a minimum. Furthermore, the TRID-II neck retrofits the 50th percentile Hybrid-III: it can be applied by just replacing the standard Hybrid-III neck. Also, the neck instrumentation available for Hybrid-III can be applied with the TRID-II neck. Figure 6 shows the TRID-II neck in full assembly. Figure 7 shows the parts of the TRID-II neck ("exploded view").

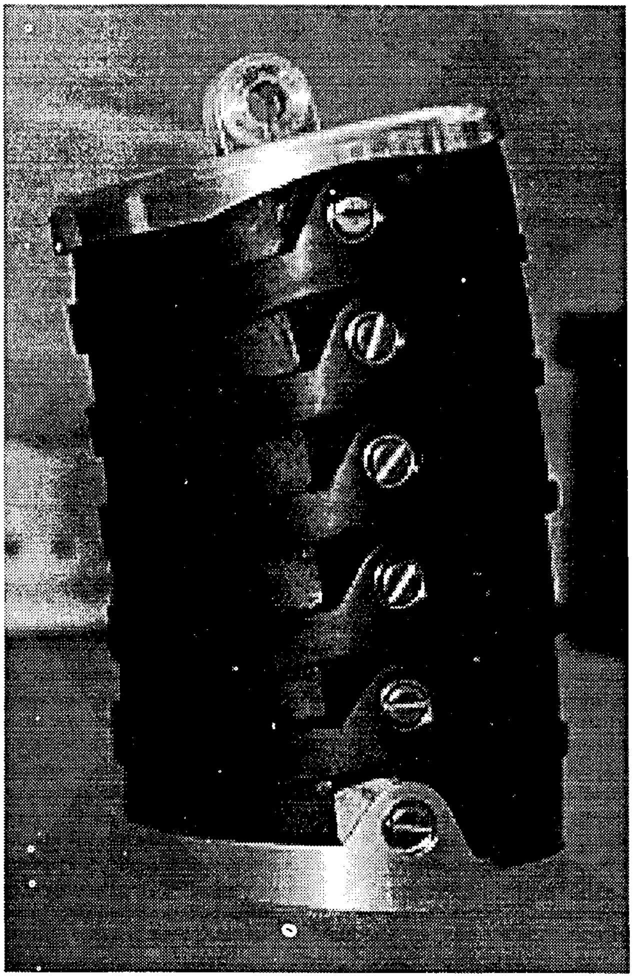

Figure 6 Full assembly TRID-II neck.

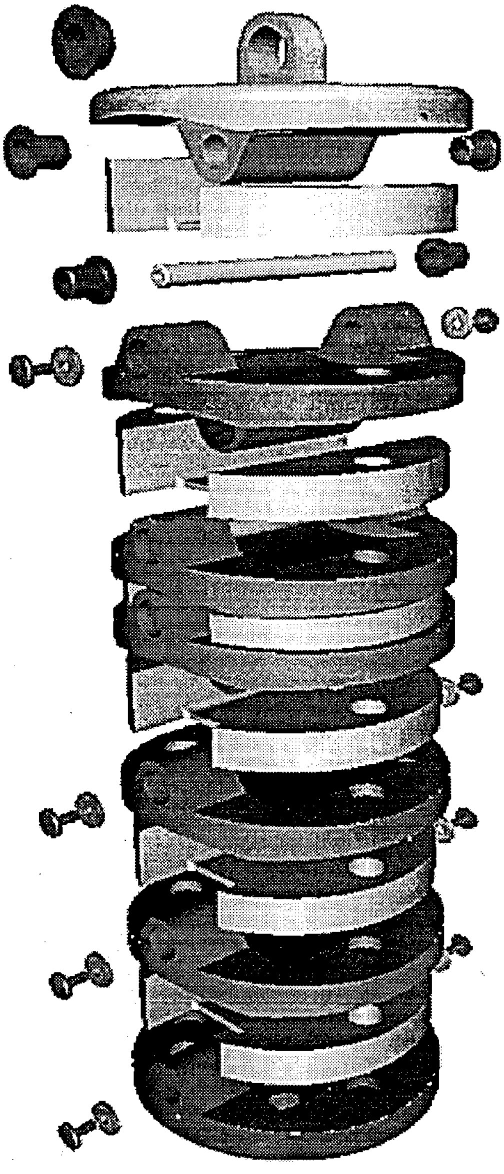

Figure 7 Exploded view TRID-II neck. The intervertebral elements and the rigid vertebral bodies.

EVALUATION DESIGN

The response of the TRID-II neck is evaluated in pendulum and sled experiments. The results are presented below.

Sled experiments

A series of sled experiments are conducted in order to compare the response of the 50th percentile TRID-II neck with the response of 50th percentile Hybrid-III neck, both necks are mounted on a 50th percentile Hybrid-III dummy. In these experiments, a 50th percentile Hybrid-III dummy was seated on a rearward faced rigid seat. The seat-back angle is 22 degrees, with no head-rest. Two different impact velocities are chosen, 5 and 8 $m.s^{-1}$. The experimental conditions meet the test conditions as used by Mertz and Patrick [27].

Results In this study, the Hybrid-III and the TRID-II responses are compared in terms of four parameters: the maximal neck bending moment of force at the occipital condyles joint, the maximum neck shear and axial force, and the maximum resultant head acceleration of the head centre of gravity, see table 1.

The table indicates that the resultant head-accelerations of the TRID-II, without a head-rests, resembles those as obtained with the Hybrid-III neck (without a head-rest). Also for the case without head-rest, the forces and moments of force are comparable.

The figure in the annex shows the resultant accelerations at the head centre of gravity and the loads at the occipital condoles joint. The figure shows the Hybrid-III, the TRID-II and literature values [27],[30]. The figure indicates that in general the TRID-II response is closer to the results from the literature than the Hybrid-III.

The head-angle time histories as derived from the sled experiments are show in figure 8 . This figure shows that the experimental data fits within the defined head-angle time corridors except for the last part of the unloading phase. The maximum values of the measured angles are on the upper side of the corridor, but the sled experiments were slightly more severe than the conditions for which the corridors are defined (i.e. 36 and 53 instead of 32 and 50 $m.s^{-1}$, respectively).

The moment of force as a function of the head angle of the TRID-II neck fits within the Mertz extension corridor, see figure 9 .

Pendulum Experiments

The reproducibility of the TRID-II neck design was evaluated for three sets of intervertebral disks with increasing rubber stiffness (configurations S1, S2, S3, S2 is the base type of material).

The evaluation tests were conducted using a Hybrid-III calibration pendulum. The components used for the neck tests included the Hybrid-III head assembly, two TRID-II neck assemblies, the Hybrid-III lower neck bracket. The neck with the Hybrid-III head was mounted on the rigid pendulum so that the head's mid-sagittal plane was vertical and coincided with the plane of motion of the pendulum longitudinal centerline.

Table 1 Sled experiments. The maximum head rotations, linear accelerations at the head centre of gravity, head-neck moments of force and forces at the occipital condyles.

Neck	Sled		Max. head rotation [deg]	Max. res. acc. at head CG [$m.s^{-2}$]	Max. force at OC		Max. moment at OC [N.m]
	Aver. acc. [$m.s^{-2}$]	ΔV [$m.s^{-1}$]			Shear [N]	Axial [N]	
H-III	36	5.1	42	70	242	219	16
TRID-II	36	5.2	64	69	257	294	26
TRID-II	36	5.2	63	69	254	292	27
TRID-II	53	7.9	84	143	317	647	40
TRID-II	53	7.9	89	152	374	692	41

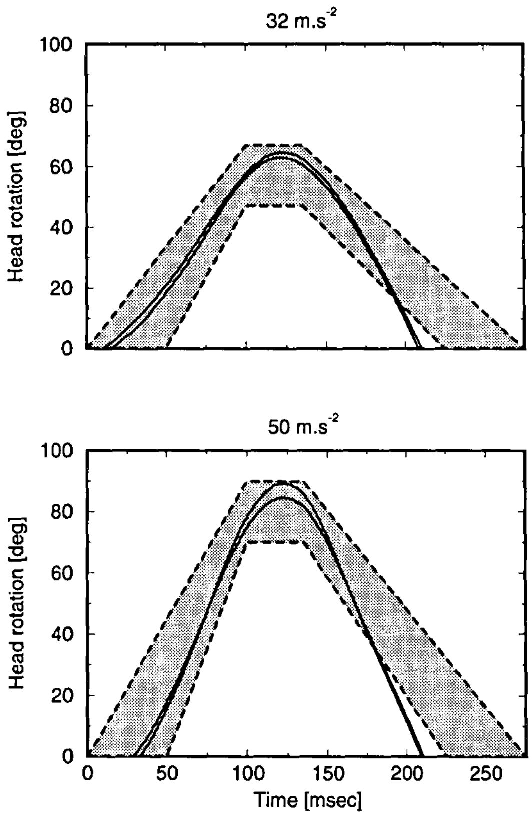

Figure 8 The defined head-angle time corridors and the TRID-II head angles as obtained in the sled experiments (solid lines).

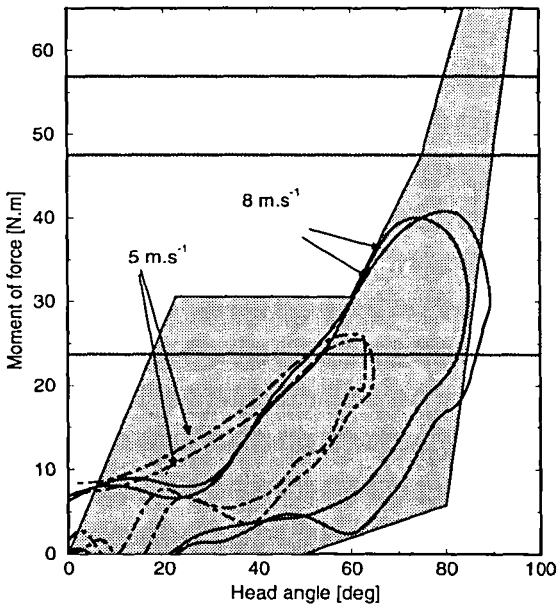

Figure 9 The moment of force-head rotation relation of the TRID-II and the Mertz corridor for extension.

The pendulum was allowed to fall freely from a height such that the velocity of impact was either 3 or 4 $m.s^{-1}$, measured at the centre of the pendulum accelerometer. A total of 9 cells of honeycomb material were used to produce the desired pendulum deceleration of 10-12 g with a duration of about 40-50 ms. A period of 15 minutes was allowed between successive tests on the same neck. The set-up was instrumented with accelerometers and force transducers complying with the Hybrid-III calibration procedures.

Results Perturbation of the test variables, i.e. intervertebral element stiffness and impact velocity, yields six different test conditions. To avoid overloading of the neck, high velocity impacts were not performed. The total head rotation in extension versus time histories as measured by the rotational potentiometers are shown in figure 10 . The responses combine the results of repetitive tests for two neck assemblies. The figure demonstrates that the effect of varying the stiffness of the intervertebral elements on the kinematic response is large and that both repeatability and repeatability of the kinematics of the TRID-II neck assemblies are good.

DISCUSSION AND CONCLUSIONS

From the state-of-the art review, it is obvious that there is a need for a Rear Impact Dummy. However, the development of such a dummy can only be done if we obtain better knowledge of the injury

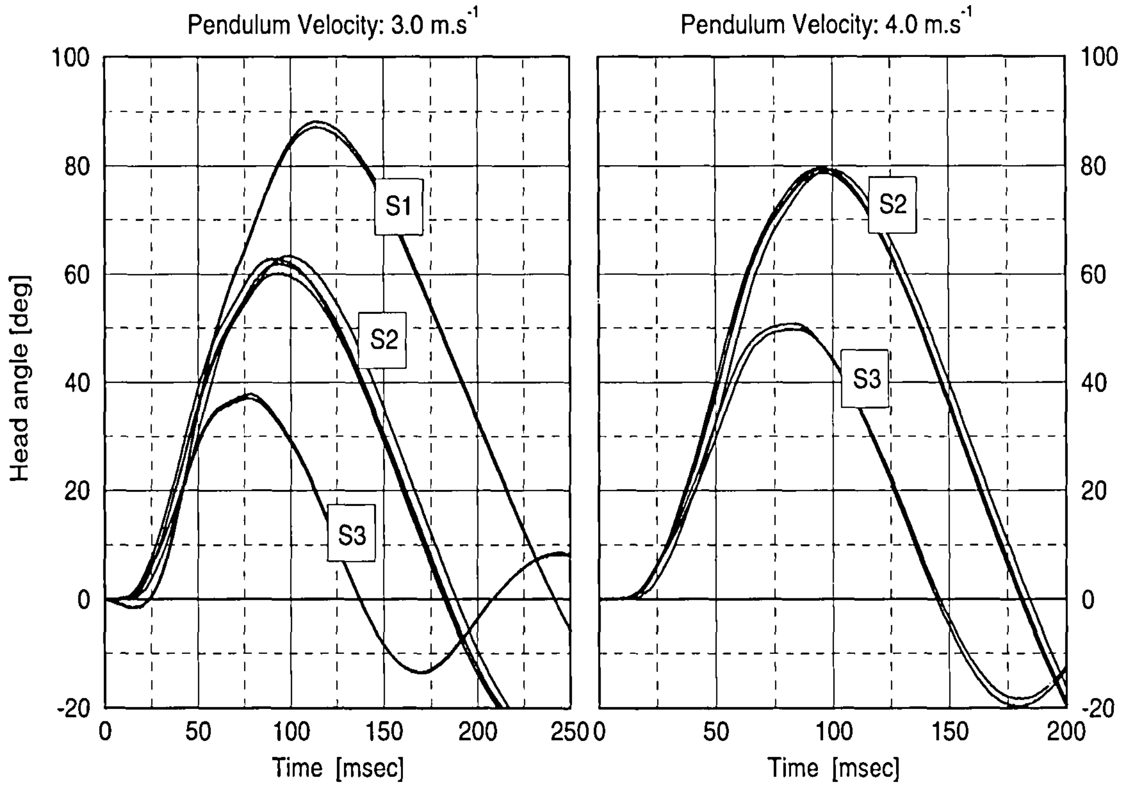

Figure 10 **The head-time histories as obtained from the pendulum experiments. Three different intervertebral elements with increasing stiffness were used (S1-S2-S3). S2 is the standard stiffness.**

mechanisms so that we can develop effective design and test tools and guidelines for new seat/headrest concepts. In this way, new and safer products can be developed. However, deviating from most other injuries, for "whiplash" there does not seems to be a single injury mechanism. The loading condition most identified with "whiplash" is hyperextension. However, "whiplash" can also be a result of other phenomena.

Rear Impact Dummies

A Rear Impact Dummy (RID) is considered an essential tool to establish the risk of injuries in rear-end collisions, such as "whiplash" trauma. TNO strongly believes that the development of a RID is necessary to understand the complex problem of neck trauma and car seat/head restraint performance in these conditions. The development of the TRID-II neck is a first step in developing the a Rear Impact Dummy (RID) that can be used to assess the performance of complete car seats.

Design Requirements

Until today no complete set of performance requirements was available for a RID-neck. In the present study, a limited kinematic set is derived from the literature: two head angle-time history corridors and a maximum head rotation-average acceleration corridor. The response corridors are based on relaxed car-occupants who are unaware of a rear impact. To enable the capability of injury assessment the Mertz neck load corridor for extension is selected.

Hybrid-III

The response of the Hybrid-III dummy has been evaluated with the maximum head rotation corridor and it was shown that the Hybrid-III neck is too stiff for low-severity rear impacts if the occupant is unaware of the impact. The Hybrid-III neck tends towards the response of a tensed occupant.

TRID-II

The design process has been described step by step and the final design, the TNO Rear-Impact Dummy Neck, version II (TRID-II), has been evaluated. The TRID-II neck consists of seven rigid vertebral elements and six deformable elements.

The TRID-II neck has been developed to retrofit the current Hybrid-III (50th percentile). Neck load transducers recommended for the Hybrid-III can also be used when the TRID-II neck is mounted in a Hybrid-III. Replacing the standard Hybrid-III neck by the TRID-II neck allows to evaluate the kinematics and dynamics of the cervical spine in rear impacts. The TRID-II neck is hence a valuable research tool to evaluate current and/or improved designs of head restraints.

Evaluation

The response of the TRID-II neck has been evaluated in a series of sled and pendulum experiments. The experiments showed that the reproducibility of the neck was good. Figure 11 shows that the maximum head-neck rotation agrees with the human head-neck rotations as derived for the literature. Also the other quantities are in good agreement with literature values.

Future Developments

The head-neck kinematics during a rear impact are very much influenced by the bending of the torso and by the seat-back/torso interaction. The mechanical properties of the seat-back are of significant importance for the torso motion. Current seat designs often have elastic properties causing rebound of the torso, that in turn aggravates the loads to the neck [35], [38]. The deeper structures of some current seat-back designs often cause an improper force distribution to the occupant's back in a rear impact [35]. This emphasises the need for the design of a Rear Impact Dummy thoracic spine and thorax back. With these new designed parts, a dummy that can replicate the bending of the torso and stresses the importance of new test procedures in which not only the headrestraint but also the seat back and its attachments to the floor can be studied.

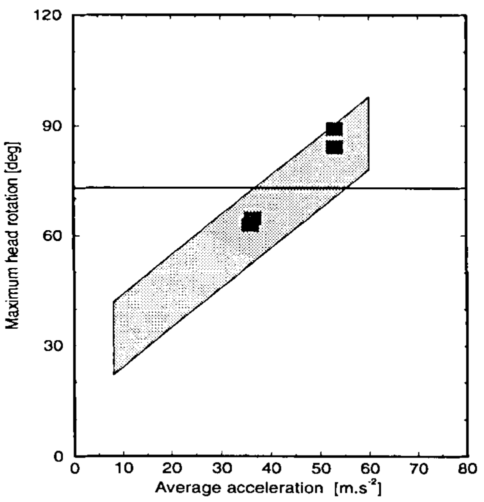

Figure 11 The maximum TRID-II head rotation (■) compared with the relaxed response corridor.

ACKNOWLEDGMENTS

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REFERENCES

[1] Tingvall, C. (1993): (Personal communication to Prof. Claes Tingvall), Dept. of Injury Prevention, Chalmers Univ. of Tech., S-412 96, Göteborg, Sweden

[2] Lubin, S. and Sehmer, J. (1993): Are Automobile Head Restraints Used Effectively? Canadian. Family Physician, Vol 39, July, 1993, pp. 1584-1588.

[3] Kampen, L.T.B. van (1993): Availability and (Proper) Adjustment of Head Restraints in The Netherlands. In: proceedings Int. IRCOBI Conf. on the Biomech. of Impacts, Sept. 8-10, Eindhoven, The Netherlands, pp. 367-378.

[4] Wismans, J. (1994): Incidentie en preventie van het "whiplash" trauma. Report TNO, Crash Safety Research Centre, Delft, The Netherlands. Oct. 1994 (In Dutch).

[5] VdS (1994): Fahrzeugsicherheit 90, Ein Beitrag zur Analyse des Unfallgeschehens. VdS, Munich, Germany (In German)

[6] Ono, K. and Kanno, M. (1993): Influences of the Physical Parameters on the Risk to Neck Injuries in Low Impact Speed Rear-end Collisions. In: proceedings Int. IRCOBI Conf. on the Biomech. of Impacts, Sept. 8-10, Eindhoven, The Netherlands, pp. 201-212.

[7] Deutscher, C. (1994): Bewegungsablauf von Fahrzeuginsassen beim Heckaufprall. Eurotax AG, ISBN 3-9520040-9-X.

[8] Nygren, Å. (1984): Injuries to Car Occupants. Some Aspects of the Interior Safety of Cars. Akta Oto-Laryngological, Supplement 395, Almqvist & Wiksell, Stockholm, Sweden, ISSN 0365-5237.

[9] Foret-Bruno, J.Y., Dauvilliers, F., Tarriere, C. and P. Mack (1991): Influence of the Seat and Head Rest Stiffness on the Risk of Cervical Injuries in Rear Impact. In: Proceedings 13th ESV Conf. Paris, France, 91-S8-W-19, NHTSA, USA, DOT HS 807 991.

[10] Morris, F. (1989): Do head restraints protect the neck from whiplash injuries? Arch Emerg Med 6, 17-21.

[11] Olney, D.B. and Marsden, A.K. (1986): The effects of head restraints and seat belts on the incidence of neck injury in car accidents. Injury 17, 365-367.

[12] Hildingsson, C. (1991): Soft Tissue Injury of the Cervical Spine. Umeå University Medical Dissertations, New Series No 296, ISSN 0346-6612, ISBN 91-7174-546-7.

[13] Kahane, C.J. (1982): An Evaluation of Head Restraints - Federal Motor Vehicle Safety Standard 202. NHTSA Technical Report. DOT HS-806 108, National Technical Information Service, Springfield, Virginia 22161, USA.

[14] O'Neill, B., Haddon, W., Kelley, A.B. and Sorenson, W.W. (1972): Automobile Head Restraints: Frequency of Neck Injury Insurance Claims in Relation to the Presence of Head Restraints. Am J Publ Health, Vol. 62, No. 3, pp. 399-406.

[15] Nygren, Å; Gustafsson, H., Tingvall, C. (1985): Effects of Different Types of Headrests in Rear-End Collisions. In: proceedings 10th International Conference on Experimental Safety Vehicles, pp. 85-90, NHTSA, USA

[16] Scott, M.W., McConell, W.E., Guzman, H.M., Howard, R.P., Bomar, J.B., Smith, H.L., Benedict, J.V., Raddin, J.H. and Hatsell, C.P. (1993): Comparison of Human and ATD Head Kinematics During Low-Speed Rearend Impacts. In: proceedings 37th Stapp Car Crash Conference. SAE paper 930094.

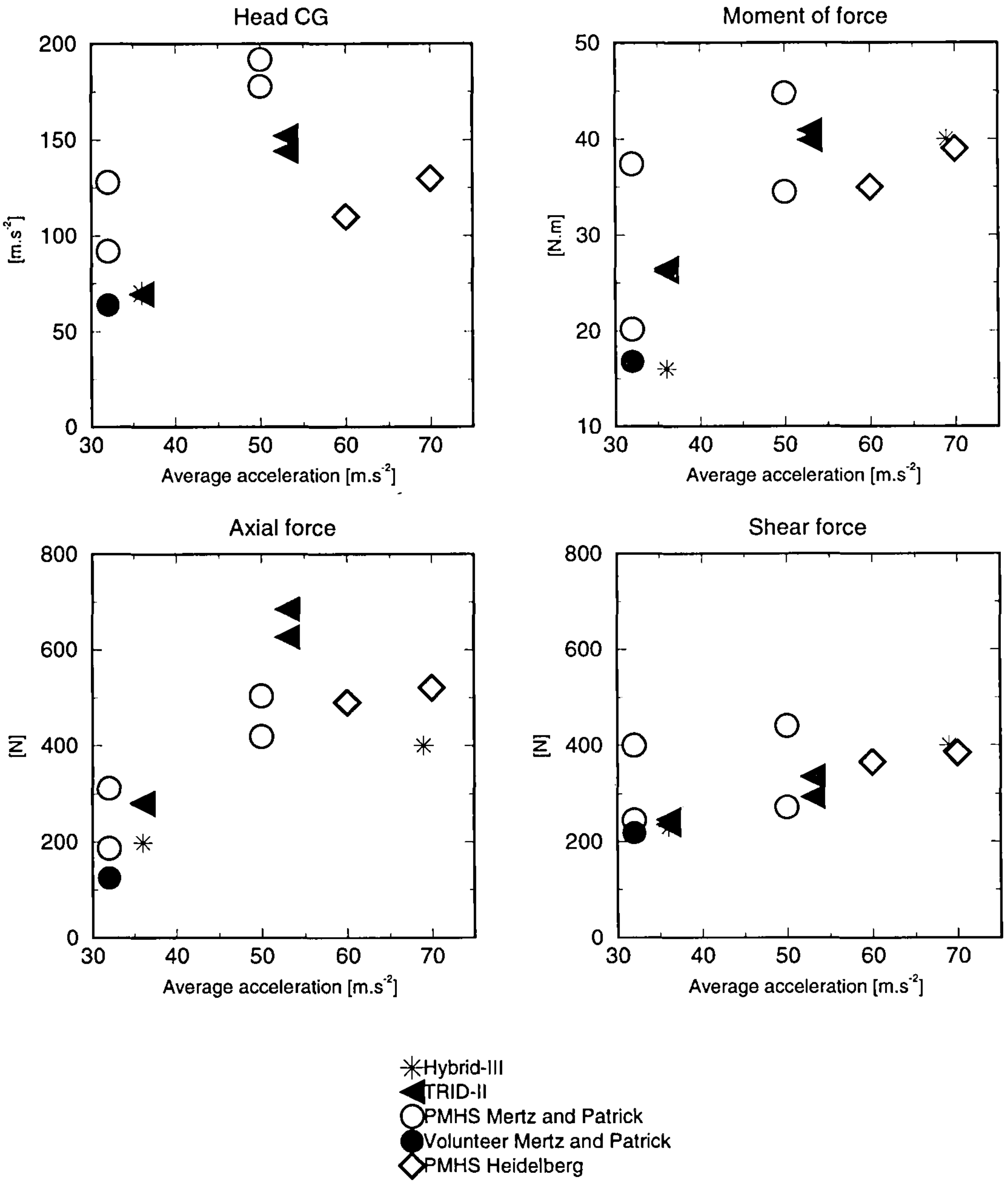
[17] McElhaney, J.H. et al. (1976): Impact Tolerance and Injury Criteria for the Neck. In: Handbook of Human Tolerance. JARI.

[18] Svensson, M.Y., Aldman, B., Hansson, H.A., Lövsund, P., Seeman, T, Suneson, A. and Örthengren (1993): Pressure effects in the spinal canal during whiplash extension motion. A possible cause of injury to the cervical spinal Ganglia. In: proceedings 1993 Int. IRCOBI conference, Eindhoven, The Netherlands.

[19] Orner, P.A. (1992): A Physician-engineer's View of Low Velocity Rearend Collisions. In: Automotive Safety: present and future technology, SP-925. SAE paper 921574.

[20] Kornhauser, M. (1996): Delta-V Threshold for cervical spine injury. Technologies for Occupant Protection Assessment, SP-1174. SAE paper 960093.

[21] Barnsley, L., Lord, S. and Bogduk, N (1994): Clinical review: whiplash injury. Pain, 58:283-307.
[22] Thunnissen, J.G.M., Wismans, J.S.H.M., Ewing, C.L. and Thomas, D.J. (1995): Human Volunteer Head-neck Response in Frontal Flexion: A New Analysis. In: proceedings 39th Stapp Car Crash Conference. SAE paper 952721
[23] White, A.A. III, and Panjabi, M.M. (1978): Clinical Biomechanics of the Spine. J.B. Lippincott Company, Philadelphia, USA, ISBN 0 397 50388 1.
[24] Schneider, L.W., Bowman, B.M., Snyder, R.G. and Peck, L.S. (1976): A Prediction of Response of the Head and Neck of the U.S. Adult Military Population to Dynamic Impact Acceleration from Selected Dynamic Test Subjects. 12 month technical report UM-HSRI-76-10. University of Michigan.
[25] Mertz, H.J. and Patrick, L.M. (1971): Strength and Response of the Human Neck. In: proceedings 15th Stapp Car Crash Conference, 1971. SAE paper 710855.
[26] Happee, R., Twisk, D., and Beusenberg, M. (1995): Analysis of Volunteer Experiments to define Neck Response requirement for Low Severity Forward and Rearward Loading. TNO report 95.OR.BV.008.1/ RHA, TNO Crash Safety Research Centre, Delft, The Netherlands.
[27] Mertz, H.J. and Patrick, L.M. (1967): Investigation of the Kinematics and Kinetics of Whiplash. In: proceedings 11th Stapp Car Crash Conference. SAE paper 670919.
[28] Tisserand, M. (1966): Comportement du rachis cervical lors de chocs dorsaux (in French). Centre de physiologie du travial de l'institut national de secrurite. Report No. 73.
[29] Szabo, T.J., Welcher, J.B., Anderson, R.D., Rice, M.M., Ward, J.A., Paulo, L.R. and Carpenter, N.J. (1994): Human Occupant Kinematic Response to Low Speed Rear-end Impacts. In: proceedings 38th Stapp Car Crash Conference. SAE paper 940532.
[30] Kallieris, D., Rizzetti, A., Mattern, R., Thunnissen, J. and Philippens, M. (1996): Cervical Human Spine Loads During Traumatomechanical Investigations. Submitted, 1996 International IRCOBI conference.
[31] Wismans, J., Philippens, M., van Oorschot, E., Kallieris, D, and Mattern, D. (1987): Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion. Proceedings 31st Stapp Car Crash Conference. SAE paper 872194.
[32] McConnell, W.E., Howard, R.P, Guzman, H.M., Bomar, J.B., Raddin, J.H., Benedict, J.V., Smith, H.L., and Hatsell, C.P. (1993): Analysis of Human Test Subject Kinematic Responses to Low Velocity Rear End Impacts. In: proceedings 37th Stapp Car Crash Conference. SAE paper 930889.
[33] McConnnell, W.E, Howard, R.P., Poppel van, J., Krause, R., Guzman, H.M., Bomar, J.B., Raddin, J.H., Benedict, J.V. and Hatsell, C.P. (1995): Human Head and Neck Kinematics after Low Velocity Rear-end Impacts. Understanding Whiplash. In: proceedings 39th Stapp car Crash Conference. SAE paper 952724.
[34] Severy, D.M. and Mathewson, J.H. (1958): Automobile Barrier and Rear-end Collision Performance. Paper 62C presented at SAE summer meeting, Atlantic City.
[35] Svensson, M.Y. (1993): Neck-Injuries in Rear-End Car Collisions Sites and biomechanical causes of the injuries, test methods and preventive measures. Ph.D. thesis, Chalmers Univ. of Tech., Sweden, ISBN 91-7032-878-1.
[36] Tarriere, C. and Sapin C. (1969): Biokinetic Study of the Head to Thorax Linkage. In: proceedings 13th Stapp Car Crash Conference. SAE paper 690815.
[37] Wilke, H.J., Wolf, S., Claes, L.E., Arand, M. and Wiesend, A. (1995): Stability increase of the lumbar spine with different muscle groups. Spine, 20:192-198.
[38] Nilson, G., Svensson, M.Y., Lövsund, P., Håland, Y. and Wiklund, K. (1994): Rear-End Collisions - The Effect of the Seat-Belt and the Crash Pulse on Occupant Motion. In proceedings 14th ESV Conf. in Munich, Germany, Paper No. 94-S10-O-07, NHTSA, USA.



Annex figure. The resultant accelerations at the head centre of gravity (CG) and the neck loads at the occipital condoles.

PERFORMANCE SPECIFICATIONS FOR THE NECK OF A MOTORCYCLIST ANTHROPOMETRIC TEST DUMMY

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ABSTRACT

A standard research methodology for comparing the performance of various motorcyclist crash protection devices such as airbags and leg protectors, has been developed under the auspices of the International Standards Organization, ISO/TC22/SC22/WG22. This methodology employs an Anthropometric Test Device, ATD, specially designed to represent a motorcyclist. Based on the Hybrid III, it incorporates several special features specific to this application. Among these is a neck which includes several unique performance specifications.

Foremost among these requirements is the recognition that the initial head-neck orientation of the motorcyclist is both different from the automobile occupant and will vary from vehicle to vehicle. Secondly, the helmeted head of the motorcyclist ATD will be subjected to inertial and impact loading not only in the fore-aft direction, but also laterally. Finally, the head and neck will be subjected to torsional loading.

Some of these requirements have been incorporated in Draft International Standard 13232. Others need further development particularly if the dummy is to be used for motorcycle airbag research. This paper discusses how current biomechanical specifications for frontal and side impact automotive ATDs are applied to this special application. Additionally, new specifications for neck torsional response are proposed. A set of general criteria for these has been proposed and accepted by the relevant technical committees and could form the basis for possible neck development.

INTRODUCTION

Over the last 25 years, research has addressed the feasibility of devices, including leg protective devices, which could protect the motorcycle rider in impacts with cars. Such research has been based on a very wide range of methodologies. To assist in the evaluation of these concepts, as well as other proposed safety devices, an international standard, ISO 13232 has been developed. This document has been prepared in order to provide a consistent methodology for assessing the relative merits of secondary motorcycle safety devices in full-scale (and computer simulated) crash tests.

The rider surrogate employed in these tests, the Motorcyclist Anthropometric Test Device (MATD), is a modified Hybrid III, (Newman et al, 1991). In order to accommodate some of the differences between car and motorcycle crashes, as well as the different injury types and distributions, a number of modifications to the base dummy have been implemented. Among these are the provision of frangible femur and tibia/fibula bones, an on-board data acquisition system, grippable hands, head and neck soft tissue extensions to accommodate a helmet, and certain modifications to the dummy neck. The current modifications to the neck allow increased range of torsional motion and increased range of initial head- neck and neck-torso positions, (Gibson et al, 1994).

The feasibility of employing airbags on motorcycles to provide rider crash protection has been discussed on several occasions, (Nieboer et al, 1991; Zellner et al, 1994; Bly, 1994). The efficacy of these devices in this particular application has not yet been firmly established. In addition, the possible detrimental consequences of such use have not been fully explored. The potential for neck injuries induced by motorcycle mounted airbags has been described (Ramet et al, 1994.) Owing to the criticality of this body region, and remaining limitations of the current MATD neck, further consideration is being given to motorcyclist surrogate neck characteristics and injury criteria.

MOTORCYCLIST CRASH KINEMATICS

Motorcycle crashes, especially those that involve an automobile, are highly complex dynamic events. The ISO 13232 standard calls for a variety of vehicle speeds and motorcycle-to-car impact configurations. Most of these crashes produce complex three dimensional MATD movement after the initial contact between the motorcycle and car has occurred. The rider kinematics result from the interaction of the rider with various parts of the motorcycle, the airbag, the struck vehicle and the ground itself. The effects of a deploying airbag on rider trajectory can be quite dramatic in some of these tests, (Ramet et al, 1994). Indeed, depending on rider initial posture, the MATD would often be regarded as an "out of position occupant", (ISO/ TC22/ SC12/WG5 Draft Report, 1994).

The design and response of the head-neck system is especially crucial due to the likely complex interaction between the MATD head, which is helmeted, and an airbag. Clearly, the neck must insure that the kinematics of the head be biofidelic. In addition, since neck loading associated with bag deployment is a potential injury threat that needs to be monitored, (Ramet et al ,1994) , the neck itself must have kinetic biofidelity.

RIDER INITIAL POSTURE

It will be appreciated that the head-neck orientation of the motorcycle rider is substantially different from that of the typical automobile occupant. Furthermore, initial head-neck orientations in the rider population are very much a function of the type or style of motorcycle ridden. Hence, appropriate adaptation of the Hybrid III, which was designed for frontal automotive crash testing, is critical for motorcycle testing.

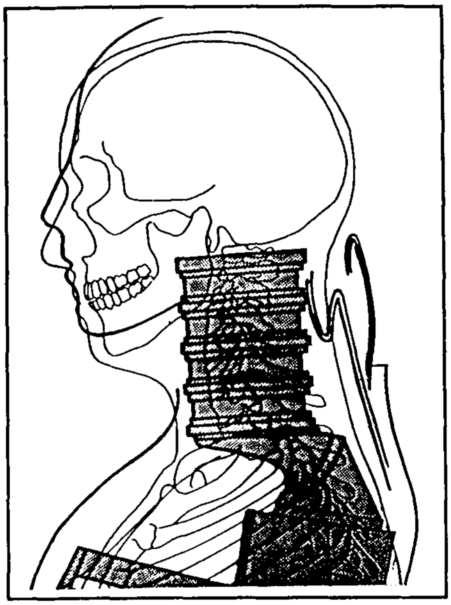

Figure 1: Hybrid III overlay on 50th percentile male (Schneider et al, 1992)

The Hybrid III head-neck system has a limited range of initial flexion/extension adjustment at the neck-torso interface only. Figure 1 shows the relatively good anatomical agreement between a mid-size male and the Hybrid III for the seated automotive posture. For this posture, the curved human neck is well-represented by the straight Hybrid III neck for it assures reasonable initial head positioning. When the motorcyclist assumes the more typical forward leaning posture, the head and neck assume an initial orientation of extension (rearward bending). This causes an effective shortening of the neck link (the distance from the occipital condyles to T1). There are two elements of this "shortening" that cannot be accommodated by the fixed length Hybrid III neck; the increased curvature (lordosis) and the reduction of the distance between all of the adjacent vertebrae as they moved down the sloped articular surfaces. This latter mechanism is illustrated in Figure 2.

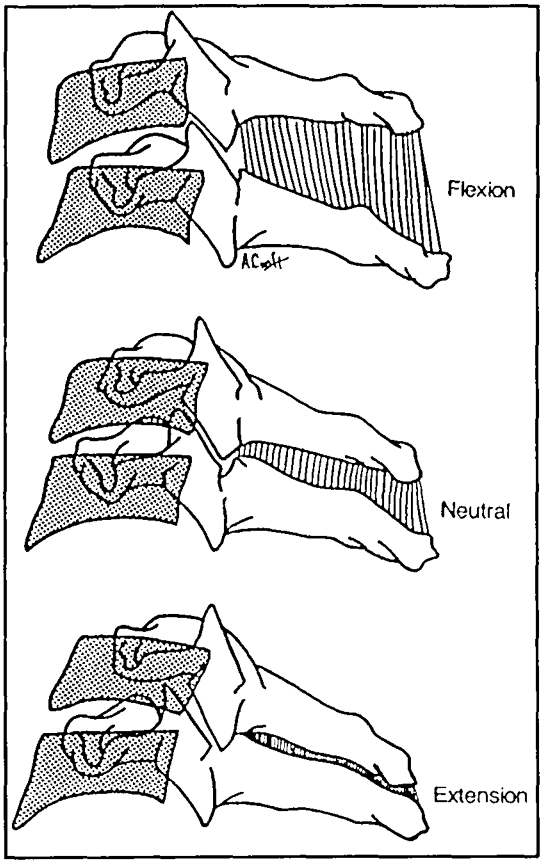

Figure 2: Vertebral articulation (Foreman & Croft, 1995)

PERFORMANCE SPECIFICATIONS

The specification of the appropriate dynamic response characteristics of an ATD neck, has been a subject of considerable discussion recently. It is perhaps not surprising that what is appropriate for the car occupant, the ejecting aircraft pilot and the motorcyclist, are all different. What is common, is the uncertainty about the limited data upon which to base a design specification. The most often referenced data base for flexion response, is that of the Naval Biodynamics Laboratory (Ewing et al, 1975). These data have recently been reanalysed to try to clarify some earlier approximations, (Thunissen et al, 1995). Typical of the observed changes in three volunteers' neck link length under dynamic sled-type loading, are those shown in Figure 3.

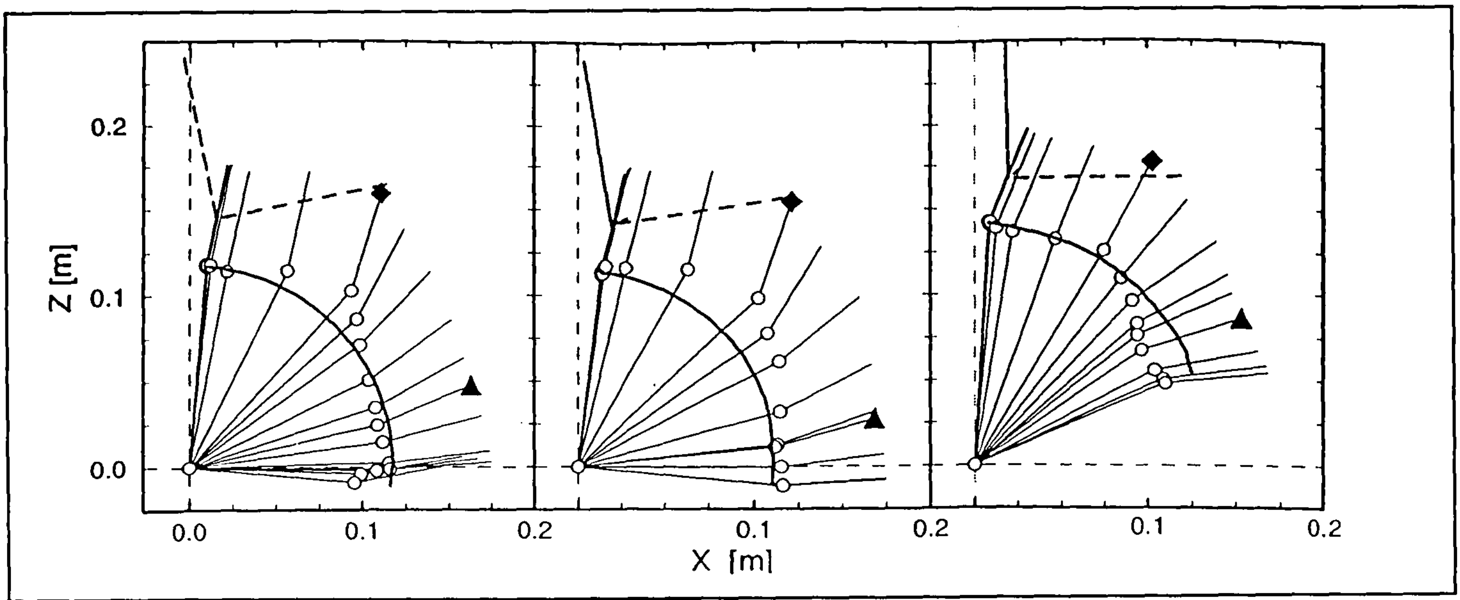

Figure 3: Relative head and neck motions represented by the two pivot linkage mechanism. The curved solid lines indicate a constant neck link length. (Thunnissen et al, 1995)

In recognition of the somewhat special requirements of an MATD, the ISO Working Group responsible for anthropomorphic test dummies, approved a set of general specifications for the performance of an ATD neck intended for use in motorcycle crash testing. The specifications are as follows: (TC22/SC12/WG5, N447, May, 1995).

- For an ATD intended exclusively for crash testing of motorcycles, the neck flexion and extension bending moment specifications can be based upon the established Mertz - Patrick corridors. However, they must be modified to account for the difference in torso inclination between the original automotive seated posture test setup and the motorcyclist's seated posture.
- For an ATD intended exclusively for crash testing of motorcycles, the kinematic response specifications for flexion can be based upon the NBDL volunteer data if appropriate corrections are made to account for the differences in initial torso and neck angle from that of the motorcyclist, the presence of a mouth-mounted mass in the NBDL volunteers, and initial tension in the neck musculature.
- For an ATD intended exclusively for crash testing of motorcycles, the neck flexion specifications for lateral bending should be consistent with ISO TR 9790 specified for side impact dummies.
- For an ATD intended exclusively for crash testing of motorcycles, the specifications for neck torsional stiffness should remain in the corridor as shown in Figure 6 of Document N436."

Flexion/Extension Bending Moments

Flexion and extension bending moment requirements are generally of the form:

Bending moment vs head angle; $M_y(\phi)$

Three initial torso angles will be considered; the head being level in each case: 0°, 15° flexion and 30° flexion. The 0° orientation replicates the posture of test subjects used in the referenced experimental sled test programs. The 15° and 30° posture reflect two typical motorcycle driving positions. For the three initial postures, the Mertz/Patrick occipital condyle bending moment corridors are adjusted as shown in Figure 4.

Flexion Kinematic Requirements

Kinematic response specifications typically are of the form:

Head angular acceleration vs time; $\alpha_y(t)$
Head linear acceleration; $a_x(t)$, $a_z(t)$

and are simply time histories of the head motion for the fore-aft test set-up. Since the volunteers are all different, the responses are different. Thus, boundaries encompassing the test data have been suggested by de Jager et al, (1994) as shown in Figures 5, 6 and 7.

A more appropriate approach is to define the mean behaviour for a particular test condition, and to set a certain number of standard deviations as the boundaries. Recent analysis of the original NBDL data by Simula (1995) and TNO (1995), provide

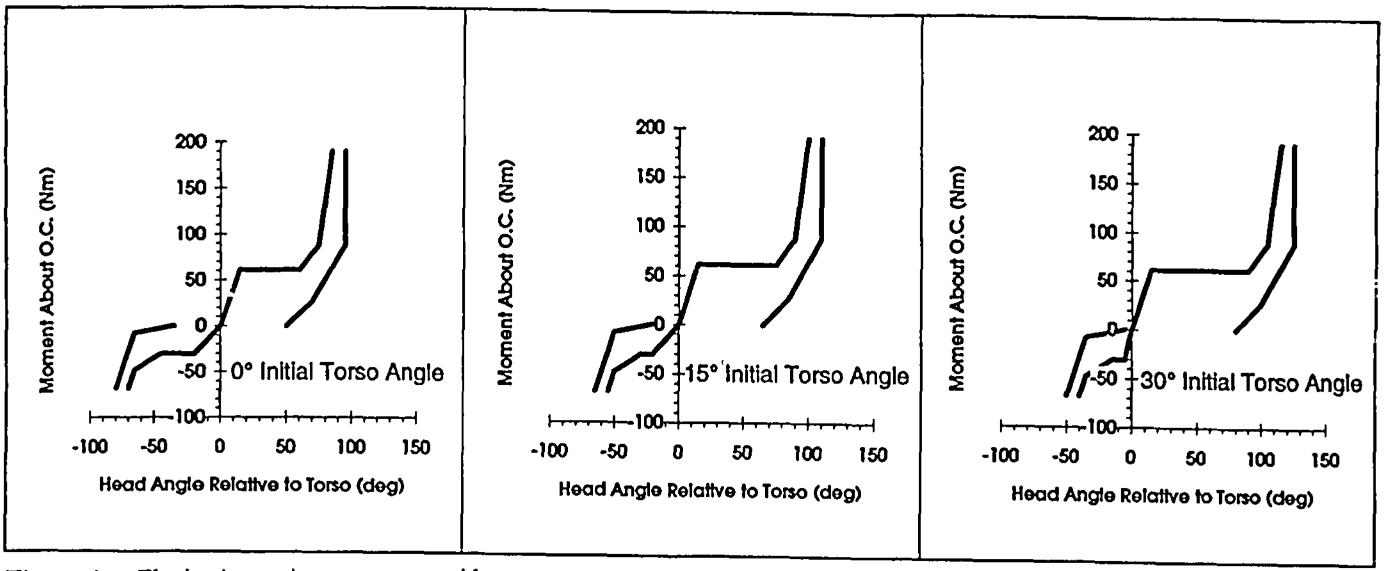

Figure 4: Flexion/extension moment corridors

the opportunity to do this. Appropriate corrections accounting for the differences in initial torso and neck angles, means that features such as head lag may not be as contentious as has recently been the case (Thunnisen et al, 1995).

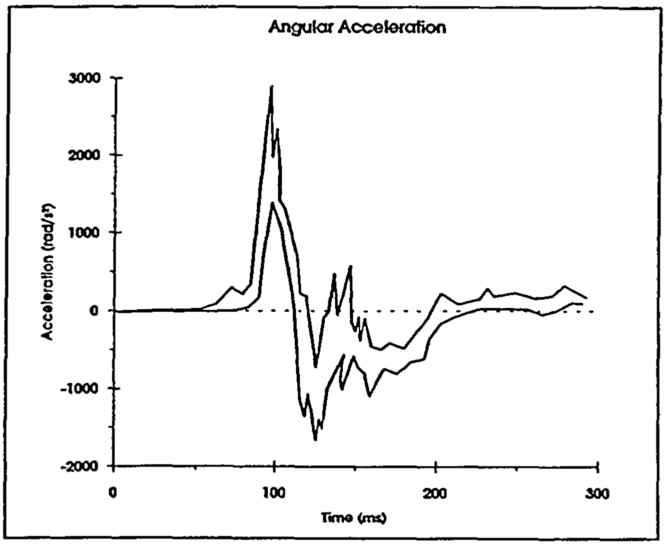

Figure 5: Boundaries for head angular acceleration around the Y axis

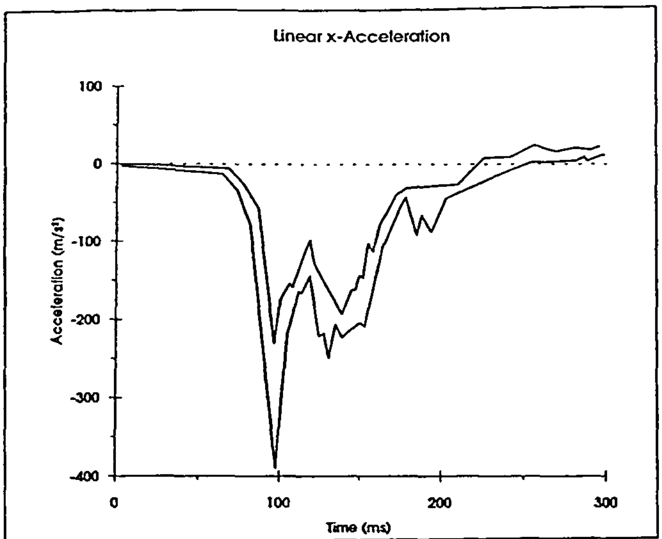

Figure 6: Boundaries for head X-acceleration

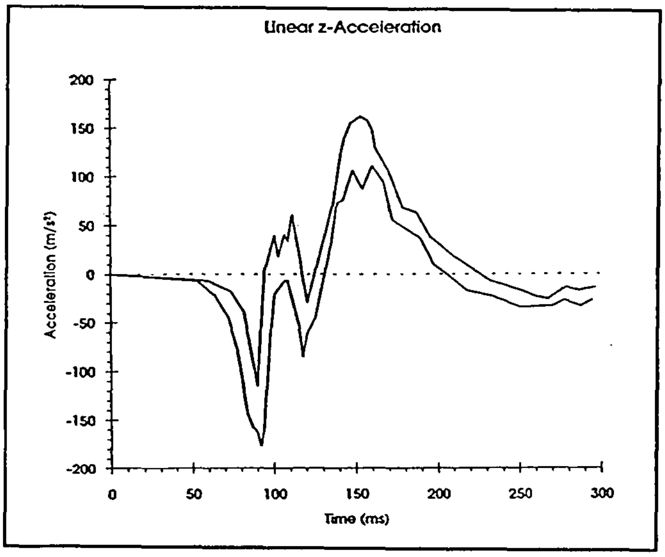

Figure 7: Boundaries for head Z-acceleration

Accounting for the mass of the mouth-mounted instrumentation of the NBDL volunteers, means that when the MATD head-nec.. assembly is tested in flexion, additional weight at the mouth location should be added. Otherwise, the specifications should be modified to account for it. Kleinberger (1995), using a finite element model of the new NHTSA ATD neck, recently examined this aspect and concluded that the effects were negligible - for the parameters that he considered. It is to be expected that th presence of a helmet on the MATD head will have a more pronounced effect.

It is evident that the so-called kinetic requirements referred to above are essentially rotational stiffness characteristics measured at the head-neck junction. The kinematic requirements, on th other hand, relate to time. These acceleration-based requirements provide a basis for a kinematically biofidelic neck. However, they could be replaced with equivalent specifications for head linear and rotational displacements. Figures 8, 9 and 10 show displacement corridors for the same NBDL database (Simula, 1995).

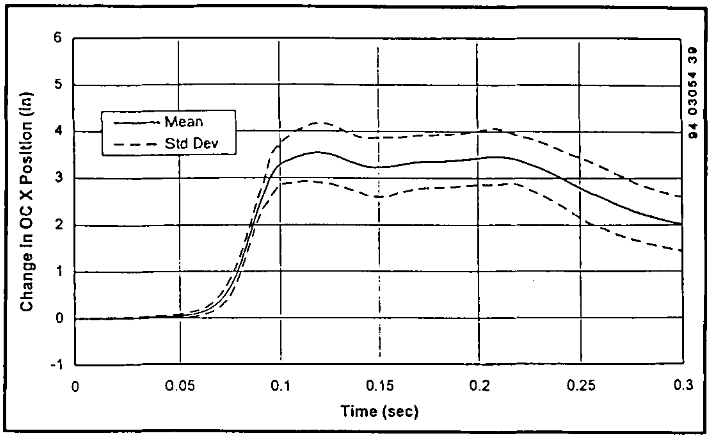

Figure 8: Occipital condyles X-direction translation relative to T1 versus time corridor for 15-G frontal pulse, rotating T1 input (Simula, 1995)

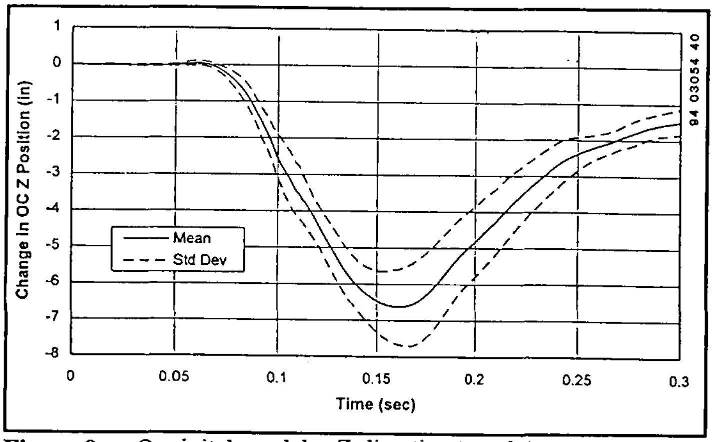

Figure 9: Occipital condyles Z-direction translation relative to T1 versus time corridor for 15-G frontal pulse, rotating T1 input (Simula, 1995)

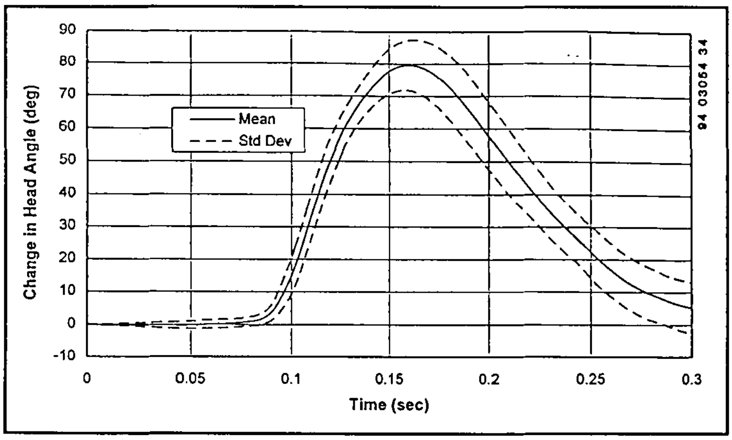

Figure 10: Head angle versus time corridor for 15-G frontal pulse, rotating T1 input (Simula, 1995)

Either acceleration-based or displacement-based criteria can be used to determine whether the head "is in the right place at the right time". This clearly is important in establishing proper interaction between the dummy head and whatever it contacts. However the MATD neck must also be able to monitor for neck injury potential. In that context, it is also necessary that the reaction forces and moments at the head-neck (and perhaps the neck-thorax) junction be dynamically biofidelic. This means that there must also be performance requirements that are based on reaction forces and moments.

In their recent analysis, Thunnissen et al have calculated the force and bending moments at the occipital condylar joint. These corridors, for the same NBDL data set, are shown in Figures 11, 12 and 13.

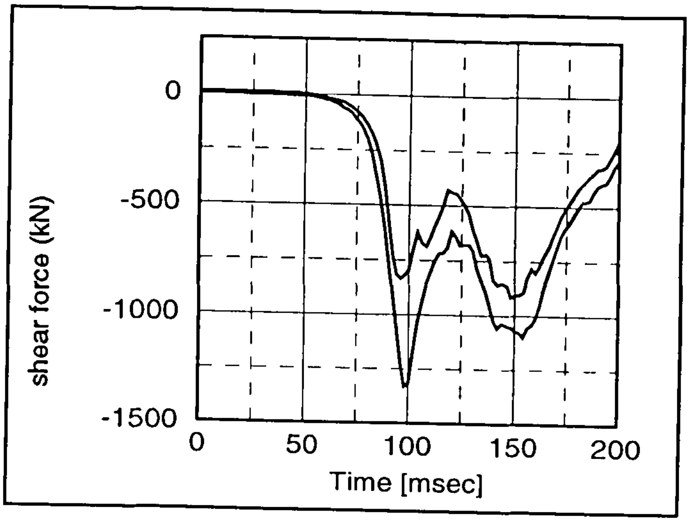

Figure 11: Shear force

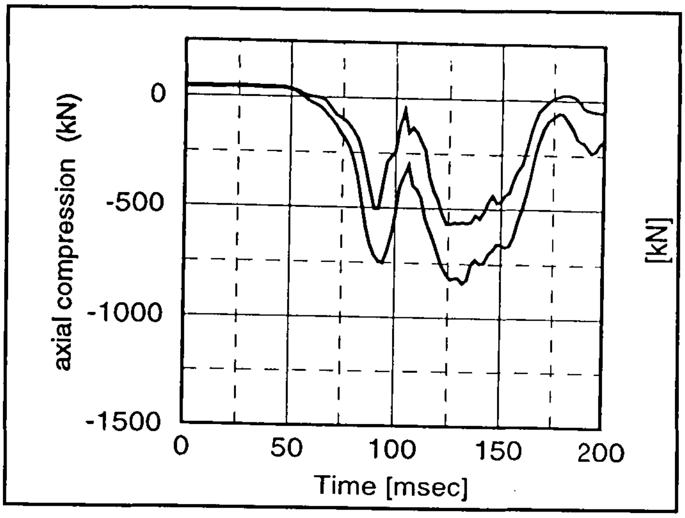

Figure 12: OC axial compression

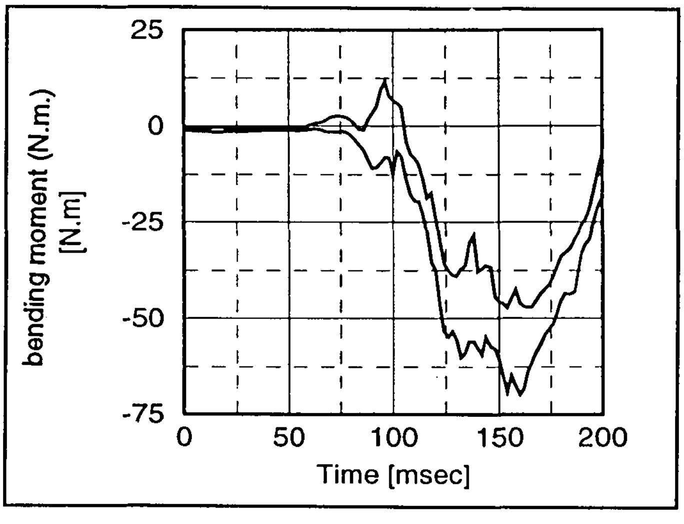

Figure 13: OC bending moment

Lateral Flexion Requirements

Generally, the neck flexion requirements for lateral bending are of the form:

Bending moment vs head angle; $M_x(\theta)$
Head angular accelerations; $\alpha_x(t)$, $\alpha_z(t)$
Head linear accelerations; $a_y(t)$, $a_z(t)$
Moment vs head twist angle; $M_z(\psi)$

Achieving a design that meets the specifications in ISO-TR9790 for side impact dummies, while being able to properly mimic appropriate fore-aft behaviour, is the most daunting challenge of the present exercise. The ISO-TR9790 specifications are quite different from those for frontal impact and, to some degree, recognize the complexity of the head motion when the neck flexes laterally.

ISO TR9790 actually stipulates three response specifications. The first of these requirements is based on the human volunteer data of Ewing et al., (1975), as analyzed by Wismans et al., (1986). The second is based on the human volunteer data of Patrick and Chou, (1976), and the third on the cadaver studies of Association Peugeot-Renault (Tarrière, 1986). All specifications require the duplication of the total respective sled test environments that were used to obtain the human volunteer and/or cadaver data. The specification of performance corridors is definitely desirable. However, each of these requirements is in the form of "windows". Appendix A contains the ISO lateral neck specifications. This same approach shall also be employed with the MATD neck since achieving kinematic or kinetic biofidelity over the entire range of head motion is considered unfeasible.

The flexion (lateral and frontal) specifications, it will be recognized, are specific to the particular motion of the sled that the volunteers rode. The sled pulses for the lateral and forward flexion experiments are shown in Figure 14. Volunteers, cadavers or ATDs would each respond differently to different inputs.

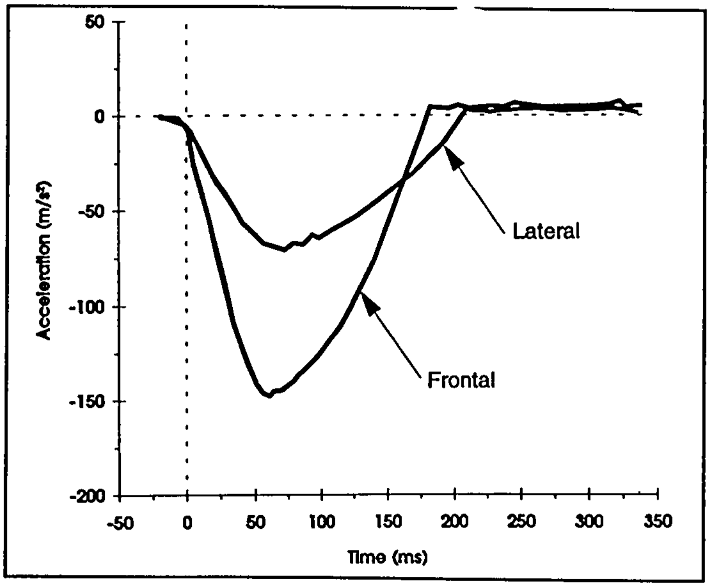

Figure 14: NBDL frontal and lateral sled pulses

Duplicating the entire sled test set up is not usually considered feasible, and so mounting the head-neck assembly directly to a sled has been done in the past. The only stipulation, when comparing to the NBDL data set, is that the sled acceleration be that of the average T1 acceleration of the test subjects. This approach has been used by deJager et al, (1994) for example, when validating their integrated multibody/finite element code MADYMO neck model. This model has the facility to address many of the uncertainties concerning neck performance specifications.

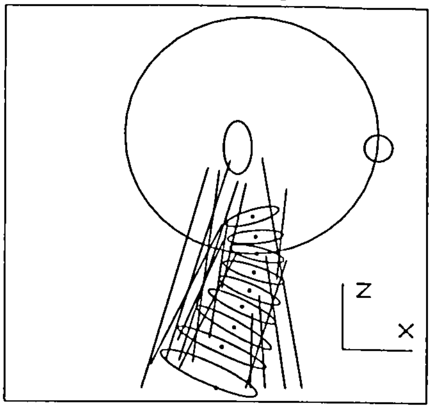

Figure 15: Lateral view of deJager model

A lateral view of the deJager model is shown in Figure 15. It consists of a series of rigid bodies representing the head and the vertebrae. The rigid bodies are connected by linear viscoelastic elements representing the mechanical behaviour of the intervertebral soft tissue. The major neck muscles are incorporated into the model (shown by simple lines in the figure) by fifteen symmetrical pairs of nonlinear springs. Muscle contraction cannot be modelled, and the tensed state of the muscles of the human volunteers cannot be completely represented. However, deJager et al have suggested that a force displacement curve for active muscle behaviour may be applied. (Ideally, a muscle model that can simulate contraction, such as that developed by Williams and Belytschko (1983), should be employed).

Notwithstanding these limitations, the model has been shown to be capable of reproducing many of the response features of the human volunteers. Important to the present work, is that the model can be used to explore the effects of different muscle pretensing and different head-neck-torso angles. In this regard, it is planned to exercise the model over a range of these variables and to adjust the current performance corridors and windows to accommodate these differences.

Torsional Stiffness Requirement

Torsional stiffness per se has not been a requirement of any other dummy neck except as a secondary feature. Clearly in the case of the MATD, based on observations of past full scale and laboratory tests, torsional response is critical to the proper assessment of neck injury. So, in addition to the ISO TR9790 lateral requirements, the torsional requirement shown in Figure 16 is to be met. This provides for the extra degree of torsional elasticity necessary. It will be necessary to "drive" the neck through significantly greater twist angles than are typically achieved in sled tests.

Currently, this requirement is being met by incorporating into the Hybrid III neck, a torsional module at the head-neck junction. This module maintains the original capability of the Hybrid III, but allows increased head twist, (Gibson et al, 1994).

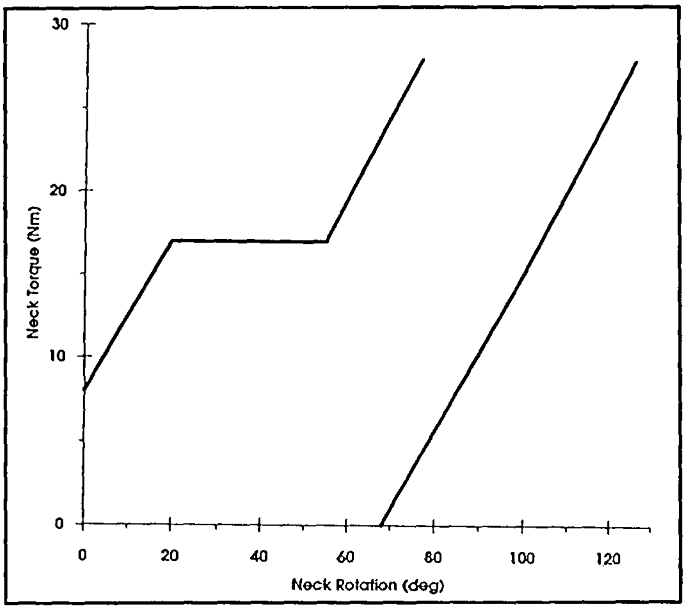

Figure 16: Axial torque corridor (ISO TC22/SC12/WG5-N436)

MATD NECK DESIGN REQUIREMENTS

The current MATD neck, as specified in ISO 13232, incorporates a number of modifications to the Hybrid III neck. As described briefly above, these include soft tissue additions to achieve realistic helmet wearing, a neck shroud to minimize air bag interaction at the front of the neck, a greater range of initial angle adjustment at the torso-neck juncture in flexion and in extension, adjustable nodding blocks so that the head can be maintained level even when the neck-torso angle is adjusted, and finally, the torsional module. These improvements go a long way to making the Hybrid III more suitable for motorcycle crash testing. However, they cannot go far enough. Sequential modification of a design never intended for this application has resulted in a complex, expensive design whose overall response is only marginally acceptable. It may lack long term durability and its reproducibility may be questionable. It has also not been possible to ensure that the performance requirements be met over the full range of initial head-neck angles since the current Hybrid III based design is unable to properly accommodate the full range of initial head-neck positions of the motorcyclist. This is due to the essentially cylindrical shape of the Hybrid III. The current MATD neck also retains the Hybrid III's central steel cable that provides the strength for axial loading. This causes the axial stiffness to be far too high.

DESIGN CONCEPTS

Based on a prior review of contemporary neck design, (Biokinetics R95-03), two potential design concepts have been chosen as the basis for the next MATD neck. The first is a continuous flexible element neck column, of specific shape and geometry, that may be rotated at its base into various postures, and that will accommodate the desired multi-directional kinematics through its unique stiffness and damping properties. The second is a fully articulated neck, having multiple deformable and non-deformable elements, in which the characteristic initial positioning and kinematics of the human neck in forward, lateral and torsional deformation are fully dependent on the geometry of the solid elements and on the stiffness of the deformable elements.

The issues surrounding these two concepts are as follows. First, the neck must be biofidelic in forward, lateral torsional and axial directions. Second, the head and neck must be able to be prepositioned at various postures, and at those positions, the response of the neck must reflect the change in stiffness and range of motion. Third, torsional compliance must be built into the neck structure, and not isolated to a torsional module. Fourth, the use of external control cables or elements is to be avoided. Lastly, the neck should be durable, practical and repeatable in a crash test environment.

All initial indications point to the articulated neck design concept as being the most suitable to achieving these requirements. However, it is recognized that this design could become complicated, and that the simpler concept of a flexible element should be partially explored first. Since mathematical modelling will be a significant part of the design exercise, it is intended that a cursory investigation of the flexible neck element occur to examine the effects of this neck's unique stiffness characteristics.

Flexible Element Neck Concept

The flexible element neck is an elastomeric column of non-uniform cross-section. It will be pre-bent with a forward convexity to represent the geometry of a human neck, such that in forward flexion, the unbending of the neck will result in an amount of axial elongation. To represent the different levels of bending stiffness along the neck, the column will be smaller in cross-section at the upper neck and larger at the bottom. Additionally, the cross-section will be "egg-shaped", which will serve to promote coincident axial rotation with lateral bending. Figure 17 shows a schematic representation of this concept.

The lower neck will be adjustable for initial positioning, and the upper neck will have a free range of motion for nodding action. A friction-static mechanism will hold the head in the proper orientation for initial positioning.

The anterior portion of the neck will be covered in dynamically transparent foam to achieve the proper anthropometrics, and a flexible bib will be installed between the lower jaw and the upper sternum.

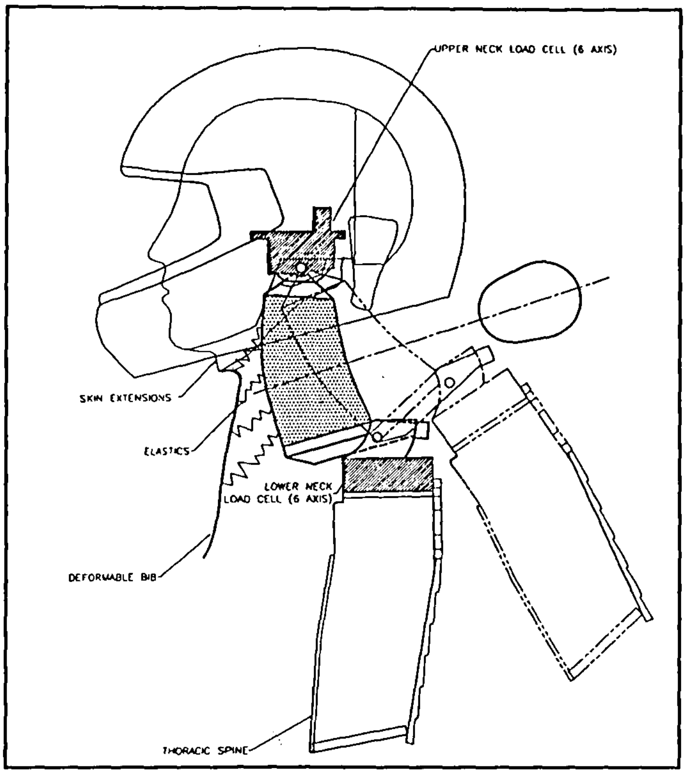

Figure 17: Schematic of flexible neck element concept

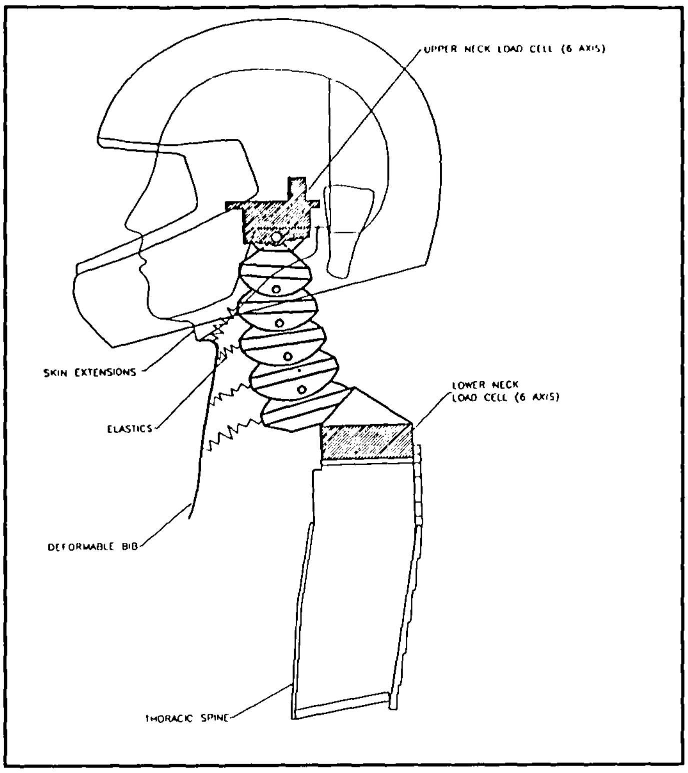

Figure 18: Schematic of pin-jointed articulating element neck concept

Articulated Neck Concept

The articulated neck concept models the action of the human cervical vertebrae. In this fashion, bending of the neck is represented by motion of one element relative to the next. It is not necessary that there be seven articulated elements as in a human neck, but that there be sufficient resolution to define the required shape of the human neck in bending. The articulated neck design will have a prescribed stiffness and range of motion at each element, such that total neck bending will be represented by the accumulated bending of these elements.

There are two articulated neck concepts that will be examined in the detailed design. The first is a series of pin-jointed elements that pivot at the averaged instant centres of vertebral rotation. Each of these elements will be a combination of solid and deformable materials, such that forward bending will be governed primarily by the pivot action, and lateral bending will be governed by elastomeric deformation. Torsion will be the result of accumulated axial rotation of the elastomeric material, rather than solely at the upper neck. Initial positioning will be achieved either through friction-static joints, or differently sized deformable wedges on either side of the pivots. The neck shroud bib as described previously will be adapted to this design concept. Figure 18 shows a schematic representation of this design concept.

The above pin-jointed articulating element neck concept is similar to a design by Svensson and Lövsund (1992). Their design, dubbed the Rear Impact Dummy (RID) neck, incorporated several pin-jointed articulating elements which were controlled by foam wedges. However, the RID neck design was primarily intended for monitoring low-speed whiplash loading, and also did not provide for lateral or torsional biofidelity. Consequently, it was not an entirely suitable platform for the new MATD neck design.

The second of the articulated design concepts is that of sliding facets. In this concept, a series of stacked elements move relative to each other on spherical surfaces. Internal, or possibly external, elastomeric materials of specific stiffnesses and damping will provide the necessary bending response in the frontal and lateral directions. Alternatively, surface friction and position-specific contact pressure between the elements will provide the desired response. The inclination and orientation of the facets will be designed to replicate the action and geometry of the human vertebrae. Torsion response will be achieved by deformation of the elastomeric materials between the elements. Figure 18 shows a schematic representation of the articulating facet neck.

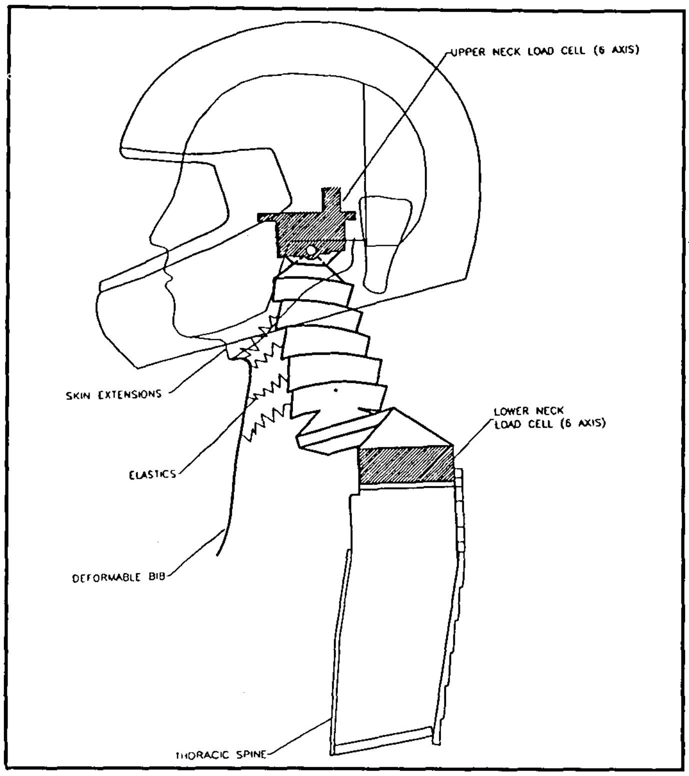

Figure 19: Schematic of articulating facet neck concept

SUMMARY

This paper has reviewed the development of the Hybrid III based MATD neck as specified in ISO 13232.. For motorcycle testing this design possesses many advantages over the Hybrid III. However, because it is based upon the Hybrid III, it is not capable of assuming the wide range of initial head-neck configurations that are necessary for a motorcyclist crash dummy. Furthermore it is incapable of responding axially in a biofidelic manner because its length is constrained by a central steel cable, and because it cannot, as a solid continuous object, mimic the motion of the complex articulated structure of the human neck.

Performance specifications upon which to base an MATD neck, which reflect the above concerns, have been provided. Additionally, some design approaches for a new MATD neck have been suggested.

Currently a consortium of organizations including Biokinetics & Associates Ltd., Dynamic Research, Inc., and the International Motorcycle Manufacturers Association are proceeding with development of a next generation MATD neck and related injury criteria.

REFERENCES

Biokinetics & Associates Ltd. "Motorcycle Crash Test Dummy Neck." R95-03, 1995.

Bly, P.H. "A Review of Motorcycle Safety." Fourteenth International Technical Conference on the Enhanced Munich, Germany, 1994.

de Jager, M., Sauren, A., Thunnissen, J., Wism Dimensional Head-Neck Model: Validation for Fr Impacts." Thirty-Eighth Stapp Car Carsh C Lauderdale, Florida, 1994.

Ewing, C.L., Thomas, D.J., Lustick, L., Becker, E., Willems, G., Muzzy III, W.H. "The Effect of the Initial Position of the Head and Neck on the Dynamic Response of the Human Head and Neck to -Gx Impact Acceleration". 19th Stapp Car Crash Conference, 1975.

Ewing, C.L., Thomas, D.J., Majewski, P.L., Black, R., Lustik, L. "Measurement of Head, T1, and Pelvic Response to -Gx Impact Acceleration". SAE 770927, Twenty-First Stapp Car Crash Conference, 1977.

Foreman, S.M., Croft, A.C. "Whiplash Injuries: The Cervical Acceleration/Deceleration Symdrome". Williams and Wilkins Publishers,1995.

Gibson, T., Shewchenko, N., Withnall, C. "Biofidelity Improvements to the Hybrid III Neck." Fourteenth International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, 1994.

ISO TR9790: "Road Vehicles - Anthropomorphic Side Impact Dummy - Lateral Neck Impact Response Requirements to Assess the Biofidelity of the Dummy". International Organization for Standardization (ISO), 1989.

ISO 13232: "Motorcycles - Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles". International Organization for Standardization (ISO), Geneva, Switzerland, 1996 (forthcoming).

ISO/TC22/SC12/WG5, N426 Road Vehicles - Test Procedures for Evaluating Out-of-Position Vehicle Occupant Interactions with Deploying Air Bags (Draft Technical Report), Stockholm, Sweden, 1994.

Kleinberger, M. personal communication, 1995.

Newman, J.A., Zellner, J.W., Wiley, K.D. "A Motorcyclist Anthropometric Test Device MATD." International IRCOBI Conference on the Biomechanics of Impacts, Berlin, Germany, 1991.

Nieboer, J.J., Goudswaard, A.P., Wismans, J., Janssen, E.G., Vermissen, A.C.M. "Computer Simulation of Motorcycle Airbag Systems." Thirteenth International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paris, France, 1991.

Patrick, L.M., Chou, C. "Response of the Human Neck in Flexion, Extension and Lateral Flexion". VRI-7-3. Vehicle Research Institute, Society of Automotive Engineers, Warrendale, Pennsylvania, 1976.

.., M., Bouquet, R., Bouallegue, M., Bermond, F., Cesari, D. "The Effect of Air Bag Inflation on the Cinematic and the Lesions of a Motorcyclist." Fourteenth International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, 1994.

Schneider, L.W., Ricci, L.L., Salloum, M.J., Beebe, M.S., King, A.I., Rouhana, S.W., Neathery, R.F."Design and Development of an Advanced ATD Thorax System for Frontal Crash Environments, Final Report, Volume 1: Primary Concept Development", Trauma Assesment Device Development Program, 1992.

Simula Government Products, Inc. "Performance Speci-fication for a Biofidelic Manikin Neck". Draft Report D930118A, March, 1995.

Svensson, M., Lövsund, P. "A Dummy for Rear-End Collisions - Development and Validation of a New Dummy Neck". IRCOBI, 1992.

Tarrière, C. "Proposal for Lateral Neck Response Requirements for Severe Impact Conditions", ISO/TC22/ SC12/WG5 Document N166-Draft 1, 1986.

Thunnissen, J., Wismans, J., Ewing, C.L., Thomas, D.J. "Human Volunteer Head-Neck Response in Frontal Flexion: A New Analysis." Thirty-Ninth Stapp Car Crash Conference, Coronado, California, 1995.

Williams, J.L., Belytschko, T.B. "A three-dimensional model of the human cervical spine for impact simulation." Journal of Biomechanical Engineering, 105:321-331, 1983.

Wismans, J., Van Oorschot, H. And Woltring, J.H. "Omni-Directional Head-Neck Response". 30th Stapp Car Crash Conference, SAE Paper No. 861893, 1986.

Zellner, J.W., Newman, J.A., Rogers, N.M. "Preliminary Research Into the Feasibility of Motorcycle Airbag Systems." Fourteenth International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, 1994.

APPENDIX A
RESPONSE REQUIREMENTS FOR THE LATERAL NECK BENDING SLED TESTS

Measurement (Unit)	Lower Bound	Upper Bound	Reference
Peak Horizontal Acceleration of T1 (G)	12	18	Ewing et al (1977)
Peak Horizontal Displacement of T1 Relative to the Sled (mm)	46	63	Ewing et al (1977)
Peak Horizontal Displacement of the Head C.G. Relative to T1 (mm)	130	162	Ewing et al (1977)
Peak Vertical Displacement of the Head C.G. Relative to T1 (mm)	64	94	Ewing et al (1977)
Time of Peak Head Excursion(s)	0.159	1.175	Ewing et al (1977)
Peak Lateral Acceleration of the Head (G)	8	11	Ewing et al (1977)
Peak Vertical (Downward) Acceleration of the Head (G)	8	10	Ewing et al (1977)
Peak Head Flexion (degrees)	44	59	Ewing et al (1977)
Peak Neck Twist (degrees)	-45	-32	Ewing et al (1977)
Peak Flexion Angle (degrees)	40	50	Patrick and Chou (1976)
Peak Bending Moment about A-P Axis at Occipital Condyles (Nm)	40	50	Patrick and Chou (1976)
Peak Bending Moment about R-L Axis at Occipital Condyles (Nm)	20	30	Patrick and Chou (1976)
Peak Twist Moment (Nm)	15	20	Patrick and Chou (1976)
Peak Shear Force at Occipital Condyles (N)	750	850	Patrick and Chou (1976)
Peak Tension Force at Occipital Condyles (N)	350	400	Patrick and Chou (1976)
Peak P-A Shear Force (N)	325	375	Patrick and Chou (1976)
Peak Resultant Head Acceleration (G)	18	24	Patrick and Chou (1976)
Peak Lateral Acceleration of T1 (G)	17	23	Tarrière (1986)
Peak Lateral Acceleration of the Head C.G. (G)	25	47	Tarrière (1986)
Peak Horizontal Displacement of the Head CG Relative to the Sled (mm)	185	226	Tarrière (1986)
Peak Head Flexion Angle (degrees)	62	75	Tarrière (1986)
Peak Head Torsion Angle (degrees)	62	75	Tarrière (1986)

STATUS OF PROVE-OUT TESTING OF THE SID-IIs ALPHA-PROTOTYPE

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Paper Number 96-S10-O-15

ABSTRACT

The prototype SID-IIs advanced side impact dummy, designed to assist the Occupant Safety Research Partnership's efforts at harmonization, is currently undergoing extensive testing and is being modified as required before worldwide sales of the beta-prototype begins. This paper summarizes the testing since the 1995 Stapp Conference paper on the dummy's technical specifications.

BACKGROUND

The SID-IIs was developed to help harmonize between existing side impact dummies towards one design worldwide by offering the beginning of a family of biofidelic Anthropomorphic Test Devices (ATD's) with as much worldwide input and consensus as possible.

The development of a small, second generation side impact dummy was proposed to the Occupant Safety Research Partnership (OSRP) of United States Council for Automotive Research (USCAR) in 1993. The proposal outlined the need for an ATD that would be better suited to help evaluate the biomechanical performance of advanced side impact countermeasures, notably airbags, for smaller occupants. Data from frontal airbag exposure tests[1] indicated that the smaller occupant (as represented by the small female Hybrid III dummy) is generally subjected to higher loading than the average size occupant (as represented by the mid-male Hybrid III dummy).

The group decided to name the new dummy the *SID-IIs* because it is a *small* [s] *second generation* [II] *side impact dummy* [SID]. The dummy is shown in Figures 1 and 2. The SID-IIs represents the initiation of OSRP harmonization efforts.

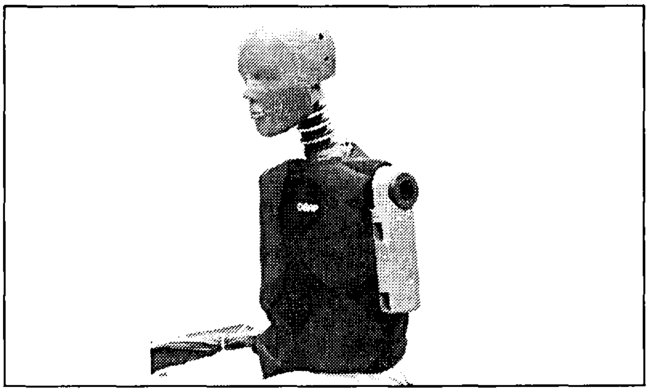

Figure 1. SID-IIs front view -- with jacket.

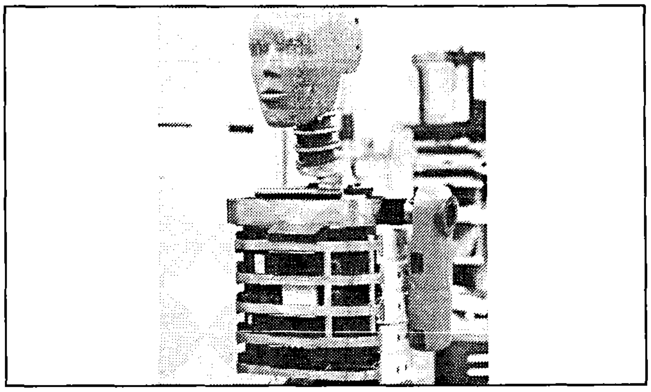

Figure 2. SID-IIs front view -- without jacket.

The SID-IIs has a total mass of 43.5 kg and an erect sitting height of 790 mm. The technical specifications were published in the 1995 Stapp Conference proceedings[2].

The SID-IIs has 111 available, non-redundant instrumentation channels. The large number of channels is necessary because of the variety of possible side impact loading scenarios this dummy

may encounter. Only a select portion of these channels would be expected to be used in any one test, and the selection would depend on the countermeasure(s) being evaluated.

FULL-VEHICLE CRASH TESTING

The SID-IIs underwent one full-vehicle crash test, conducted at the Ford Merkenich (Cologne, Germany) crash test facility during February 1996. A Ford right-hand drive Mondeo sedan with a Chrysler Neon door trim panel, a General Motors (GM) Grand Am seat and a Delphi Interior and Lighting Systems combination chest-head side airbag was impacted on the passenger (left-hand) side by a European Experimental Vehicle Committee (EEVC) 950 kg moving barrier at 50 km/h. A Plascore® aluminum honeycomb barrier face, designed to meet the European requirements, was used in the test. The crash test was conducted according to the Draft European Step II Side Impact Directive requirements. A pre-crash setup is shown in Figure 3.

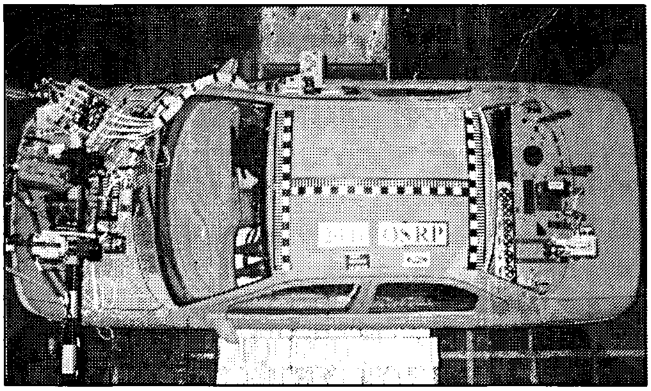

Figure 3. European step-II dynamic side impact pre-test setup.

The SID-IIs was seated in mid-position and laterally centered on the seat. The stub arm was forward at a 45° angle. The dummy had an optional foam neck shroud installed to keep the airbag from becoming trapped between the head and neck. The neck shroud was specifically designed to not restrict or change the dummy neck performance. The airbag was electronically, remotely fired at 1 ms after the barrier contacted the vehicle. Ninety-seven (97) of the possible 111 SID-IIs data channels were used in the test. The other channels were not used due to non-availability of several of the unique load cells at the time of the test (i.e., lower neck: 5 channel instead of 6 channel load cell used; lower abdomen: 1 vertical accelerometer was damaged prior to test; iliac: 1 instead of 2 load cells used; acetabulum: 1 instead of 2 load cells used; upper femur-to-acetabulum load cells not available; knee: clevis load cells were not used; tibia: 3 channel instead of 4 channel load cells used).

The test vehicle was instrumented with triaxial accelerometers on the right and left rockers at the B-pillar and at the longitudinal center-of-gravity. The moveable deformable barrier cart had triaxial accelerometers on the right and left frame rails and at the longitudinal center-of-gravity. Additionally, 6 uniaxial load cells were mounted on the cart behind the deformable barrier face. High speed film and video cameras documented the crash test.

The 20-30 liter airbag (Figure 4) so effectively cushioned the small dummy in this in-position test, that many of the dummy measurements were very low. For example, the highest thoracic or abdominal rib deflection was 6 mm. The data are tabulated, and typical unfiltered (1000 Hz) data time histories are presented in Appendix A. The airbag was chosen to be representative of an advanced technology expected to be evaluated by the dummy. In hindsight, a test without a side airbag would have led to greater dummy loads, and might have been a better test of the dummy.

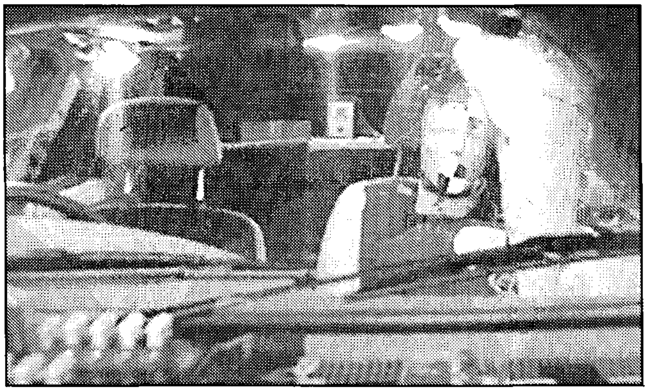

Figure 4. SID-IIs viewed through windshield of the crash vehicle during the crash.

The data from the test had a few anomalies. Most notable was a number of short duration data spikes on some of the data plots (Appendix A, Figures A5, A8 and A9). Two possibilities exist: first, since the dummy was not grounded, airbag inflation-induced static electricity could have caused the data spikes. Secondly, the shoulder mechanism permitted

metal-to-metal contact between the arm bone and the fixed shoulder detent mechanism (Figures 5 and 6). It is believed that the shoulder design generated most of the data spikes and this area of the dummy is being extensively redesigned.

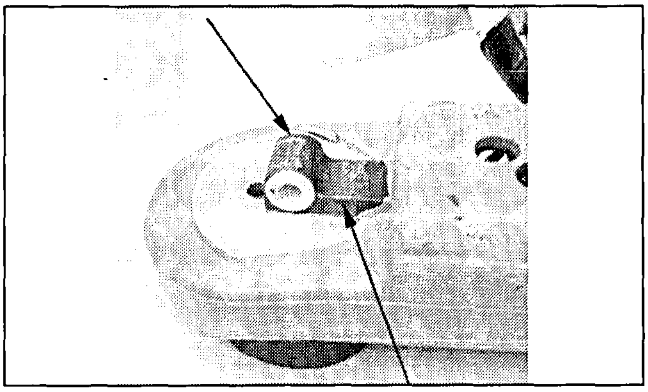

Figure 5. Post-test photograph of the arm attachment to the shoulder. Arrows indicate witness marks.

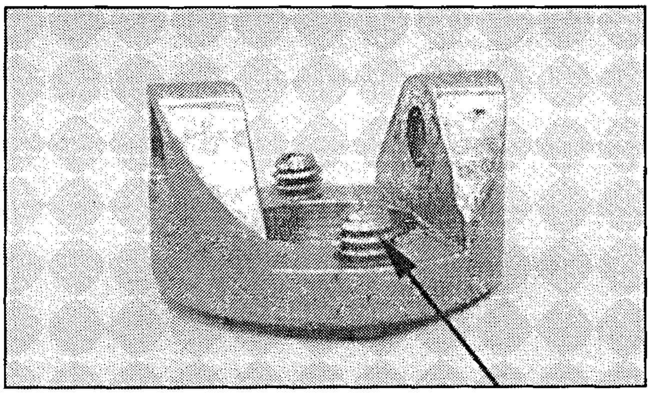

Figure 6. Post-test photograph of shoulder detent assembly which contacted arm bone. Arrow indicates point of contact.

Additionally, noise from the ankle assembly was noted in the tibia data. There were witness marks on the ankle, indicating metal-to-metal contact had occurred (Figure 7). We note that once the soft ankle stops currently being incorporated into the mid-male Hybrid III dummy are available for the small female Hybrid III, these stops will become standard on the SID-IIs production dummy and can be easily retrofitted on the beta-prototypes.

The foot sole plates of the dummy were also damaged. The sole plates were bent into a toes-up position during the test. It was not clear from the films what caused the feet to twist. The feet were from an older small female Hybrid III dummy and the sole plates were not hardened as on newer versions of the small female Hybrid III.

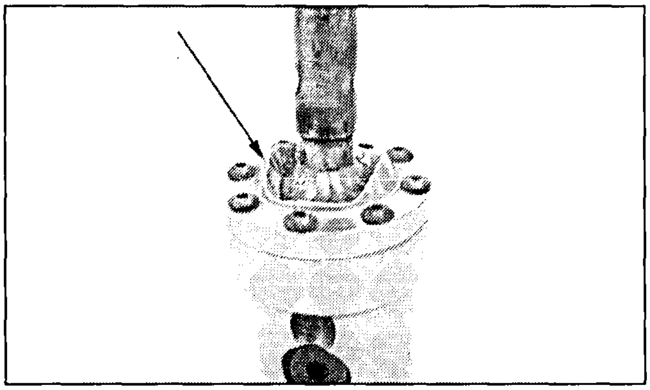

Figure 7. Post-test photograph of ankle assembly. Arrow indicates point of contact.

SLED TESTING

The SID-IIs was tested at GM against various trim panels and padded walls. The dummy performed well in these comparatively low speed tests (Figure 8). The data are given in tabular form in Appendix B, Table B1.

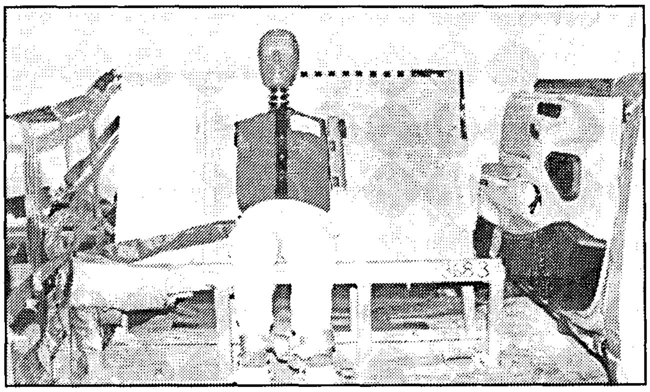

Figure 8. Typical Heidelberg-type sled test into door trim panel.

The dummy then was sled tested at Ford against rigidly backed trim panels and on a Heidelberg-type load cell fixture (Figure 9) with various padding stiffnesses over the load plates. Aluminum load plates were located to interact with the shoulder, thorax, abdomen, pelvis, thigh and knee. The padding was formed from 100 mm thick slabs of a paper-honey-comb-like material in 70, 140, 210 and 280 kPa stiffnesses [10, 20, 30, and 40 psi]. The data are tabulated in Appendix B, Tables B2 - B6 for the trim panel and padded wall tests.


Figure 9. Typical Heidelberg-type sled test into paper-honeycomb-like material.

The prototype high carbon spring steel ribs were found to be softer than intended -- Rockwell Hardness 41 instead of in the low 50's. Therefore, in some of the more severe sled tests, the ribs were twisted and bent out of shape (Figure 10). However, the dummy should have survived these tests without damage. More durable ribs are being designed. When the production dummies are built, the ribs will be made from Vascomax® steel -- a durable steel, substantially more expensive than high carbon spring steel.

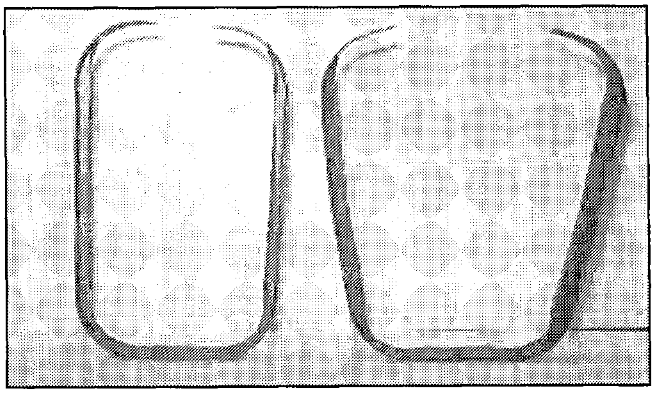
Figure 10. Distorted thoracic ribs.

As can be seen from the data in Appendix B, most of the sled tests discussed in this section exercised the dummy more severely than the crash test. Because of the higher severity of these tests, additional problems surfaced which need resolution. The arm-to-shoulder attachment and the ribs need to be fine tuned and rib stops need to be added to protect the linear potentiometer from bottoming out. These problems will be resolved before the beta-prototype is made available during the summer of 1996.

VERIFICATION TESTING

A number of verification tests have been conducted on all the dummy components and compared to the *preliminary* verification requirements given in the 1995 Stapp Conference paper[2]. These tests are tabulated and shown in bar graph form in Appendix C. The data show laboratory-to-laboratory differences as well as one-laboratory variation. The stability of the alpha-prototype parts is also demonstrated in these charts.

Meeting the preliminary corridors is *not* a high priority until all the biomechanical tests have been conducted. First, the biomechanical requirements will have to be prioritized. Then, the preliminary verification corridors will be adjusted as necessary once we are ensured the dummy meets the biomechanical requirements.

During verification testing, the shoulder plug did not remain attached to the arm. The shoulder plug needs to be redesigned so that it stays attached to the arm during all tests.

BIOMECHANICAL TESTING

Several additional biomechanical tests have been conducted using the scaled response targets published in the 1995 Stapp Conference paper[2]. The biomechanical tests conducted were: head response target 1, neck response target 2, shoulder response target 1, thorax response targets 1 and 3, abdomen response target 2 and pelvis response targets 1, 3 and 4.

Head Response Target 1

This response target consists of a 200 mm head drop onto a rigid surface. The results are tabulated in Appendix D, Table D1. The average peak head acceleration for the left side tests exceeds the upper bound slightly (160.3 G vs. 158 G upper bound). The average peak head acceleration for the right side tests is at the upper bound (157.5 G). The reason for this is due to an old head skin, which met the corridor when new. These tests will be repeated with new skins.

Neck Response Target 2

This response target calls for supporting the dummy between two rigid plates such that only the

neck and head are free to move. A deceleration sled is accelerated to 5.8 m/s and decelerated at a constant 6.7 G's for 88 ms. The results are tabulated in Appendix D, Table D2.

The response of the neck was lower than all the target values. This is due to two reasons. First, the sled pulse actually achieved was a speed of 5.9 m/s but with an average constant deceleration of 6.6 G's for for 60 ms, which is a substantially shorter time duration than required. Second, the dummy torso was considered too soft due to damage incurred in prior testing. Therefore, the required impulse was not transmitted to the head and neck. These tests will be rerun with the stiffer sled pulse and new ribs.

Shoulder Response Target 1

This response target consists of impacting the shoulder with a rigid pendulum impactor at 4.5 m/s. Two tests were conducted. The pendulum force-time history from one test is shown in Appendix D, Figure D1. The pendulum force-time history exceeds the upper bound. The average peak pendulum force from both tests is 4.4 kN versus an upper bound of 2.4 kN.

Thorax Response Target 1

This response target requires the thorax to be impacted at both 4.3 m/s and 6.7 m/s with a rigid pendulum impactor. Two tests were conducted at each pendulum velocity. A representative test pendulum force and T1 acceleration-time histories are shown in Appendix D, Figures D2 - D4.

The 4.3 m/s pendulum force-time history is slightly higher than the 4.3 m/s pendulum force corridor for both tests (2.7 kN vs. 2.5 kN upper bound). The 4.3 m/s T1 acceleration-time history is also higher than the 4.3 m/s T1 acceleration corridor for both tests (20 G vs. 16 G upper bound). The 6.7 m/s pendulum force-time history is at the upper bound of the 6.7 m/s pendulum force corridor for one test and exceeds the upper bound slightly in the second test (3.7 kN and 3.9 kN vs. 3.75 kN upper bound).

Thorax Response Target 3

This response target requires a Heidelberg-type rigid wall sled to impact the dummy at 6.8 m/s. The actual sled speed obtained was 6.6 m/s. The results are tabulated in Appendix D, Table D2. The shoulder plus thorax plus abdomen plate loading-time history is shown in Appendix D, Figure D5.

The biomechanical corridor shown in Appendix D, Figure D5 is considered too stiff given that it was generated from a scaled 18 year old male cadaver with two rib fractures. This cadaver generated a 50th percentile normalized 15 kN thorax plate loading. There are only two other cadaver tests at 6.8 m/s against a rigid wall. The two other tests include a 28 year old female cadaver with nine rib fractures and 47 year old female with seven rib fractures. Originally, the biomechanical corridor used data from cadavers with six or fewer rib fractures. This eliminated all but the very strong and stiff 18 year old male cadaver. When the data from this cadaver is scaled to the 5th percentile female, the thorax response target is much greater (13.5 kN) than would be expected to be sustained by the majority of small females. Therefore, for this response target, it was decided that we would accept the two female cadaver data points, acknowledging the more than six rib fractures.

The revised thorax response target 3 is shown in Appendix D, Figure D6. This new corridor includes the two female cadavers scaled to a 5th percentile female including the addition of 500 N for muscle tone. The SID-IIs results fall within the revised corridor. Conversely, the SID-IIs thorax would have to have been made considerably stiffer, almost rigid, to attain the original biomechanical corridor in Appendix D, Figure D5.

Abdomen Response Target 2

This target consisted of impacting the dummy at 6.8 m/s with a rigid wall Wayne State University (WSU)-type sled. The abdominal load plate-time history is shown in Appendix D, Figure D7.

The abdomen loading falls for the most part within the corridor except for the unloading that occurs 5 ms into the loading event. This is caused by the shoulder and arm interaction with the rigid wall. Note that the bottom of the SID-IIs truncated arm falls between the upper and lower abdomen ribs and this location may have contributed to the abdomen plate unloading.

Pelvis Response Target 1

This test consists of rigid pendulum impacts at various velocities between 6 and 10 m/s. The impactor is defined as a 10 kg rigid impactor with a 350 mm diameter face with a 600 mm radius of curvature. The results of the pendulum force versus velocity are in Appendix D, Figure D8. The results for the two tests conducted exceeded the upper bound by less than 500 N.

Pelvis Response Target 3

This response target utilizes the results from 6.8 m/s rigid wall Heidelberg-type sled tests. The results are tabulated in Appendix D, Table D4. The lower spine lateral acceleration (38 G) and peak rib deflection (32 mm) are below the response target (105 G and 87 mm lower bound). The pelvic lateral acceleration is within the response target bound (77 G vs. 70 - 94 G bounds). However, the pelvis plate loading, which included the thigh loading exceeded the response target (7.5 kN vs. 5.8 kN upper bound). We believe pelvic response target 3 to be in error and upon rexamination will be corrected if necessary.

Pelvis Response Target 4

This response target consists of a rigid wall WSU-type sled at 6.8 m/s. The pelvic plate load-time history is shown in Appendix D, Figure D9. The pelvis loading exceeds the upper bound of the response corridor (7.5 kN vs. 5 kN). It is important to note that this response corridor includes the thigh loading. The pelvis plate rate of loading is faster than the corridor requires. This indicates the pelvis plug is too stiff.

WORLDWIDE COMMENTS

Three recurring questions have been asked: 1) Why is the alpha-prototype dummy designed to the English (SAE) system and not metric? 2) Why does the dummy resemble a BIOSID and is it a smaller version of the BIOSID? and 3) If harmonization is part of the reason for the SID-IIs, why was the dummy manufactured without worldwide input?

English Units

The original intent was to design and manufacture the alpha-prototype as a metric dummy. Early in the design process it was decided the SID-IIs would correspond to the 5th percentile female anthropometry. It was determined that the dummy could be brought to the alpha-prototype stage quicker if the Hybrid III small female (5th percentile) head, neck and lower extremity assemblies were used and not redesigned to be metric. In addition, the committee implemented the recommendation of dummy technicians to not mix English (SAE) fasteners and metric fasteners. This saved the project at least six months of development time. Thus, the alpha-prototype was designed using English units.

The production dummy, available approximately mid-1997, will be entirely metric.

BIOSID-like

The original biomechanical basis for all the existing side impact dummies was reviewed. It was decided to eliminate data with massive rib fractures, since it represented catastrophic failure of the cadaver. Additionally, new cadaver data from research conducted at the WSU involving combined shoulder and thorax impacts was included. The SID-IIs is biomechanically based on this new analysis. The ISO/TC22/SC12/WG5 is currently in the process of updating ISO Technical Reports 9790-1 through -6[3,4,5,6,7,8,9] to incorporate the new biomechanical data.

Contrary to what the alpha-prototype resembles, the SID-IIs is not a smaller version of the BIOSID. All design aspects were considered from the three mid-male side impact dummies (SID, EUROSID-1 and BIOSID). The committee considered the detection of localized loading of the shoulder, thorax and abdomen very important. This lead to a multiple rib design. The multiple rib design of the thorax is similar to both the EUROSID-1 and BIOSID dummies.

The torso instrumentation was completely revised to respond in the range of airbag inflation rates (at least 8-10 m/s). The mid-male BIOSID dummy today has a lag in the string potentiometer displacement responses which introduces errors in the calculation of the Viscous Criterion (V*c).

Furthermore, the pelvis was completely redesigned from any dummy to provide an accurate reflection of its load paths. The pelvis was designed to accept instrumentation for the ilium and total

acetabulum loads (including the greater trochanter and upper femur load paths), as well as pubic symphysis load. In addition, the thigh was adjusted to provide greater inward adduction movement.

The SID-IIs 1995 Stapp Conference paper[2] provides further detail of the design of all the body regions.

Worldwide Input

OSRP realized from the start the difficulty of starting to design an alpha-prototype SID-IIs and obtaining worldwide consensus. It was believed that the quickest approach was to provide a piece of hardware that experts worldwide could evaluate. Even so, the experts of ISO/TC22/SC12/WG5, Anthropomorphic Test Devices, were kept informed of the proposed design of the dummy and its progress. Their input was sought throughout the SID-IIs development program.

If the worldwide evaluation of the SID-IIs shows a need for modification, OSRP is willing and committed *to change or completely redesign* the SID-IIs.

FUTURE WORK TOWARDS THE BETA-PROTOTYPE

The available biomechanical tests as given in the 1995 Stapp Conference paper[2] are being prioritized since it may not be possible or practicable to meet *all* the requirements for each body section. For example, some of the ISO biomechanical tests were developed using an "APR" foam pad. We have not found any of this padding still in existence nor any commercial padding that meets the limited data available on the "APR" pad. Since these biomechanical tests cannot be duplicated, they consequently will receive a low priority.

The biomechanical tests are being conducted as rapidly as possible and the dummy will be revised as necessary to meet these requirements. Modifications could include slight changes in rib metal thickness, damping material thickness, in-jacket rib foam material or thickness, the energy absorbing plugs for the shoulder and pelvis, and to the firmness or thickness of head and neck rubber or vinyl parts. This tuning is not expected to change any substantial part of the dummy and is expected to be complete before the beta-prototypes are available for purchase and evaluation.

HARMONIZATION

Individuals around the world are all basically the same biomechanically, so having different dummies in different markets is not warrented from a biomechanical standpoint. The ultimate goal is to have one dummy specified in worldwide regulation.

Since the SID-IIs is a non-regulated dummy, it is hoped that following worldwide evaluation and modifications, the SID-IIs could become a consensus dummy. This dummy could then become the first in a family of technologically advanced side impact dummies. Future plans are to work with interested parties (manufacturers, governments and researchers) to design a mid-sized adult male side impact dummy. This advanced mid-male side impact dummy would have the consensus of worldwide experts and could be offered to regulatory bodies to update their procedures.

To meet this goal, OSRP is willing *to participate in the design of a mid-male side impact dummy,* if delegates and experts from around the world become actively involved in the *consensus* of designing a new mid-male side impact dummy.

ACKNOWLEDGMENTS

Beyond the named authors, further help was provided by Dawn Barnes, Jeff Berliner, Randy Dillinder, John Hiben, George Kovacs, Joe McCleary, Megan Moreau, Joe Prater and Jeff Robbins from OSRP-member companies, Craig Morgan from Denton, Inc., and Pete Kempf from First Technology Safety Systems.

REFERENCES

1. Melvin, J.W., Horsch, J.D., McCleary, D., Wideman, L.C., Jensen, J.L. and Wolanin, M.J., "Assessment of Air Bag Deployment Loads with the Small Female Hybrid III Dummy," Proceedings of the 37th Stapp Car Crash Conference, SAE Paper 933119, 1993.

2. Daniel, R.P., Irwin, A., Athey, J., Balser, J., Eichbrecht, P., Hultman, R.W., Kirkish, S., Kneisly, A., Mertz, H., Nusholtz, G., Rouhana,

S., Scherer, R., Salloum, M. and Smrcka, J., "Technical Specifications of the SID-IIs Dummy," Proceedings of the 39th Stapp Car Crash Conference, SAE Paper 952735, 1995

3. ISO TR9790-1. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Head Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

4. ISO TR9790-2. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Neck Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

5. ISO TR9790-3. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Thoracic Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

6. ISO/TC22/SC12/WG5, "Proposed Revision of ISO TR9790-3," Document N249, September 1989.

7. ISO TR9790-4. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Shoulder Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

8. ISO TR9790-5. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Abdominal Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

9. ISO TR9790-6. Road Vehicles -- Anthropomorphic Side Impact Dummy -- Lateral Pelvic Impact Response Requirements to Assess the Biofidelity of the Dummy, American National Standards Institute, New York, 1988.

APPENDIX A -- FULL-VEHICLE CRASH TEST DATA

Table A1.
Full-Vehicle Crash Test Data

Description	Units	SAE Filter Class	C#2001	
HIC (15 ms)		1000	226.30	
Shoulder Displacement - Dy	mm	600	24.93*	
Upper Thoracic Rib Disp - Dy	mm	600	36.07	
Mid Thoracic Rib Disp - Dy	mm	600	30.91	
Low Thoracic Rib Disp - Dy	mm	600	24.49	
Upper Abdominal Rib Disp - Dy	mm	600	20.12	
Low Abdominal Rib Disp - Dy	mm	600	33.92*	
Upper Thoracic Rib V*c	m/s	180	0.77	
Middle Thoracic Rib V*c	m/s	180	0.56	
Lower Thoracic Rib V*c	m/s	180	0.31	
Upper Abdominal Rib V*c	m/s	180	0.15	
Lower Abdominal Rib V*c	m/s	180	1.05*	
* Data Spike at Peak				
			Max	Min
Head Accel - Ax	G	1000	11.10	-7.79
Head Accel - Ay	G	1000	58.07	-7.78
Head Accel - Az	G	1000	29.69	-5.06
Head Resultant	G	1000	61.67	0.00
Upper Neck Load - Fx	kN	1000	0.16	-0.25
Upper Neck Load - Fy	kN	1000	0.78	-0.20
Upper Neck Load - Fz	kN	1000	0.54	-0.09
Upper Neck Moment - Mx	Nm	1000	25.95	-67.91
Upper Neck Moment - My	Nm	1000	26.19	-14.73
Upper Neck Moment - Mz	Nm	1000	17.57	-12.76
Lower Neck Load - Fx	kN	1000	0.20	-0.35
Lower Neck Load - Fy	kN	1000	1.74	-0.44
Lower Neck Load - Fz	kN	1000	1.06	-0.26
Lower Neck Moment - Mx	Nm	1000	142.58	-79.14
Lower Neck Moment - My	Nm	1000	60.79	-71.79
Shoulder Load - Fx	kN	1000	0.26	-0.35
Shoulder Load - Fy	kN	1000	2.56	-0.18
Shoulder Load - Fz	kN	1000	0.37	-0.45
Shoulder Accel - Ax	G	1000	114.11	-91.09
Shoulder Accel - Ay	G	1000	158.27	-137.38
Shoulder Accel - Az	G	1000	245.57	-185.03
Arm (Shoulder) Accel - Ax	G	1000	96.89	-62.24
Arm (Shoulder) Accel - Ay	G	1000	227.41	-255.29
Arm (Shoulder) Accel - Az	G	1000	120.37	-88.93
Arm (Elbow) Accel - Ax	G	1000	57.74	-39.85
Arm (Elbow) Accel - Ay	G	1000	558.38	-394.17
Arm (Elbow) Accel - Az	G	1000	133.58	-69.14
Upper Thoracic Rib Accel - Ax	G	1000	273.19	-333.63
Upper Thoracic Rib Accel - Ay	G	1000	397.70	-143.78
Upper Thoracic Rib Accel - Az	G	1000	219.25	-57.57
Mid Thoracic Rib Accel - Ax	G	1000	257.94	-346.44
Mid Thoracic Rib Accel - Ay	G	1000	315.80	-113.10
Mid Thoracic Rib Accel - Az	G	1000	78.23	-73.47
Low Thoracic Rib Accel - Ax	G	1000	155.43	-60.16
Low Thoracic Rib Accel - Ay	G	1000	235.32	-134.33
Low Thoracic Rib Accel - Az	G	1000	160.46	-99.20
Upper Abdominal Rib - Ax	G	1000	135.40	-57.85
Upper Abdominal Rib - Ay	G	1000	95.44	-51.52
Upper Abdominal Rib - Az	G	1000	57.53	-138.54
Low Abdominal Rib Accel - Ax	G	1000	94.12	-61.92
Low Abdominal Rib Accel - Ay	G	1000	113.37	-66.63
Low Abdominal Rib Accel - Az	G	1000	Bad Accelerometer	
Thoracic Spine Opp. Up Thor. Rib Accel - Ay	G	1000	73.14	-28.47
Thoracic Spine Opp. Mid Thor. Rib Accel - Ay	G	1000	70.14	-33.09
Thoracic Spine Opp. Lo Thor. Rib Accel - Ay	G	1000	87.99	-63.18
Thoracic Spine Opp. Up Abd. Rib Accel - Ay	G	1000	78.79	-43.05
Upper Thoracic Rib Load - Fx	kN	1000	1.63	-0.07
Mid Thoracic Rib Load - Fx	kN	1000	1.21	-0.02
Low Thoracic Rib Load - Fx	kN	1000	1.37	-0.01
Upper Abdominal Rib Load - Fx	kN	1000	0.37	-0.05
T-1 Accel - Ax	G	1000	28.84	-47.72
T-1 Accel - Ay	G	1000	22.38	-71.95
T-1 Accel - Az	G	1000	11.65	-21.31
T-12 Accel - Ax	G	1000	53.65	-28.82
T-12 Accel - Ay	G	1000	45.24	-73.20
T-12 Accel - Az	G	1000	15.80	-18.66

Table A1. (Continued)
Full-Vehicle Crash Test Data

Lumbar Spine Load - Fx	kN	1000	0.20	-0.89
Lumbar Spine Load - Fy	kN	1000	0.60	-1.23
Lumbar Spine Load - Fz	kN	1000	1.39	-0.80
Lumbar Spine Moment - Mx	Nm	1000	55.19	Data Dropout
Lumbar Spine Moment - My	Nm	1000	Data Anomaly	-25.22
Lumbar Spine Moment - Mz	Nm	1000	16.21	-13.51
Pelvis Accel - Ax	G	1000	Data Anomaly	-4.12
Pelvis Accel - Ay	G	1000	80.21	-37.83
Pelvis Accel - Az	G	1000	12.66	-16.63
Illiac Load - Fy	kN	1000	3.59	-0.07
Pubic Load - Fy	kN	1000	0.70	-0.10
Acetabulum Load - Fy	kN	1000	1.76	-0.17
Left Femur Load - Fx	kN	1000	0.15	-0.24
Left Femur Load - Fy	kN	1000	0.46	-1.49
Left Femur Load - Fz	kN	1000	0.95	-0.20
Left Femur Moment - Mx	Nm	1000	184.72	-63.32
Left Femur Moment - My	Nm	1000	19.86	-42.90
Left Femur Moment - Mz	Nm	1000	18.91	16.24
Right Femur Load - Fx	kN	1000	0.42	-0.15
Right Femur Load - Fy	kN	1000	0.60	-0.18
Right Femur Load - Fz	kN	1000	0.52	-0.39
Right Femur Moment - Mx	Nm	1000	106.68	-75.75
Right Femur Moment - My	Nm	1000	25.07	-44.57
Right Femur Moment - Mz	Nm	1000	24.68	-101.42
Left Upper Tibia Load - Fz	kN	1000	1.07	-0.39
Left Upper Tibia Moment - Mx	Nm	1000	79.10	-37.52
Left Upper Tibia Moment - My	Nm	1000	19.65	-9.96
Right Upper Tibia Load - Fz	kN	1000	0.59	-1.31
Right Upper Tibia Moment - Mx	Nm	1000	39.37	-111.22
Right Upper Tibia Moment - My	Nm	1000	23.18	-30.82
Left Lower Tibia Load - Fx	kN	1000	0.14	-0.09
Left Lower Tibia Moment - Mx	Nm	1000	71.76	-23.24
Left Lower Tibia Moment - My	Nm	1000	6.33	-19.15
Right Lower Tibia Load - Fx	kN	1000	0.20	-0.08
Right Lower Tibia Moment - Mx	Nm	1000	8.28	-171.56
Right Lower Tibia Moment - My	Nm	1000	15.21	-26.62
MDB Center of Gravity - Ax	G	60	0.99	-16.22
MDB Center of Gravity - Ay	G	60	4.15	-4.80
MDB Center of Gravity - Az	G	60	3.94	-1.48
MDB Front Left - Ax	G	60	1.02	-15.93
MDB Front Left - Ay	G	60	3.29	-1.01
MDB Front Left - Az	G	60	2.76	-1.31
MDB Front Right - Ax	G	60	0.84	-16.79
MDB Front Right - Ay	G	60	1.72	-3.00
MDB Front Right - Az	G	60	4.24	-2.87
MDB Load Cell Upper Right - Fx	kN	60	32.16	0.20
MDB Load Cell Upper Left - Fx	kN	60	33.59	-0.23
MDB Load Cell Lower Right - Fx	kN	60	31.60	-5.79
MDB Load Cell Lower Leftt - Fx	kN	60	30.31	-4.61
Vehicle Center of Gravity - Ax	G	60	4.08	-5.73
Vehicle Center of Gravity - Ay	G	60	17.67	-3.15
Vehicle Center of Gravity - Az	G	60	13.43	-5.88

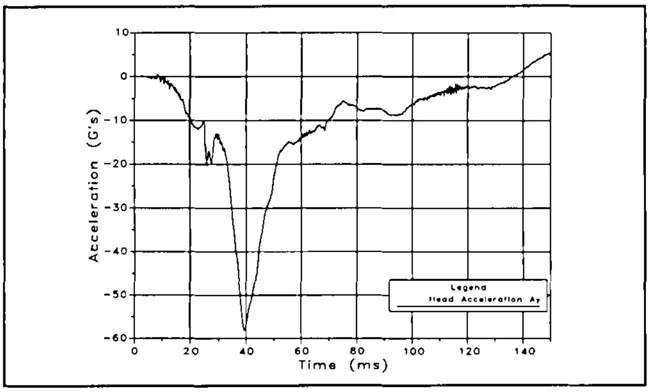

Figure A1. Head acceleration - Ay.

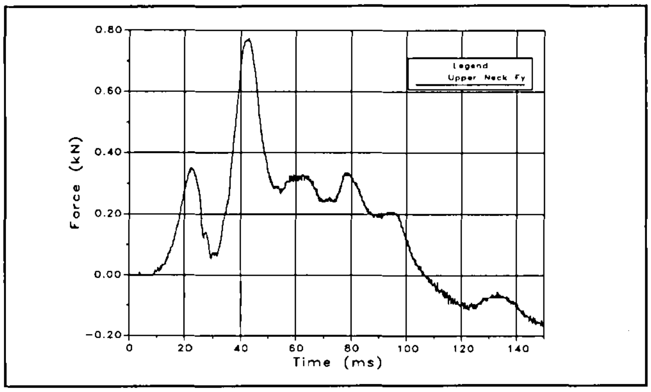

Figure A2. Upper neck load - Fy.

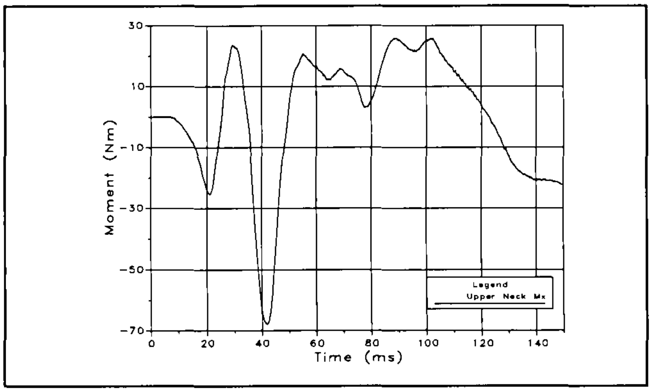

Figure A3. Upper neck moment - Mx.

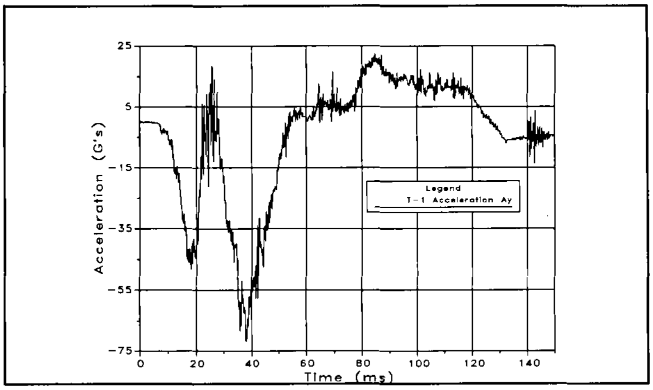

Figure A4. T1 acceleration - Ay.

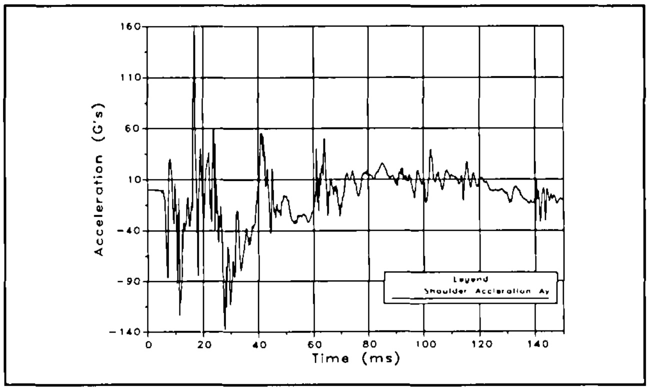

Figure A5. Shoulder acceleration - Ay.

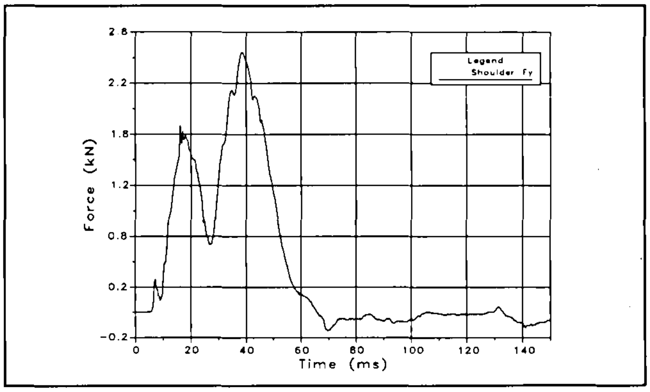

Figure A6. Shoulder load - Fy.

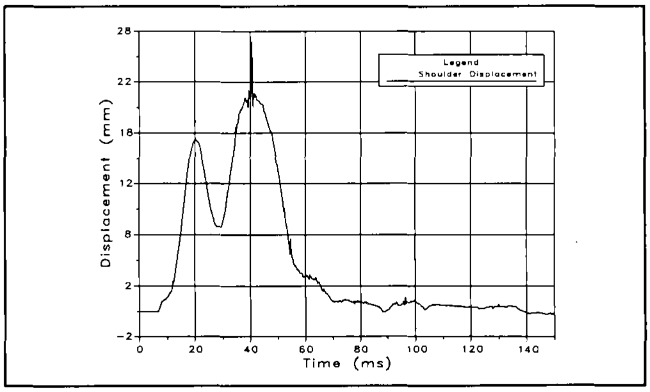

Figure A7. Shoulder deflection - Dy.

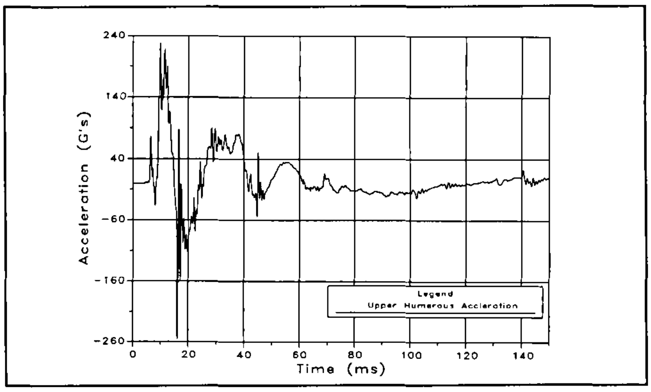

Figure A8. Upper humerus acceleration - Ax.

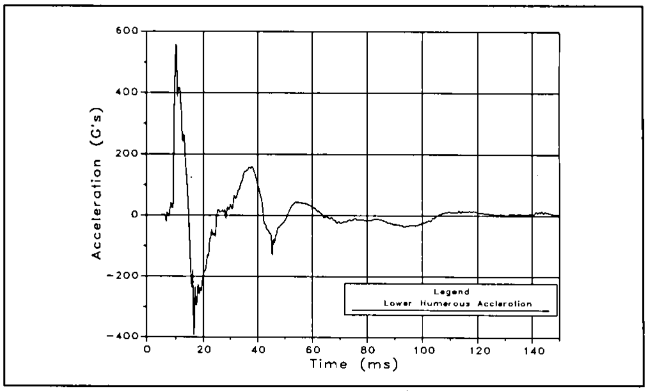

Figure A9. Lower humerus acceleration - Ax.

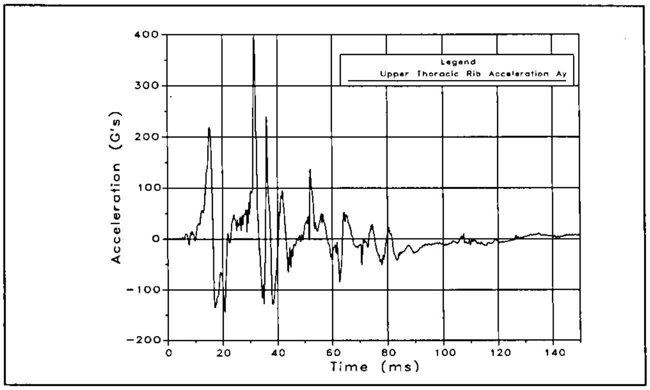

Figure A10. Typical thoracic rib acceleration - Ay.

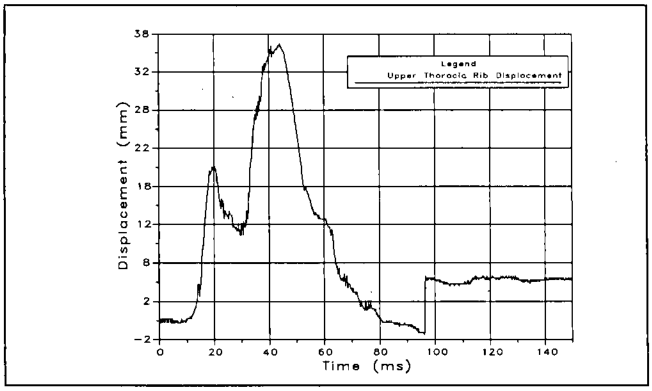

Figure A11. Typical thorax rib deflection - Dy.

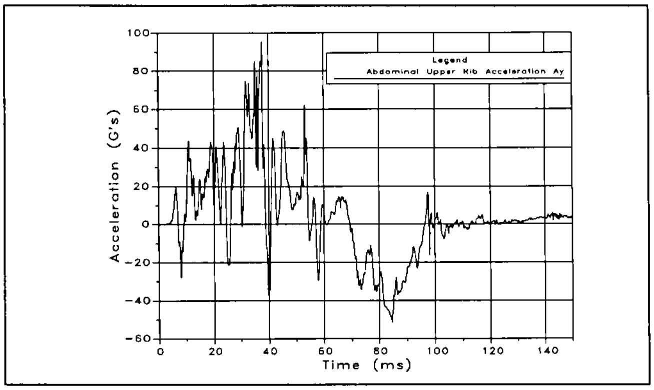

Figure A12. Typical abdominal rib accel. - Ay.

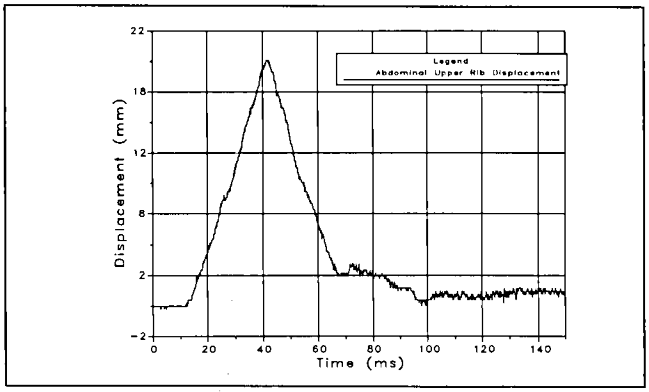

Figure A13. Typical abdominal rib deflection - Dy.

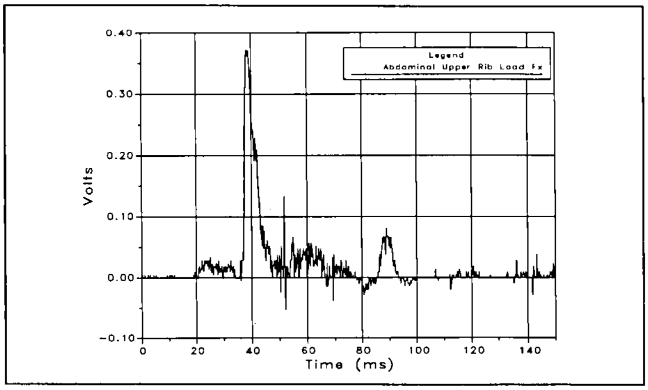

Figure A14. Typical abdominal rib load - Fx.

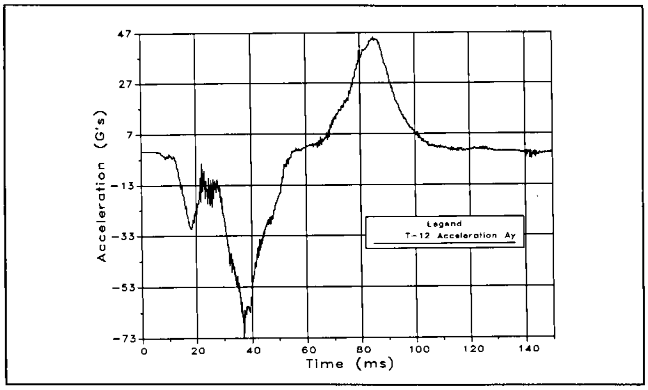

Figure A15. T12 acceleration - Ay.

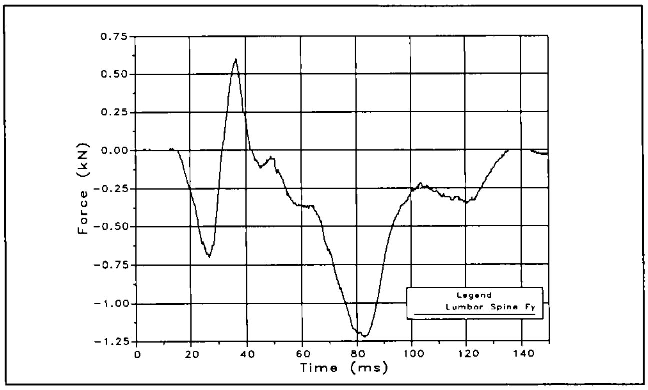

Figure A16. Lumbar load - Fy.

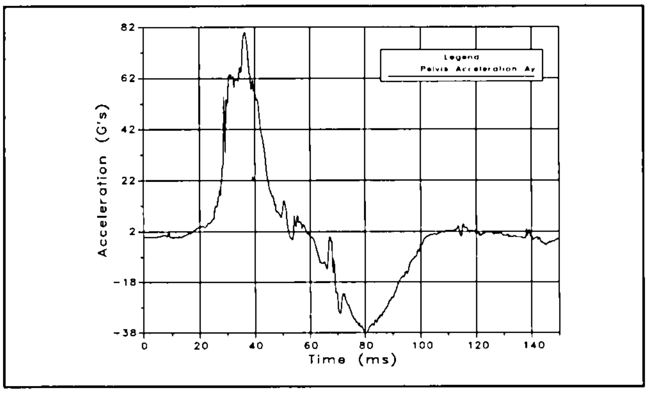

Figure A17. Pelvic lateral acceleration - Ay.

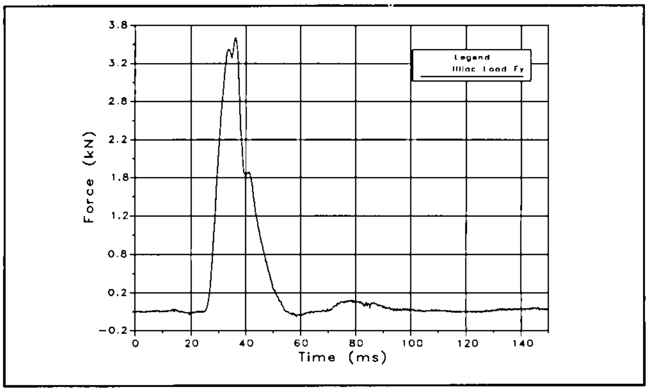

Figure A18. Ilium load - Fy.

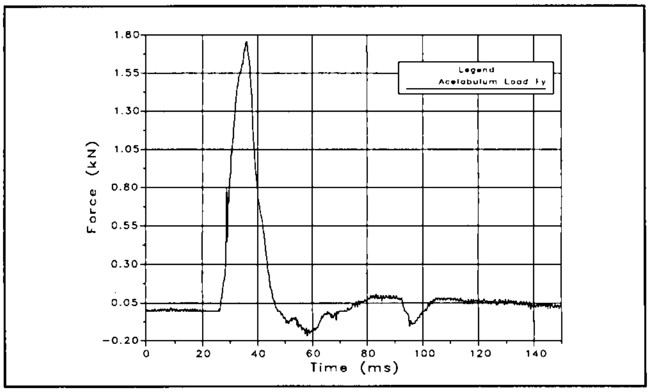

Figure A19. Acetabulum load - Fy.

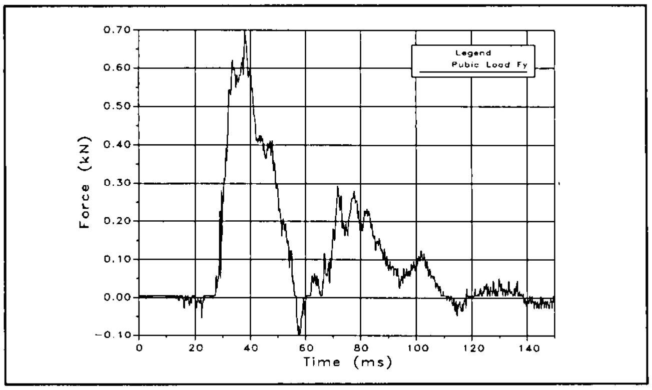

Figure A20. Pubic symphysis load - Fy.

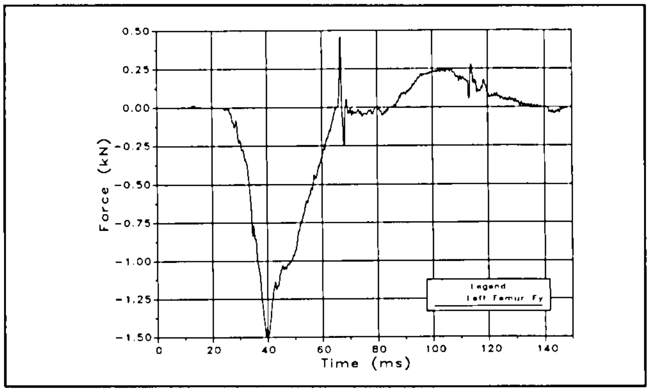

Figure A21. Typical upper femur load - Fy.

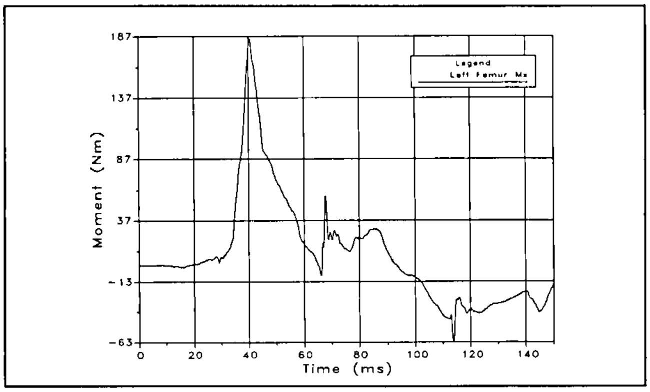

Figure A22. Typical upper femur moment - Mx.

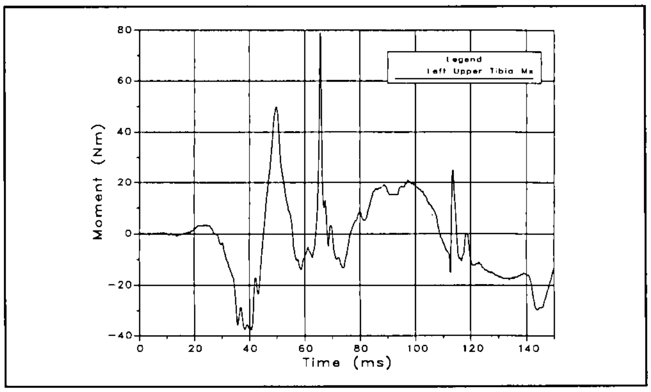

Figure A23. Typical upper tibia moment - Mx.

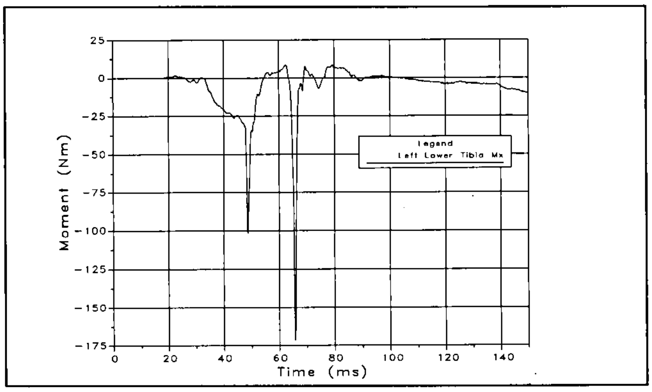

Figure A24. Typical lower tibia moment - Mx.

APPENDIX B -- SLED TESTING DATA

Table B1.
Heidelberg-type Sled into Door Trim Sled Test Data

	Units	SAE Filter Class	Test 3681		Test 3682		Test 3683		Test 3684	
Speed	km/h		24.6		23.5		23.4		23.5	
Sled Acc.	G	60	9.38		8.65		8.55		8.56	
HIC (36 ms)		1000	100		88		46		127	
TTI(d)	G	FIR	62		78		71		64	
Pelvis Ay	G	FIR	62		57		56		80	
Sh Dis Dy	mm	180	18.8		14.8		15		36.1	
1st Rib Dy	mm	180	15.7		16.1		16.6		21.6	
2nd Rib Dy	mm	180	24.1		29		28.9		29.7	
3rd Rib Dy	mm	180	30.7		40.6		40.5		34.7	
1st Abd Dy	mm	180	34.7		48.6		47.2		35.4	
2nd Abd Dy	mm	180	18.5		29.4		28.6		23.6	
1st Rib V*c	m/s	180	0.14		0.17		0.12		0.19	
2nd Rib V*c	m/s	180	0.26		0.38		0.32		0.31	
3rd Rib V*c	m/s	180	0.41		0.7		0.62		0.42	
1st Abd V*c	m/s	180	0.55		0.96		0.9		0.5	
2nd Abd V*c	m/s	180	0.15		0.54		0.47		0.27	
			Max	Min	Max	Min	Max	Min	Max	Min
Head Acc Ax	G	1000	1.3	-6.8	1.6	-5.9	1.8	-6.9	1.4	-5
Head Acc Ay	G	1000	33.9	-1.9	36.9	-1.5	0	0	21.4	-2.2
Head Acc Az	G	1000	3.3	-25.4	4.4	-27.4	4.4	-27.3	2.7	-32.2
Head Acc Res	G	1000	34.4	0	37.2	0	27.8	0	36.8	0
Sh Ld Fx	N	600	164.3	-79.9	87.2	-67.9	53.6	-65.8	63.8	112.8
Sh Ld Fy	N	600	1752.9	-74.9	1424.9	-88.8	1415.9	-132.1	2484.8	-130
Sh Ld Fz	N	600	329.7	-60	316.4	-102.9	378.3	-74.6	297.4	-307.3
Sh Ld Result	N	600	1756.8	0	1430.1	0	1419.2	0	2484.9	0
Up Spine Ay	G	180	40.4	-4.4	38.7	-7.1	40.8	-6.3	43.8	-8.4
T12 Ay	G	180	41.2	-7.3	49.1	-10	49.3	-9.5	55.5	-10.6
1st Rib Ay	G	180	63.1	-17.1	81.2	-27.2	69.7	-19.7	55.1	-8.8
2nd Rib Ay	G	180	0	0	0	0	0	0	0	0
3rd Rib Ay	G	180	92	-50.4	180.3	-67.9	99.7	-50.3	96.2	-20.2
1st Abd Ay	G	180	99.8	-53.1	210.3	-92.9	117.5	-67.1	92	-32.2
2nd Abd Ay	G	180	91.6	-27.8	147.3	-75.4	132.1	-47.5	54.9	-34.4
Pel Acc Ax	G	180	3.9	-6.5	10.9	-8.3	12.9	-6.5	6	-14.7
Pel Acc Ay	G	180	65.4	-6.9	60.6	-6.2	56.2	-6.3	86.8	-4.5
Pel Acc Az	G	180	8.7	-8.5	11.6	-4.8	13.7	-4.8	8.1	-7.8
Pelvic Pesultant	G	180	65.4	0	61.2	0	56.2	0	87.4	0
Iliac Ld Fy	N	600	1623	-109	343	-188	378	-136	1131	-141
Acetabulum Fy	N	600	2038	-1003	3302	-919	3264	-910	2403	-715
Pubic Ld Fy	N	600	790	-115	943	-138	915	-106	1250	-128

Table B2.
Door Component 11.2 m/s Sled Test Data

	Units	SAE Filter Class	Test I04046		Test I04047	
Speed	m/s		10.97		11.01	
HIC (15 ms)		1000	1046		1683	
TTI	G	FIR	139		151	
Pelvis Accl - Ay	G	FIR	123		119	
Shoulder Disp - Dy	mm	180	63		56	
Up Thorax Disp - Dy	mm	180	54		51	
Mid Thorax Disp - Dy	mm	180	67		64	
Lo Thorax Disp - Dy	mm	180	58		58	
Up Abdmn Disp - Dy	mm	180	68		66	
Lo Abdmn Disp - Dy	mm	180	41		46	
Up Thorax V*c	m/s	180	1.274		1.304	
Mid Thorax V*c	m/s	180	1.985		1.671	
Lo Thorax V*c	m/s	180	1.205		1.793	
Up Abdmn V*c	m/s	180	2.044		2.498	
Lo Abdmn V*c	m/s	180	0.933		1.066	
			Max	Min	Max	Min
Head Accl - Ax	G	1000	2.1	-13.0	1.9	-22.0
Head Accl - Ay	G	1000	211.4	-4.5	270.8	-4.7
Head Accl - Az	G	1000	56.6	-10.3	66.0	-13.4
Head Accl. - Resultant	G	1000	211.5	0.1	272.1	0.0
Up Neck Load - Fx	N	1000	42.0	-440.9	36.9	-474.6
Up Neck Load - Fy	N	1000	794.9	-167.7	788.6	-149.2
Up Neck Load - Fz	N	1000	2014.5	-105.2	2315.6	-146.9
Up Neck Moment - Mx	N·m	600	27.4	-38.7	35.4	-37.9
Up Neck Moment - My	N·m	600	4.1	-24.6	5.1	-22.3
Up Neck Moment - Mz	N·m	600	11.5	-2.6	14.2	-3.3
Low Neck Load - Fx	N	1000	89.0	-285.6	65.1	-281.5
Low Neck Load - Fy	N	1000	1678.2	-236.8	1645.3	-157.9
Low Neck Load - Fz	N	1000	1796.1	901.2	1945.6	920.7
Low Neck Moment - Mx	N·m	600	160.7	-38.7	152.8	-37.2
Low Neck Moment - My	N·m	600	56.0	80.7	70.7	-77.6
Shoulder Load - Fy	N	600	4617.0	-283.2	5764.6	-229.7
Shoulder Accl - Ay	G	180	274.5	-126.6	230.7	-106.7
Up Thorax Accl - Ay	G	180	226.8	-79.4	187.5	-139.2
Mid Thorax Accl - Ay	G	180	172.1	-51.6	201.3	-77.4
Lo Thorax Accl - Ay	G	180	380.6	-165.1	410.4	-163.9
Up Abdmn Accl - Ay	G	180	558.6	-289.3	526.0	-178.0
Lo Abdmn Accl - Ay	G	180	243.1	174.0	217.8	-126.7
Thorax Spine T12 - Ay	G	180	85.4	-13.4	116.6	-12.9
Lumbar Load - Fx	N	1000	286.9	-575.1	290.9	-491.5
Lumbar Load - Fy	N	1000	569.3	-1339.3	453.3	-1249.4
Lumbar Load - Fz	N	1000	1693.8	-68.9	2631.0	-26.4
Lumbar Moment - Mx	N·m	1000	65.3	-31.3	54.9	-31.0
Lumbar Moment - My	N·m	1000	31.3	-34.1	36.7	-35.6
Lumbar Moment - Mz	N·m	1000	8.9	-0.5	19.6	-1.6
Pelvic Acceleration - Ax	G	180	24.2	-26.3	43.0	-31.5
Pelvic Acceleration - Ay	G	180	128.6	-30.5	127.6	-47.7
Pelvic Acceleration - Az	G	180	29.1	-35.1	20.3	-44.1
Pelvic Acceleration - Res.	G	180	127.9	0.1	127.5	0.0
Iliac Load - Fy	N	600	NA	NA	NA	NA
Acetabulum Load - Fy	N	600	863.8	-376.3	889.2	-915.0
Pubic Load - Fy	N	600	104.7	-1801.9	203.0	-1793.0

Table B3.
70 & 210 kPa Padded Wall at 6.8 m/s

	Units	SAE Filter Class	Test I04050		Test I04051		Test I04055	
Speed	m/s		6.82		6.77		6.54	
HIC (15 ms)		1000	22		34		24	
TTI	G	FIR	34		34		33	
Pelvis Accl - Ay	G	FIR	35		34		35	
Shoulder Disp - Dy	mm	180	13		20		14	
Up Thorax Disp - Dy	mm	180	9		12		9	
Mid Thorax Disp - Dy	mm	180	17		18		18	
Lo Thorax Disp - Dy	mm	180	19		19		20	
Up Abdmn Disp - Dy	mm	180	27		25		28	
Lo Abdmn Disp - Dy	mm	180	12		10		16	
Up Thorax V*c	m/s	180	0.026		0.067		0.020	
Mid Thorax V*c	m/s	180	0.071		0.083		0.070	
Lo Thorax V*c	m/s	180	0.071		0.081		0.115	
Up Abdmn V*c	m/s	180	0.163		0.146		0.493	
Lo Abdmn V*c	m/s	180	0.108		0.030		0.103	
Shoulder Load Plate - Fy	N	180	795		720		543	
Thorax Load Plate - Fy	N	180	2059		2121		2118	
Abdomen Load Plate - Fy	N	180	2127		1916		1939	
Pelvis Load Plate - Fy	N	180	2104		1693		1841	
Thigh Load Plate - Fy	N	180	1305		1272		1006	
Shoulder Load Plate - Dy	mm	60	41		27		37	
Thorax Load Plate - Dy	mm	60	21		16		24	
Abdomen Load Plate - Dy	mm	60	57		59		54	
Pelvis Load Plate - Dy	mm	60	16		15		14	
Thigh Load Plate - Dy	mm	60	28		30		24	
			Max	Min	Max	Min	Max	Min
Head Accl - Ax	G	1000	0.4	-3.5	0.4	-4.3	0.3	-4.0
Head Accl - Ay	G	1000	10.7	-0.8	12.2	-0.5	11.2	-0.6
Head Accl - Az	G	1000	18.1	-2.5	20.8	-1.5	19.2	-1.5
Head Accl. - Resultant	G	1000	20.6	0.1	24.1	0.0	22.0	0.0
Up Neck Load - Fx	N	1000	17.4	-95.4	14.6	-115.5	19.3	-93.0
Up Neck Load - Fy	N	1000	329.5	-49.0	362.6	-37.7	337.2	-35.4
Up Neck Load - Fz	N	1000	607.2	-111.0	725.0	-53.7	622.7	-85.8
Up Neck Moment - Mx	N·m	600	20.0	-12.5	25.4	-13.2	20.4	-15.3
Up Neck Moment - My	N·m	600	4.2	-6.7	3.3	-7.6	1.0	-8.2
Up Neck Moment - Mz	N·m	600	8.0	-0.7	8.8	-2.6	7.0	-1.6
Low Neck Load - Fx	N	1000	57.1	-105.2	18.2	-96.7	29.0	-113.5
Low Neck Load - Fy	N	1000	634.3	-38.3	756.2	-45.2	690.3	-48.2
Low Neck Load - Fz	N	1000	537.3	-179.1	563.6	-242.0	434.4	-250.6
Low Neck Moment - Mx	N·m	600	85.4	-70.1	92.8	-6.7	83.6	-6.0
Low Neck Moment - My	N·m	600	19.9	-18.5	23.0	19.4	20.5	-21.2
Shoulder Load - Fy	N	600	1209.4	-236.0	1571.5	-262.6	1216.5	-246.7
Shoulder Accl - Ay	G	180	64.5	-236.1	61.5	-11.6	53.9	-32.5
Up Thorax Accl - Ay	G	180	29.9	-20.3	38.9	-22.1	25.5	-16.4
Mid Thorax Accl - Ay	G	180	54.9	-34.5	50.1	-38.7	49.0	-35.5
Lo Thorax Accl - Ay	G	180	79.0	-43.2	77.0	-45.0	76.4	-45.8
Up Abdmn Accl - Ay	G	180	60.3	-13.8	67.5	-24.4	63.2	-21.6
Lo Abdmn Accl - Ay	G	180	31.3	-9.8	34.8	-10.3	46.0	-13.7
Thorax Spine T12 - Ay	G	180	20.1	-1.7	22.2	-3.4	20.9	-2.8
Lumbar Load - Fx	N	1000	NA	NA	NA	NA	NA	NA
Lumbar Load - Fy	N	1000	57.6	-1262.3	64.5	-1325.1	76.2	-1253.0
Lumbar Load - Fz	N	1000	572.9	-72.7	514.2	-152.6	584.0	-119.2
Lumbar Moment - Mx	N·m	1000	58.9	-6.2	67.5	-5.2	59.5	-7.0
Lumbar Moment - My	N·m	1000	1.3	-16.4	4.6	-15.1	2.3	-15.2
Lumbar Moment - Mz	N·m	1000	2.8	-16.5	2.0	-14.9	2.3	-14.8
Pelvic Acceleration - Ax	G	180	7.4	-5.3	6.5	-6.3	6.9	-5.6
Pelvic Acceleration - Ay	G	180	38.2	-0.3	8.7	-9.4	40.4	-1.4
Pelvic Acceleration - Az	G	180	9.3	-8.0	38.7	-0.4	7.7	-13.0
Pelvic Resultant	G	180	35.7	0.1	36.3	0.1	38.2	0.0
Iliac Load - Fy	N	600	31.4	-140.3	36.9	-6.2	57.2	-123.9
Acetabulum Load - Fy	N	600	1406.0	-89.2	1163.6	-51.2	1240.1	-66.3
Pubic Load - Fy	N	600	82.9	-421.9	65.8	-366.1	65.1	-373.1

Table B4.
140 & 280 kPa Padded Wall at 6.8 m/s

	Units	SAE Filter Class	Test I04052	Test I04053	Test I04054
Speed	m/s		6.65	6.59	6.59
HIC (15 ms)		1000	26	24	27
TTI	G	FIR	35	33	34
Pelvis Accl - Ay	G	FIR	49	43	42
Shoulder Disp - Dy	mm	180	16	16	16
Up Thorax Disp - Dy	mm	180	13	11	11
Mid Thorax Disp - Dy	mm	180	19	18	19
Lo Thorax Disp - Dy	mm	180	21	19	21
Up Abdmn Disp - Dy	mm	180	29	26	29
Lo Abdmn Disp - Dy	mm	180	12	11	11
Up Thorax V*c	m/s	180	0.054	0.050	0.047
Mid Thorax V*c	m/s	180	0.090	0.061	0.090
Lo Thorax V*c	m/s	180	0.102	0.075	0.107
Up Abdmn V*c	m/s	180	0.233	0.153	0.220
Lo Abdmn V*c	m/s	180	0.048	0.030	0.044
Shoulder Load Plate - Fy	N	180	798	626	615
Thorax Load Plate - Fy	N	180	2126	1909	2206
Abdomen Load Plate - Fy	N	180	2069	1988	2142
Pelvis Load Plate - Fy	N	180	2914	2436	2496
Thigh Load Plate - Fy	N	180	2351	2249	2237
Shoulder Load Plate - Dy	mm	60	31	21	24
Thorax Load Plate - Dy	mm	60	19	18	18
Abdomen Load Plate - Dy	mm	60	54	48	55
Pelvis Load Plate - Dy	mm	60	8	8	9
Thigh Load Plate - Dy	mm	60	3	3	3

	Units	SAE Filter Class	Test I04052 Max	Test I04052 Min	Test I04053 Max	Test I04053 Min	Test I04054 Max	Test I04054 Min
Head Accl - Ax	G	1000	0.6	-4.1	0.5	-3.9	0.4	-3.8
Head Accl - Ay	G	1000	11.1	-0.8	11.2	-0.6	11.5	-0.5
Head Accl - Az	G	1000	19.8	-1.4	19.8	-1.0	20.5	-1.6
Head Accl. - Resultant	G	1000	22.6	0.1	22.6	0.0	23.5	0.0
Up Neck Load - Fx	N	1000	12.6	-91.1	10.6	-102.5	16.2	-91.5
Up Neck Load - Fy	N	1000	335.4	-32.4	339.6	-41.9	346.2	-42.7
Up Neck Load - Fz	N	1000	659.6	-33.8	664.1	-61.2	646.7	-60.7
Up Neck Moment - Mx	N·m	600	21.2	-13.5	19.5	-14.5	22.2	-16.2
Up Neck Moment - My	N·m	600	2.3	-8.3	1.1	-7.5	1.3	-7.5
Up Neck Moment - Mz	N·m	600	7.2	-1.4	6.3	-1.3	6.8	-1.6
Low Neck Load - Fx	N	1000	24.4	-122.6	28.2	-103.7	24.2	-121.8
Low Neck Load - Fy	N	1000	653.4	-58.3	669.0	-37.9	690.8	-41.5
Low Neck Load - Fz	N	1000	489.7	-258.7	501.3	-252.8	478.6	-295.0
Low Neck Moment - Mx	N·m	600	81.9	-7.8	77.7	-5.4	83.2	-6.9
Low Neck Moment - My	N·m	600	15.2	-23.1	19.8	-21.2	17.4	-22.2
Shoulder Load - Fy	N	600	1378.9	-246.2	1269.0	-209.6	1404.7	-236.4
Shoulder Accl - Ay	G	180	61.3	-14.1	77.1	-16.4	121.9	-16.3
Up Thorax Accl - Ay	G	180	24.7	-20.5	28.6	-16.9	33.1	-15.7
Mid Thorax Accl - Ay	G	180	47.7	-35.8	43.9	-36.4	48.9	-34.1
Lo Thorax Accl - Ay	G	180	79.3	-48.6	72.5	-48.6	77.9	-46.9
Up Abdmn Accl - Ay	G	180	75.2	-20.6	68.3	-27.2	71.1	-21.1
Lo Abdmn Accl - Ay	G	180	30.0	-13.1	26.9	-14.3	31.6	-13.0
Thorax Spine T12 - Ay	G	180	22.1	-3.1	18.9	-1.9	22.4	-2.1
Lumbar Load - Fx	N	1000	NA	NA	NA	NA	NA	NA
Lumbar Load - Fy	N	1000	81.8	-1061.7	62.9	-1138.2	72.5	-1192.5
Lumbar Load - Fz	N	1000	441.0	-170.5	450.1	-75.1	490.6	-74.2
Lumbar Moment - Mx	N·m	1000	53.3	-6.6	55.2	-9.6	59.6	6.9
Lumbar Moment - My	N·m	1000	2.6	-12.1	4.9	-9.8	6.7	-12.8
Lumbar Moment - Mz	N·m	1000	2.2	-7.8	2.0	-5.3	0.1	-0.2
Pelvic Acceleration - Ax	G	180	11.1	-12.1	7.3	-9.7	8.8	-7.0
Pelvic Acceleration - Ay	G	180	54.8	-7.4	48.4	-6.9	47.1	-5.9
Pelvic Acceleration - Az	G	180	21.5	-11.4	4.8	-8.4	11.3	-11.3
Pelvic Resultant	G	180	53.4	0.1	48.4	0.0	45.3	0.0
Iliac Load - Fy	N	600	32.7	-218.2	54.4	-148.3	16.6	-155.6
Acetabulum Load - Fy	N	600	2200.9	-149.6	1856.6	-1049.3	1920.2	-159.4
Pubic Load - Fy	N	600	69.8	-541.3	34.1	-485.3	65.9	-459.5

Table B5.
70 & 210 kPa Padded Wall at 8.9 m/s

	Units	SAE Filter Class	Test I04056		Test I04057		Test I04058	
Speed	m/s		8.79		8.79		8.7	
HIC (15 ms)		1000	89		83		105	
TTI	G	FIR	43		51		55	
Pelvis Accl - Ay	G	FIR	50		39		35	
Shoulder Disp - Dy	mm	180	18		27		21	
Up Thorax Disp - Dy	mm	180	NA		21		25	
Mid Thorax Disp - Dy	mm	180	28		28		32	
Lo Thorax Disp - Dy	mm	180	27		29		31	
Up Abdmn Disp - Dy	mm	180	40		43		46	
Lo Abdmn Disp - Dy	mm	180	15		17		17	
Up Thorax V*c	m/s	180	NC		0.283		0.161	
Mid Thorax V*c	m/s	180	0.247		0.396		0.353	
Lo Thorax V*c	m/s	180	0.246		0.346		0.380	
Up Abdmn V*c	m/s	180	0.597		0.681		0.795	
Lo Abdmn V*c	m/s	180	0.106		0.166		0.197	
Shoulder Load Plate - Fy	N	180	663		941		495	
Thorax Load Plate - Fy	N	180	2609		2724		3209	
Abdomen Load Plate - Fy	N	180	2411		2860		2866	
Pelvis Load Plate - Fy	N	180	4901		1653		1399	
Thigh Load Plate - Fy	N	180	1459		2110		2391	
Shoulder Load Plate - Dy	mm	60	75		30		21	
Thorax Load Plate - Dy	mm	60	67		74		76	
Abdomen Load Plate - Dy	mm	60	96		108		92	
Pelvis Load Plate - Dy	mm	60	52		65		69	
Thigh Load Plate - Dy	mm	60	68		73		73	
			Max	Min	Max	Min	Max	Min
Head Accl - Ax	G	1000	1.3	-8.7	1.6	-6.8	1.8	-7.5
Head Accl - Ay	G	1000	45.2	-0.3	39.9	-1.2	45.2	-1.2
Head Accl - Az	G	1000	30.5	-1.0	30.4	-1.0	33.8	-1.3
Head Accl. - Resultant	G	1000	45.2	0.1	40.4	0.1	138.3	0.1
Up Neck Load - Fx	N	1000	17.5	-267.8	29.1	-208.4	29.8	-236.1
Up Neck Load - Fy	N	1000	567.1	-69.6	641.8	-36.6	662.3	-32.7
Up Neck Load - Fz	N	1000	1086.6	-37.2	1083.5	-46.3	1150.3	-74.0
Up Neck Moment - Mx	N·m	600	25.9	-13.9	23.8	-18.0	21.4	-13.7
Up Neck Moment - My	N·m	600	3.5	-20.0	1.2	-15.2	0.5	-16.6
Up Neck Moment - Mz	N·m	600	11.1	-1.4	12.1	-1.2	10.8	-3.0
Low Neck Load - Fx	N	1000	81.7	-61.5	54.4	-91.0	22.6	-148.1
Low Neck Load - Fy	N	1000	1217.0	-72.0	1242.3	-26.4	1343.7	-46.2
Low Neck Load - Fz	N	1000	809.1	-525.3	722.4	-482.6	673.9	-599.1
Low Neck Moment - Mx	N·m	600	126.7	-10.8	149.3	-4.7	149.2	-5.6
Low Neck Moment - My	N·m	600	25.2	-43.1	27.4	-36.7	30.8	-36.3
Shoulder Load - Fy	N	600	1385.1	-182.9	1806.8	-142.2	1476.7	-1265.0
Shoulder Accl - Ay	G	180	89.5	-34.4	135.6	-40.6	145.4	-45.6
Up Thorax Accl - Ay	G	180	53.8	-13.6	71.2	-19.1	53.9	-26.3
Mid Thorax Accl - Ay	G	180	50.4	-35.1	68.0	-46.3	73.1	-55.5
Lo Thorax Accl - Ay	G	180	65.6	-49.7	99.1	-66.4	103.0	-70.8
Up Abdmn Accl - Ay	G	180	82.9	-109.2	105.9	-85.7	86.1	-59.9
Lo Abdmn Accl - Ay	G	180	58.6	-29.1	72.7	-32.6	110.8	-45.8
Thorax Spine T12 - Ay	G	180	36.1	-2.0	44.5	-3.2	33.5	-1.5
Lumbar Load - Fx	N	1000	NA	NA	NA	NA	NA	NA
Lumbar Load - Fy	N	1000	122.0	-946.1	93.8	-1410.9	108.9	-1415.8
Lumbar Load - Fz	N	1000	1259.2	-58.8	1253.4	-98.5	1464.7	-85.0
Lumbar Moment - Mx	N·m	1000	44.9	-25.1	61.4	-13.4	58.8	-12.1
Lumbar Moment - My	N·m	1000	2.3	-49.0	3.5	-44.5	3.1	-35.1
Lumbar Moment - Mz	N·m	1000	3.4	-25.4	4.4	-16.9	4.1	-11.4
Pelvic Acceleration - Ax	G	180	24.9	-11.8	5.7	-11.2	7.9	-11.5
Pelvic Acceleration - Ay	G	180	55.9	-0.9	5.6	-15.8	39.7	-4.0
Pelvic Acceleration - Az	G	180	10.5	-19.5	44.8	-1.4	7.3	-13.5
Pelvic Resultant	G	180	52.7	0.1	43.5	0.1	37.8	0.1
Iliac Load - Fy	N	600	1775.2	-207.5	520.9	-339.7	661.9	-304.1
Acetabulum Load - Fy	N	600	1859.7	-136.6	667.2	-69.2	818.9	-163.5
Pubic Load - Fy	N	600	105.2	-330.2	62.1	-263.8	55.8	-334.8

Table B6.
140 & 280 kPa Padded Wall at 8.9 m/s

	Units	SAE Filter Class	Test I04059		Test I04060		Test I04061	
Speed	m/s		8.72		8.75		8.69	
HIC (15 ms)		1000	185		158		116	
TTI	G	FIR	50		55		52	
Pelvis Accl - Ay	G	FIR	80		83		82	
Shoulder Disp - Dy	mm	180	21		22		24	
Up Thorax Disp - Dy	mm	180	21		24		23	
Mid Thorax Disp - Dy	mm	180	28		30		30	
Lo Thorax Disp - Dy	mm	180	31		31		32	
Up Abdmn Disp - Dy	mm	180	48		48		49	
Lo Abdmn Disp - Dy	mm	180	22		22		23	
Up Thorax V*c	m/s	180	0.167		0.230		0.207	
Mid Thorax V*c	m/s	180	0.290		0.342		0.267	
Lo Thorax V*c	m/s	180	0.320		0.372		0.349	
Up Abdmn V*c	m/s	180	0.810		0.869		0.736	
Lo Abdmn V*c	m/s	180	0.162		0.163		0.193	
Shoulder Load Plate - Fy	N	180	402		672		542	
Thorax Load Plate - Fy	N	180	3039		2987		3214	
Abdomen Load Plate - Fy	N	180	2986		2972		3057	
Pelvis Load Plate - Fy	N	180	5532		5774		5250	
Thigh Load Plate - Fy	N	180	4736		4857		5057	
Shoulder Load Plate - Dy	mm	60	7		21		19	
Thorax Load Plate - Dy	mm	60	58		59		55	
Abdomen Load Plate - Dy	mm	60	76		76		73	
Pelvis Load Plate - Dy	mm	60	27		29		29	
Thigh Load Plate - Dy	mm	60	9		5		8	
			Max	Min	Max	Min	Max	Min
Head Accl - Ax	G	1000	2.2	-14.7	2.4	-15.2	1.1	-8.9
Head Accl - Ay	G	1000	69.9	-0.3	66.2	-0.4	53.0	-0.4
Head Accl - Az	G	1000	31.1	-1.2	31.6	-1.3	31.4	-1.1
Head Accl. - Resultant	G	1000	71.9	0.0	68.0	0.1	53.8	0.0
Up Neck Load - Fx	N	1000	60.3	-225.2	43.4	-257.4	12.0	-264.5
Up Neck Load - Fy	N	1000	427.0	-51.7	508.4	-23.0	568.9	-44.9
Up Neck Load - Fz	N	1000	1116.9	-55.6	1120.9	-95.7	1113.3	-82.9
Up Neck Moment - Mx	N·m	600	20.7	-16.4	22.1	-13.7	19.9	-16.2
Up Neck Moment - My	N·m	600	1.4	-20.2	2.8	-22.2	2.9	-22.8
Up Neck Moment - Mz	N·m	600	7.9	-4.4	8.1	-3.4	9.3	-3.1
Low Neck Load - Fx	N	1000	76.2	-89.4	61.7	-120.6	61.2	-116.3
Low Neck Load - Fy	N	1000	1163.2	-60.4	1196.5	-29.7	1192.1	-49.9
Low Neck Load - Fz	N	1000	826.4	-464.4	870.0	-522.2	796.6	-545.8
Low Neck Moment - Mx	N·m	600	111.3	-8.9	118.4	-2.2	121.7	-6.4
Low Neck Moment - My	N·m	600	15.2	-48.6	27.0	-49.7	26.9	-50.2
Shoulder Load - Fy	N	600	1498.1	-162.1	1502.1	-139.5	1616.8	-168.3
Shoulder Accl - Ay	G	180	111.8	-31.1	109.2	-29.1	147.1	-32.2
Up Thorax Accl - Ay	G	180	60.6	-25.4	54.2	-26.8	56.8	-18.5
Mid Thorax Accl - Ay	G	180	58.5	-35.4	63.2	-43.2	63.2	-40.8
Lo Thorax Accl - Ay	G	180	82.5	-57.8	92.6	-53.2	90.9	-53.2
Up Abdmn Accl - Ay	G	180	80.0	-151.4	88.7	-45.1	79.9	-119.2
Lo Abdmn Accl - Ay	G	180	71.5	-45.7	91.7	-46.1	59.5	-20.0
Thorax Spine T12 - Ay	G	180	42.2	-2.7	43.6	-4.2	42.6	-6.6
Lumbar Load - Fx	N	1000	NA	NA	NA	NA	NA	NA
Lumbar Load - Fy	N	1000	117.6	-1100.4	148.3	-698.8	114.3	-1167.2
Lumbar Load - Fz	N	1000	1253.9	-122.2	1171.6	-563.1	1202.3	-90.0
Lumbar Moment - Mx	N·m	1000	55.7	-22.8	58.1	-30.3	59.6	-28.1
Lumbar Moment - My	N·m	1000	10.0	-30.0	13.9	-25.0	5.2	-28.2
Lumbar Moment - Mz	N·m	1000	4.7	-9.1	7.2	-5.6	4.0	-12.6
Pelvic Acceleration - Ax	G	180	29.7	-11.4	13.6	-10.1	20.9	-14.2
Pelvic Acceleration - Ay	G	180	86.0	-3.5	86.7	-3.7	88.2	-20.7
Pelvic Acceleration - Az	G	180	18.2	-15.9	9.9	-17.1	10.2	-17.3
Pelvic Resultant	G	180	85.8	0.2	87.7	0.1	89.1	0.1
Iliac Load - Fy	N	600	995.9	-338.1	945.6	-274.8	1249.4	-283.8
Acetabulum Load - Fy	N	600	2571.8	-174.2	2776.0	-453.3	2165.7	-1659.1
Pubic Load - Fy	N	600	67.2	-915.0	20.8	-341.3	113.1	-749.0

APPENDIX C -- VERIFICATION TESTING DATA

Table C1.
Head Drop - Left Side

Head Drops - Left Side	Verification Corridors									
Run Number		129737	129739	129746	129757	129958	129966	129988	130009	130034
Peak Resultant (G's)	130 - 160	159.1	158.7	157.3	158.9	162.0	164.9	161.3	160.3	160.1

Table C2.
Head Drop - Right Side

Head Drops - Right Side	Verification Corridors					
Run Number		129738	129740	129747	129758	130010
Peak Resultant (G's)	130 - 160	155.1	156.5	159.9	159.1	156.7

Table C3.
Neck Pendulum Impact - Left Side

Neck Pendulum Impacts - Left Side	Verification Corridors													
Run Number		129742	129743	129744	129745	129753	129760	129960	129967	129987	129989	129990	130008	130035
Pendulum Velocity - 10 m/s	2.1 - 2.5	2.2	2.2	2.2	2.3	2.2	2.2	2.5	2.3	2.4	2.4	2.4	2.2	2.2
Pendulum Velocity - 20 m/s	4.0 - 5.0	4.4	4.5	4.4	4.8	4.5	4.5	4.9	4.7	4.7	4.7	4.7	4.4	4.3
Pendulum Velocity - 30 m/s	5.8 - 7.0	6.2	6.5	6.2	6.8	6.4	6.5	6.8	6.7	6.7	6.5	6.5	6.2	6.1
Peak Rotation (degree)	70 - 86	92.0	93.2	89.0	90.6	88.3	89.1	94.8	95.1	97.7	98.7	97.9	96.8	89.6
Time From Peak Rotation to Zero (ms)	45 - 63	62.5	63.8	62.7	60.4	63.1	62.8	62.0	63.8	63.8	64.2	63.3	65.9	64.4
Peak Moment About Occipital Condyles (Nm)	48 - 59	60.5	63.1	63.8	67.7	65.2	63.9	63.2	61.1	58.9	56.8	57.2	54.1	57.6
Time From Peak Moment to 10 Nm (ms)	22 - 32	34.1	32.9	37.5	29.5	40.1	37.3	30.3	N/A	N/A	N/A	N/A	N/A	N/A
Pendulum Speed (m/s)	6.9 - 7.1	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0

Table C4.
Thorax with Arm Involvement Impact

6.7 m/s Thorax With Arm Impacts	Verification Corridors											
Run Number		25228	25229	129789	129791	129954	129976	129978	129980	129995	130013	130045
Pendulum Force (kN)	4.5 - 5.6	5.3	5.4	5.5	5.5	5.2	5.0	5.1	5.2	5.3	5.0	5.1
T1 Acceleration (G's)	42 - 53	50.7	50.4	48.7	48.7	49.3	40.6	45.0	45.2	46.3	43.4	47.0
T12 Acceleration (G's)	17 -26	38.6	38.7	39.0	38.4	36.8	32.8	36.4	36.0	37.0	35.8	37.2
Upper Rib Acceleration (G's)	67 - 98	101.0	104.0	115.4	113.1	106.9	95.6	114.5	103.3	101.1	121.3	102.3
Middle Rib Acceleration (G's)	86 - 122	126.0	130.0	137.7	137.8	128.3	132.6	132.8	130.8	126.5	138.8	128.8
Lower Rib Acceleration (G's)	104 - 157	158.0	162.0	169.6	173.4	166.3	170.1	160.5	166.1	161.4	159.1	165.1
Shoulder Rib Deflection (mm)	12.0 - 22.0	26.7	27.8	26.3	25.5	28.9	29.4	34.4	32.6	31.5	34.3	30.0
Upper Rib Deflection (mm)	17 - 24	18.8	19.2	21.2	21.3	21.9	28.8	22.4	23.7	23.1	24.3	21.2
Middle Rib Deflection (mm)	26 - 34	23.4	23.5	25.0	25.0	29.3	34.7	26.5	28.3	28.1	26.7	26.3
Lower Rib Deflection (mm)	34 - 43	26.7	26.6	28.7	28.9	27.1	29.0	22.9	25.3	26.6	23.1	25.4

Table C5.
Thorax without Arm Involvement Impact

6.7 m/s Thorax Without Arm Impacts	Verification Corridors											
Run Number		S2D-03	25220	25221	129767	129768	129770	129793	129794	129947	129951	129952
Pendulum Force (kN)	3.8 - 4.6	3.6	3.7	3.9	3.6	3.6	3.6	3.7	3.7	3.6	3.6	4.0
T1 Acceleration (G's)	24 - 30	28.0	28.8	28.6	27.2	26.9	27.3	27.7	27.2	27.1	25.7	27.5
T12 Acceleration (G's)	15 - 20	20.0	23.0	25.3	23.2	22.3	23.0	22.4	23.1	22.2	22.6	21.6
Upper Rib Acceleration (G's)	163 - 219	155.0	152.0	150.0	151.5	158.4	147.1	160.4	156.9	157.8	154.5	157.2
Middle Rib Acceleration (G's)	163 - 219	151.0	130.0	148.0	146.6	155.5	150.8	158.8	156.9	152.3	151.1	153.4
Lower Rib Acceleration (G's)	163 - 219	151.0	136.0	141.0	137.8	143.7	145.3	147.3	145.8	138.7	N/A	139.4
Upper Rib Deflection (mm)	41 - 57	50.0	51.5	48.7	N/A	N/A	N/A	58.6	55.7	58.0	56.9	58.4
Middle Rib Deflection (mm)	41 - 57	53.0	54.2	52.9	54.2	58.8	54.6	60.1	56.5	66.2	66.7	66.2
Lower Rib Deflection (mm)	41 - 57	53.0	50.3	50.7	51.9	56.7	55.5	58.7	54.7	50.7	49.9	48.9

6.7 m/s Thorax Without Arm Impacts	Verification Corridors											
Run Number		129953	129968	129969	129970	129977	129992	130011	130012	130023	130024	130025
Pendulum Force (kN)	3.8 - 4.6	3.6	3.7	3.6	3.6	3.7	3.7	N/A	3.8	3.6	3.6	3.5
T1 Acceleration (G's)	24 - 30	26.3	28.3	26.5	26.1	28.9	28.0	26.3	27.1	26.3	25.9	26.3
T12 Acceleration (G's)	15 - 20	21.8	20.8	20.3	20.1	23.9	23.9	21.5	21.2	22.3	22.6	21.1
Upper Rib Acceleration (G's)	163 - 219	159.8	162.7	165.2	166.0	155.3	155.2	152.9	154.9	149.2	146.9	150.6
Middle Rib Acceleration (G's)	163 - 219	154.8	N/A	157.8	157.7	150.6	156.2	151.9	154.5	152.3	150.0	152.7
Lower Rib Acceleration (G's)	163 - 219	140.8	143.9	143.3	145.0	139.7	144.9	138.1	139.4	143.1	140.4	142.6
Upper Rib Deflection (mm)	41 - 57	57.6	56.9	61.7	61.1	52.8	54.3	56.0	59.8	56.3	54.3	59.0
Middle Rib Deflection (mm)	41 - 57	67.6	65.0	69.8	69.9	62.2	62.0	63.5	66.4	64.2	63.6	66.8
Lower Rib Deflection (mm)	41 - 57	51.3	49.3	51.1	51.6	47.6	48.0	47.7	50.4	50.0	50.2	51.2

Table C6.
Shoulder Impacts

4.5 m/s Shoulder Impacts	Verification Corridors													
Run Number		S2J-01	S2J-02	25211	129772	129783	129784	129955	129975	129981	129996	130014	130015	130046
Pendulum Force (kN)	2.3 - 3.3	2.2	2.2	2.5	2.6	2.6	2.5	2.6	2.6	2.5	2.5	2.5	2.5	2.5
Shoulder Deflection (mm)	17 - 24	23.0	21.0	23.9	24.2	20.1	19.9	23.0	26.3	27.4	25.6	28.9	25.1	26.4

Table C7.
Abdominal Impact

4.5 m/s Abdominal Impacts	Verification Corridors																
Run Number		S2I-04	S2I-05	25216	25217	129776	129777	129778	1297792	1299493	129956	129971	129972	129982	130000	130016	130033
Pendulum Force (kN)	2.1 - 2.6	1.8	1.9	2.2	2.1	2.2	2.2	2.2	2.2	2.1	2.3	2.3	2.2	2.3	2.2	2.4	2.4
T1 Acceleration (G's)	7.0 - 10.0	9.0	9.0	9.5	9.3	9.0	8.8	9.9	9.2	8.3	9.0	8.9	9.0	9.6	8.7	8.9	9.5
T12 Acceleration (G's)	10.0 - 13.0	13.0	13.0	13.5	13.4	14.3	14.2	14.0	14.0	14.7	13.9	14.0	13.9	14.3	13.8	13.2	15.3
Upper Rib Acceleration (G's)	66 - 106	66.0	69.0	55.5	53.6	61.6	60.2	60.3	61.5	63.9	65.8	71.3	68.1	54.7	68.5	63.6	63.7
Lower Rib Acceleration (G's)	66 - 106	66.0	66.0	60.7	61.8	66.6	67.1	65.2	63.5	62.8	64.5	N/A	65.3	58.8	64.5	64.5	66.8
Upper Rib Deflection (G's)	31 - 42	42.0	41.0	36.1	36.3	38.4	36.2	36.9	37.7	38.3	41.6	41.8	41.6	36.5	42.2	42.3	41.5
Lower Rib Deflection (G's)	31 - 42	34.0	34.0	35.9	36.5	N/A	36.7	37.5	37.9	29.6	31.8	32.1	33.4	28.1	32.9	33.5	29.8

Table C8.
Pelvis Impacts

6.7 m/s Pelvis Impacts	Verification Corridors											
Run Number		129773	129774	129780	129782	129950	129957	129973	129974	130001	130026	130028
Pendulum Force (kN)	5.4 - 6.8	7.4	7.4	7.2	7.5	6.9	7.2	7.0	7.1	7.2	6.7	6.8
Pelvis Acceleration (G's)	49 - 77	67.0	72.5	76.1	75.4	81.5	84.2	86.7	82.7	78.6	80.5	81.2

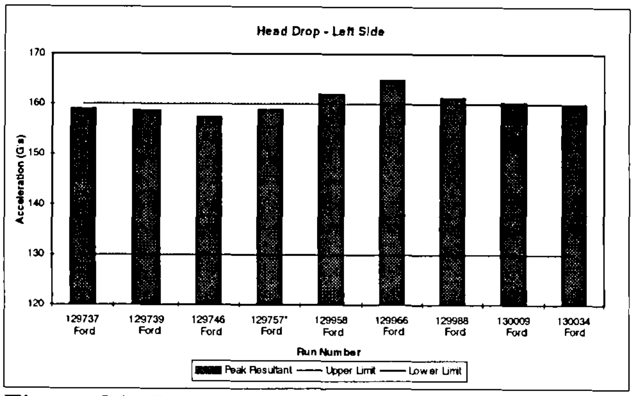

Figure C1. Left side head drop repeatability.

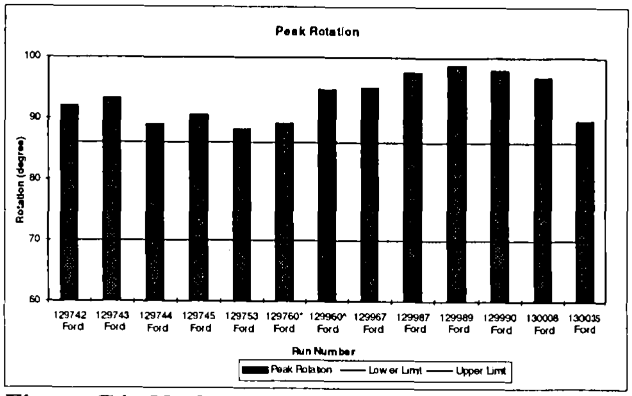

Figure C4. Neck rotation repeatability.

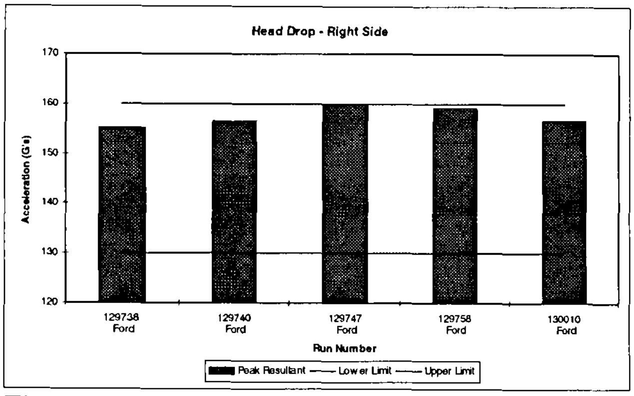

Figure C2. Right side head drop repeatability.

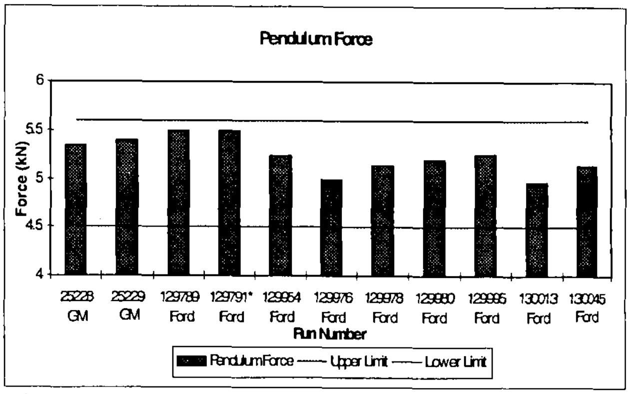

Figure C5. Thorax with arm pendulum repeatability.

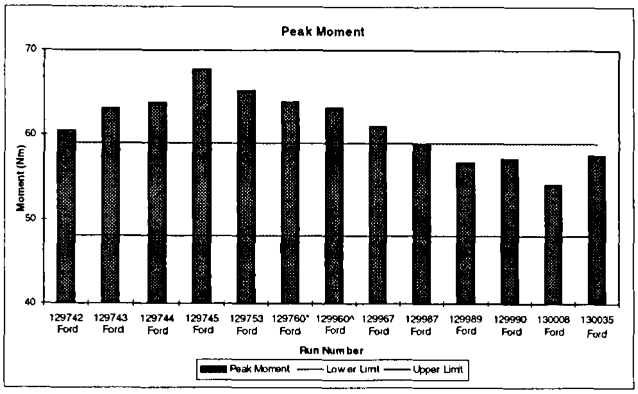

Figure C3. Neck moment impact repeatability.

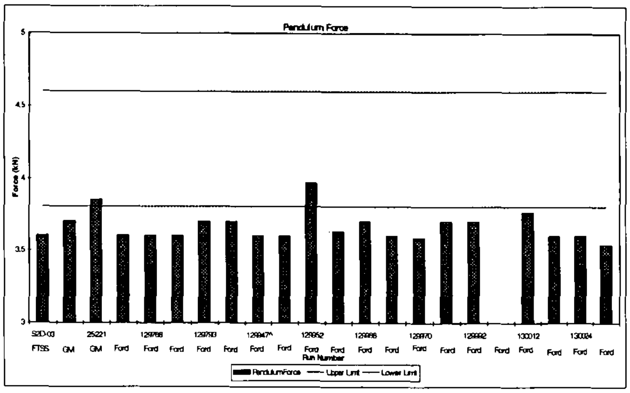

Figure C6. Thorax without arm involvement pendulum repeatability.

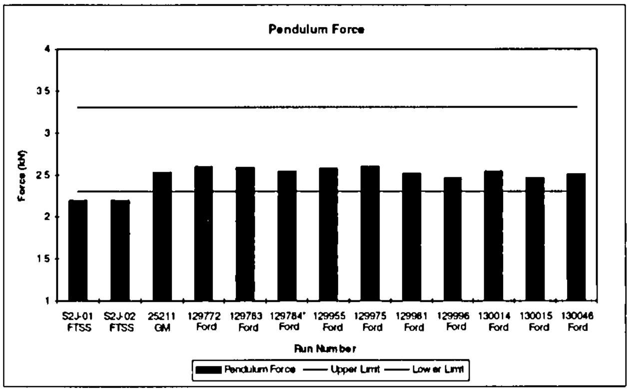

Figure C7. Shoulder pendulum repeatability.

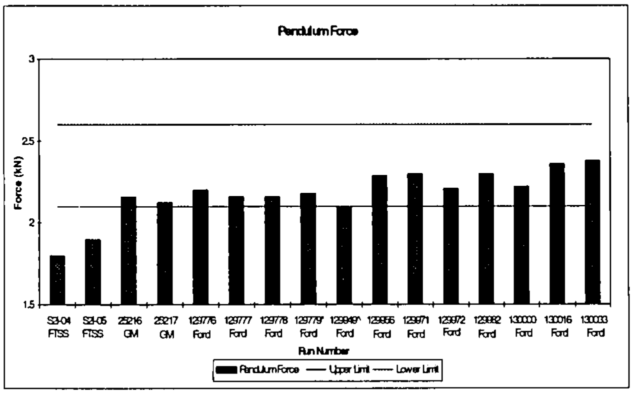

Figure C8. Abdominal pendulum repeatability.

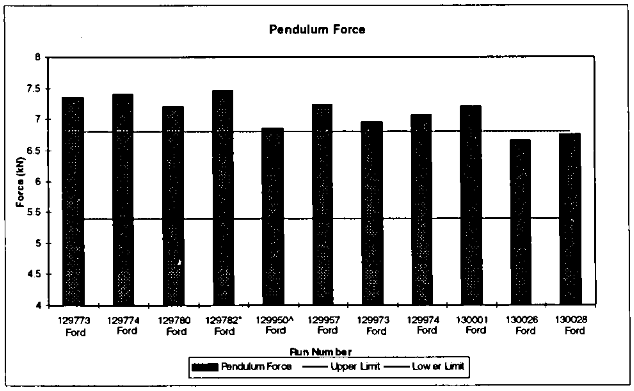

Figure C9. Pelvis pendulum repeatability.

APPENDIX D -- BIOMECHANICAL TESTING

Table D1.
Head Response Target Number 1 -- 200 mm Rigid Surface Drop

	Units	Ave Peak Acceleration	Lower Bound	Upper Bound
Left Side	G	160.3	106	158
Right Side	G	157.5	106	158

Table D2.
Neck Response Target Number 2 -- 5.8 m/s at 6.7 G Sled Test Data

Measurement	Units	Lower Bound	Upper Bound	14048	14049
Peak Flexion Angle	degrees	40	50	24	24
Peak A-P Moment at Occipital Condyles	N·m	20	30	1	1
Peak R-L Moment at Occipital Condyles	N·m	40	50	12	12
Peak Twist Moment	N·m	15	20	6	5
Peak Shear Force at Occipital Condyles	N	750	850	246	250
Peak Tension Force at Occipital Condyles	N	350	400	209	195
Peak P-A Shear Force	N	325	375	54	55
Peak Head Resultant Acceleration	g	18	24	10	10

Table D3.
Pelvis Response Target Number 3 -- 6.8 m/s Rigid Wall Data

Measurement	Units	14069	Lower Bound	Upper Bound
Peak T12 Lateral Accl.	G	37.6	105	143
Peak Rib Deflection	mm	32	87	117
Peak Pelvic Lateral Accl.	G	77	70	94
Peak Pelvis Plate Load	kN	7.5	4.3	5.8

Table D4.
6.8 m/s Rigid Wall Data

	Units	SAE Filter Class	Test I04069	
Speed	m/s		6.61	
HIC (15 ms)		1000	76	
TTI	G	FIR	66	
Pelvis Accl - Ay	G	FIR	56	
Shoulder Disp - Dy	mm	180	43	
Up Thorax Disp - Dy	mm	180	29	
Mid Thorax Disp - Dy	mm	180	32	
Lo Thorax Disp - Dy	mm	180	26	
Up Abdmn Disp - Dy	mm	180	31	
Lo Abdmn Disp - Dy	mm	180	12	
Up Thorax V*c	m/s	180	0.349	
Mid Thorax V*c	m/s	180	0.437	
Lo Thorax V*c	m/s	180	0.288	
Up Abdmn V*c	m/s	180	0.469	
Lo Abdmn V*c	m/s	180	0.072	
Shoulder Load Plate - Fy	N	180	1104	
Thorax Load Plate - Fy	N	180	4063	
Abdomen Load Plate - Fy	N	180	1424	
Pelvis Load Plate - Fy	N	180	4423	
Thigh Load Plate - Fy	N	180	3313	
			Max	Min
Head Accl - Ax	G	1000	0.5	-3.2
Head Accl - Ay	G	1000	16.6	-0.5
Head Accl - Az	G	1000	32.7	-1.1
Head Accl. - Resultant	G	1000	35.4	0.0
Up Neck Load - Fx	N	1000	8.6	-156.2
Up Neck Load - Fy	N	1000	366.0	-43.1
Up Neck Load - Fz	N	1000	1113.3	-49.3
Up Neck Moment - Mx	N·m	600	30.2	-24.2
Up Neck Moment - My	N·m	600	1.9	-11.3
Up Neck Moment - Mz	N·m	600	8.7	-1.6
Low Neck Load - Fx	N	1000	41.5	-142.6
Low Neck Load - Fy	N	1000	1033.7	-66.1
Low Neck Load - Fz	N	1000	806.4	-268.3
Low Neck Moment - Mx	N·m	600	109.3	-9.4
Low Neck Moment - My	N·m	600	15.5	-42.0
Shoulder Load - Fy	N	600	2353.9	-141.1
Shoulder Accl - Ay	G	180	212.5	-73.2
Up Thorax Accl - Ay	G	180	120.6	-92.1
Mid Thorax Accl - Ay	G	180	141.3	-73.0
Lo Thorax Accl - Ay	G	180	241.9	-111.4
Up Abdmn Accl - Ay	G	180	347.3	-221.5
Lo Abdmn Accl - Ay	G	180	118.4	-27.6
Thorax Spine T12 - Ay	G	180	37.6	-3.2
Lumbar Load - Fx	N	1000	3.1	-47.3
Lumbar Load - Fy	N	1000	111.9	-1128.0
Lumbar Load - Fz	N	1000	301.6	-304.5
Lumbar Moment - Mx	N·m	1000	72.1	-12.8
Lumbar Moment - My	N·m	1000	13.6	-4.2
Lumbar Moment - Mz	N·m	1000	8.3	-0.7
Pelvic Acceleration - Ax	G	180	18.4	-20.8
Pelvic Acceleration - Ay	G	180	76.9	-13.4
Pelvic Acceleration - Az	G	180	20.6	-13.7
Pelvic Resultant	G	180	67.0	0.1
Iliac Load - Fy	N	600	27.1	-324.3
Acetabulum Load - Fy	N	600	2724.8	-414.2
Pubic Load - Fy	N	600	224.6	-528.4

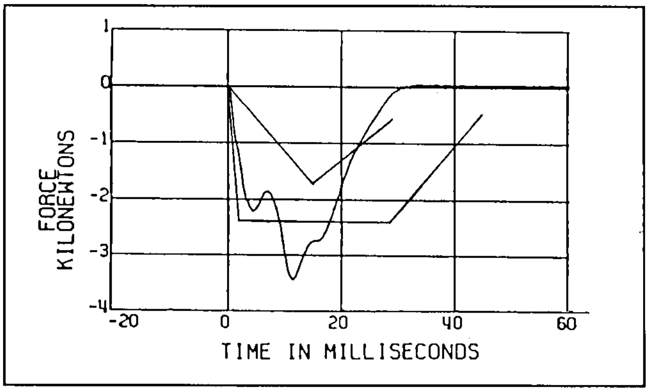

Figure D1. Shoulder response target number 1 4.5 m/s pendulum impact - pendulum force-time history.

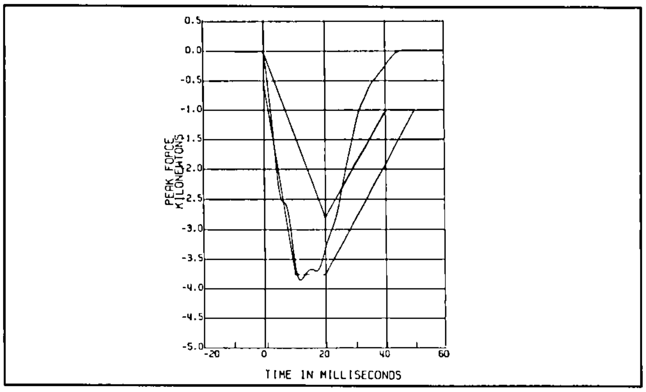

Figure D4. Thorax response target number 1 6.7 m/s pendulum impact - pendulum force-time history.

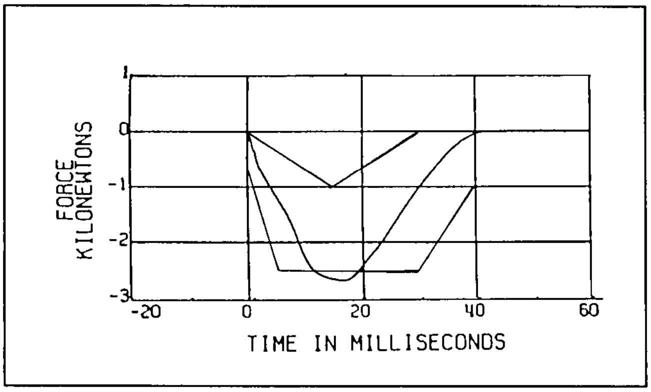

Figure D2. Thorax response target number 1 4.3 m/s pendulum impact - pendulum force-time history.

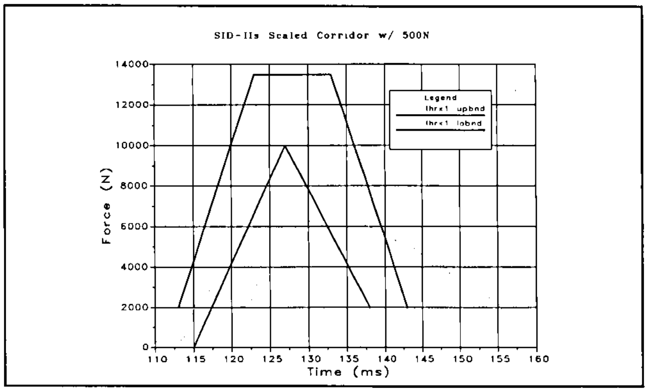

Figure D5. Thorax response target number 3 6.8 m/s rigid wall Heidelberg - load plate force-time history.

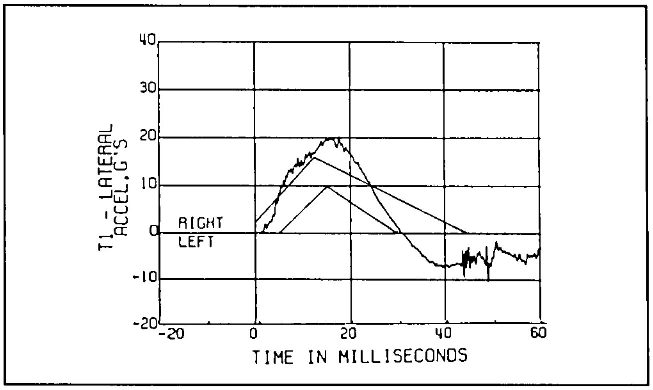

Figure D3. Thorax response target number 1 4.3 m/s pendulum impact - T1 acceleration-time history.

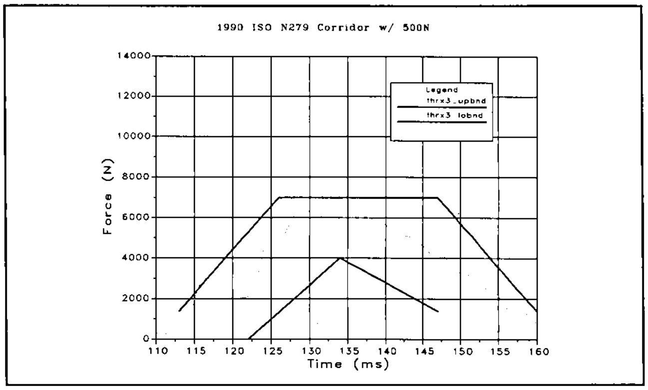

Figure D6. Thorax response target number 3 6.8 m/s rigid wall Heidelberg sled - load plate force-time history.

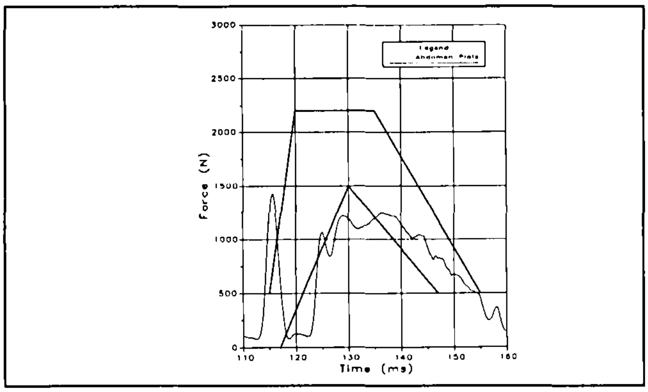

Figure D7. Abdominal response target number 2
6.8 m/s rigid wall WSU sled - load plate force-time history.

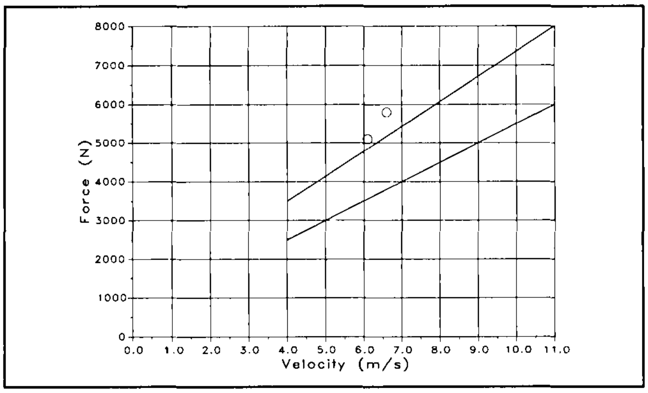

Figure D8. Pelvis response target number 1
6 - 10 m/s pendulum impact - pendulum vs. velocity.

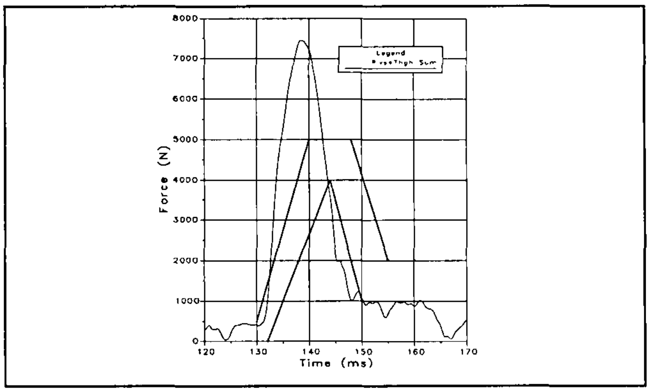

Figure D9. Pelvis response target number 4
6.8 rigid wall WSU sled - load plate force-time history.

AN INVESTIGATION OF SEAT DESIGN PARAMETERS INFLUENCING NECK LOADS IN LOW SPEED VEHICLE REAR-IMPACTS

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ABSTRACT

The application of finite element methods to the analysis of occupant neck responses in rear-end vehicle crashes is presented. A finite element (FE) model of a 50th percentile Hybrid III dummy, which had been previously used for simulating frontal impact, was appropriately modified to handle rear-impact cases. The crux of these modifications was the development of a deformable FE model of the Hybrid III neck. This new neck model was correlated using data from the Amended Part 572 Head-Neck Pendulum compliance test, and finally incorporated into the Hybrid III dummy model to permit better analysis of the head-neck region. Responses of the so modified full dummy model were correlated with experimental sled test data.

The FE Hybrid III rear-impact model was used within the PAM_CRASH explicit dynamic finite element code to conduct a parametric study of seat properties on the head-neck responses. Recommendations are presented for mechanical and geometrical seat properties to reduce head and neck loads in rear-impact.

INTRODUCTION

Neck injuries frequently occur in motor vehicle accidents, in particular 'whiplash' injuries resulting from rear-end collisions. In order to study the effect of seat and head restraint design on the neck loads, a numerical simulation of a vehicle occupant in rear-impact was undertaken.

While extensive work has been conducted using finite element analysis to model occupant kinematics in many crash situations, the number of simulations of dummies and their responses in rear-impact cases have however been limited.

The aim of this study was to create and verify an FE model of the Hybrid III neck which could be used to predict possible injury risks to the neck during a rear-impact. Hence, this project was defined by two main objectives:

1. Create a deformable FE model of the Hybrid III neck which will yield improved head-neck response data.

2. Utilise the deformable FE neck model with the Hybrid III dummy model to investigate the influence of seat properties on head-neck responses in rear-impact.

Many FE dummy models are available in the various FE codes. Most of these are used for frontal impact analyses and are modelled by very similar methods consisting of rigid body linkages connected by user defined joint resistance characteristics. For this study an existing FE dummy model, seated and belt restrained for frontal-impact simulation, was utilised for the rear-impact analyses. Because the model was specifically designed for frontal-impact simulations, modifications were required for it to be applicable for the rear-impact case. This involved creating and verifying the response of a deformable FE Hybrid III neck model to replace the rigid neck model on the unmodified dummy. A deformable neck model was necessary for the rear-impact simulations to improve the dynamic response characteristics of this region. The unmodified Hybrid III dummy model utilised a neck representation which was rigid with a pin joint at each end. Such a model produced reasonable dummy head kinematic output in frontal impact, but would be insufficient in rear-impact analyses when head to head-restraint contact was involved.

A deformable FE model of the Hybrid III neck was developed and validated using the Amended Part 572 Head-Neck Pendulum compliance test (herein referred to as the Neck Calibration Test). This deformable Hybrid III neck not only improved kinematic response but allowed internal stresses within the structure to be analysed if

required and provided neck force/moment data. The deformable neck was grafted onto the full dummy model whereupon rear-impact simulations were carried out and correlated with experimental rear-impact sled test data.

Simulations of rear-impact with different seating conditions allowed the study of various seating parameters and its influence on the sensitivity of neck responses. Rear-impact simulations were carried out with variations being made to selected seat configurations and mechanical properties.

DEVELOPMENT AND VERIFICATION OF THE DEFORMABLE HYBRID III NECK MODEL

The FE Hybrid III neck was modelled using solid elements to represent the butyl rubber and aluminium disks of which the Hybrid III neck structure comprises. The Hybrid III neck structure and the FE model are illustrated in figures 1 and 2 respectively.

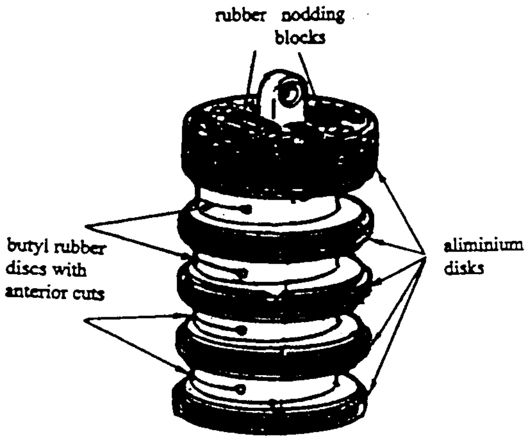

Figure 1. Structure of the Hybrid III neck.

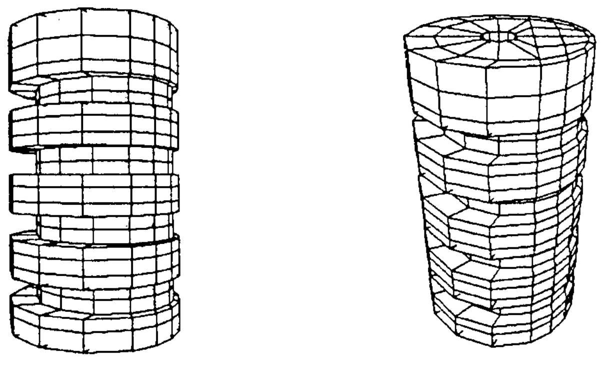

Figure 2. Deformable finite element model of the Hybrid III neck.

To simulate the neck calibration test, this new neck model was attached to a head-form model and a pendulum model. The calibration involves a head-neck assembly mounted on the end of a pendulum which is loaded by a controlled impact. The pendulum is raised to a specified drop height and released. The impact surface of the pendulum strikes a cluster of honeycomb cells which determines the impact pulse shape. This impact pulse produces head and neck rotations, neck forces and neck moments which are used to verify whether the neck's response characteristics are within the specified guidelines. Data acquired from each calibration test include the pendulum impact velocity, the pulse generated at the pendulum impactor, head/neck rotations, and the neck forces and moments. The Hybrid III neck calibration test case was chosen as the validation guideline as it provided input and output data which could be used for direct comparison with the computer model. Simulations of the neck calibration test were used to verify the neck model responses. Figure 3 shows the test setup specification for an extension neck calibration test (taken from the calibration manual) and figure 4, the FE simulation.

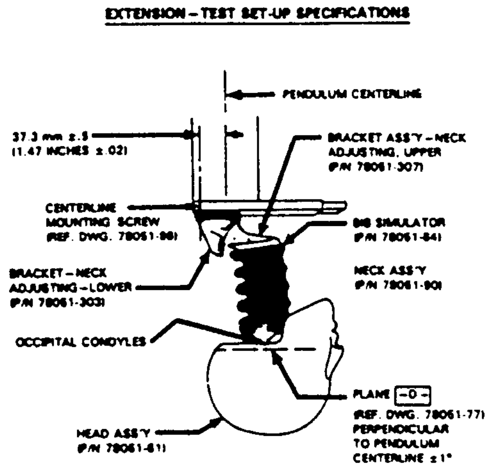

Figure 3. Hybrid III neck calibration test setup.

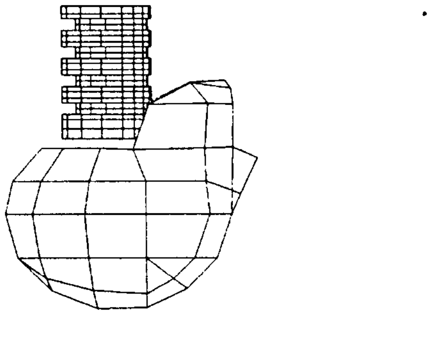

Figure 4. FE model of neck calibration test.

A flexion-torsion joint was used to model the occipital condyle joint (between the head and the neck) and the Blatz-Ko rubber material model representation for solids was used to represent the rubber. The aluminium disks, pendulum, and the head were given rigid body representations as their deformations were insignificant compared to the butyl rubber elements.

Neck Calibration Test Cases

Six calibration test cases, three in extension and three in flexion, each utilising pendulum impacts of different severity, were simulated using the FE Hybrid III neck calibration model. In each calibration mode of extension and flexion, a standard calibration test as well as two calibrations of less severe impacts were carried out. By conducting multiple experiments under varying severity, it was anticipated that the data would allow verification of the FE neck model over a broader loading range rather than just the standard flexion and extension test case. A consequence of limited correlation is that it is not known whether the model will perform adequately in less severe loading conditions.

Several condyle joint stiffness values from published data were tested with the best results obtained by utilising values used by Yang et al.. In the case of the Hybrid III neck rubber representation, a method of reverse engineering similar to that used by Khalil et al. was applied in which the rubber modulus was varied after each calibration simulation until a reasonable match between experimental and simulation results were acquired. This method was necessary as the rubber material representation was inadequate.

An illustration of an extension calibration simulation is shown in figure 5. In each simulation case, the material model of the Hybrid III neck rubber was altered until the head-neck angular deflections of the FE simulation achieved a reasonable match with experimental data. The rubber modulus value which achieved the match was be referred to as the Nominal Neck Modulus (NNM). Correlation between measured and simulated neck response time-histories for extension and flexion calibrations are presented in figures 6 to 8 and figures 9 to 11 respectively.

From the neck calibration simulations it was found that under less severe loading conditions, the neck rubber material model behaviour was less stiff. This suggested that the NNM of the rubber material is greater in high severity loading conditions and lower where these conditions were less severe. A reason for these variations were the wide ranging strain-rate dependent, high strain, and hysteresis properties of rubber which the FE material model did not adequately account for. For these reasons, validation at the single standard test specification does not necessarily mean the model will be valid under other loading severalties.

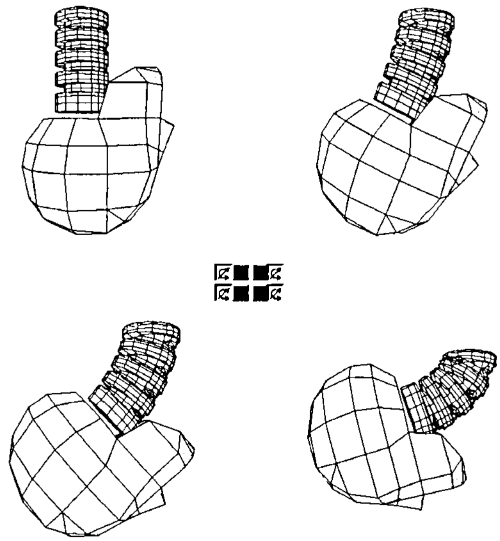

Figure 5. Animation of an extension calibration test.

In order to match the time-histories under differing loading conditions it was necessary to vary the NNM. The NNM was varied significantly at different severities of loading. In extension, the NNM was varied from 14.75 MPa to 10.75 MPa at pendulum impact velocities of 6.09m/s to 3.26m/s to achieve satisfactory neck response data. Similarly, in the flexion calibration simulations, the NNM was varied from about 15MPa to 7.5 MPa at impact velocities of 7.12m/s to 3.08m/s respectively.

The requirement for much higher NNM values for the more severe calibration simulations illustrated that the stiffness of the neck increased with higher strain-rates. This pattern was consistent in both extension and flexion calibrations. Although NNM values were varied by up to 100% for the different severity neck calibration simulations, only a small variation was required at the lower impact velocities. In other words, at lower impact velocities (lower strain rates), the neck rubber material response was becoming more constant. From this, it was assumed that the NNM was more stable during low-speed impact simulations and as a result would provide a more reliable foundation for the proposed low-speed rear-impact simulations that were being carried out.

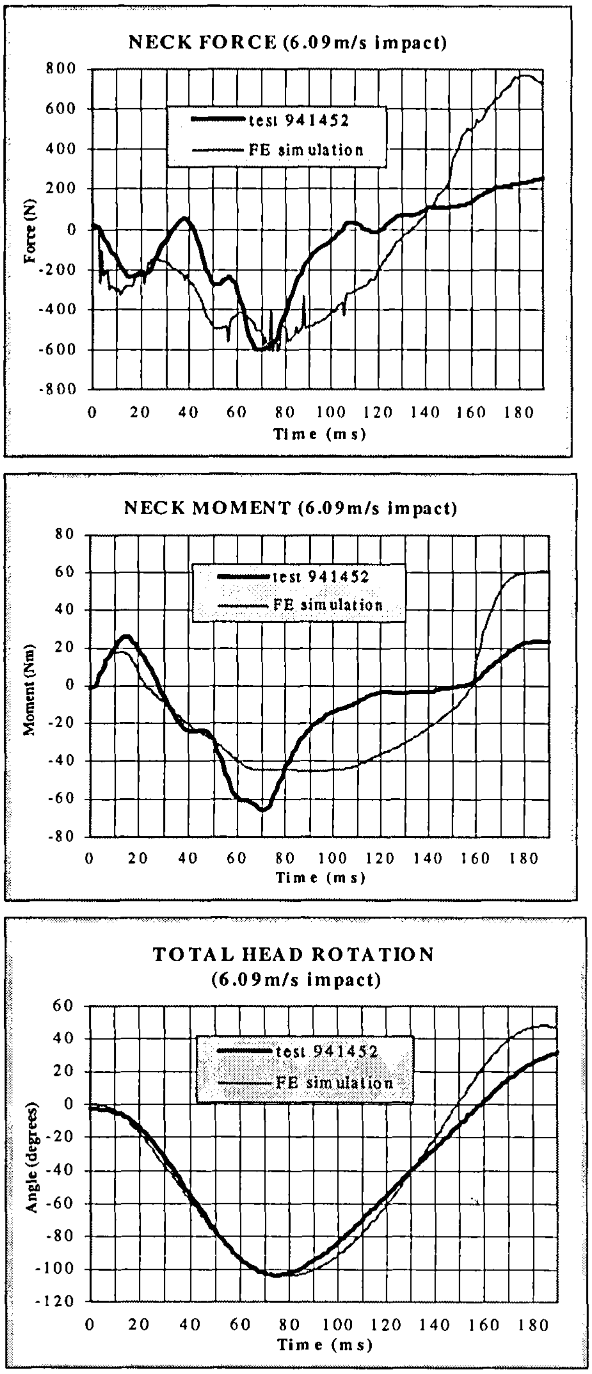

Figure 6. Correlation graphs of simulation 1.
Standard Extension Calibration (high severity impact)
Pendulum Impact Velocity = 6.09 m/s
Nominal Neck Modulus = 14.75 MPa

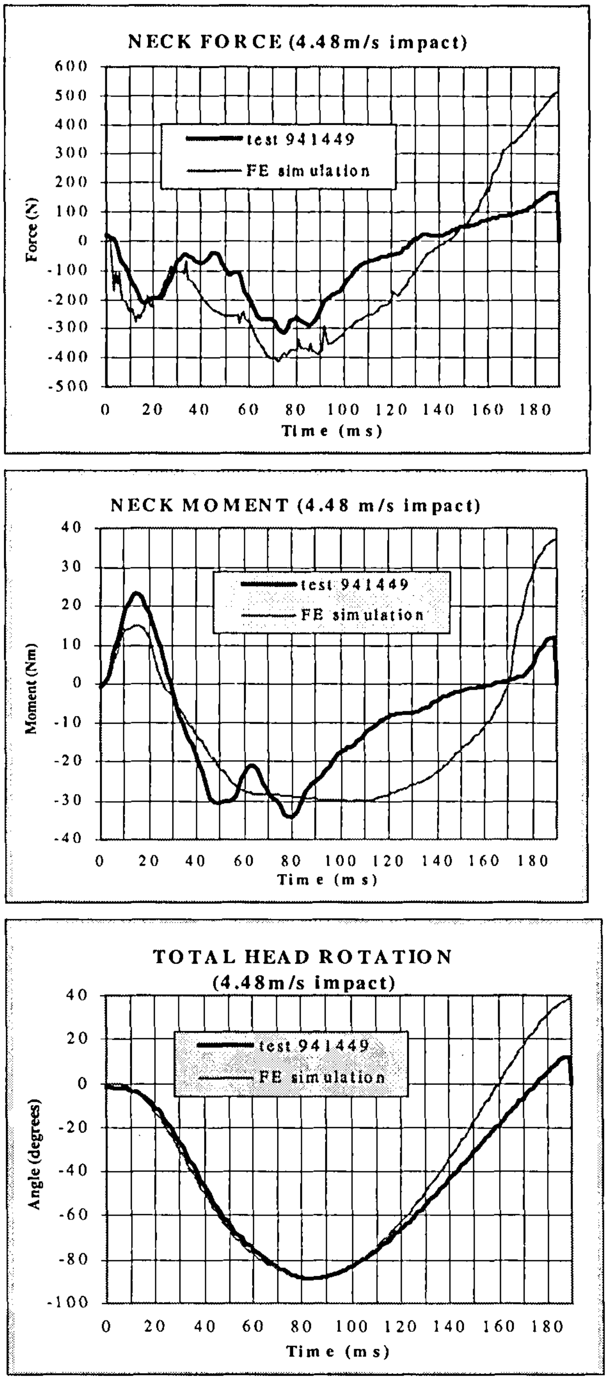

Figure 7. Correlation graphs of simulation 2.
Extension Calibration (medium severity impact)
Pendulum Impact Velocity = 4.48 m/s
Nominal Neck Modulus = 11.25 MPa

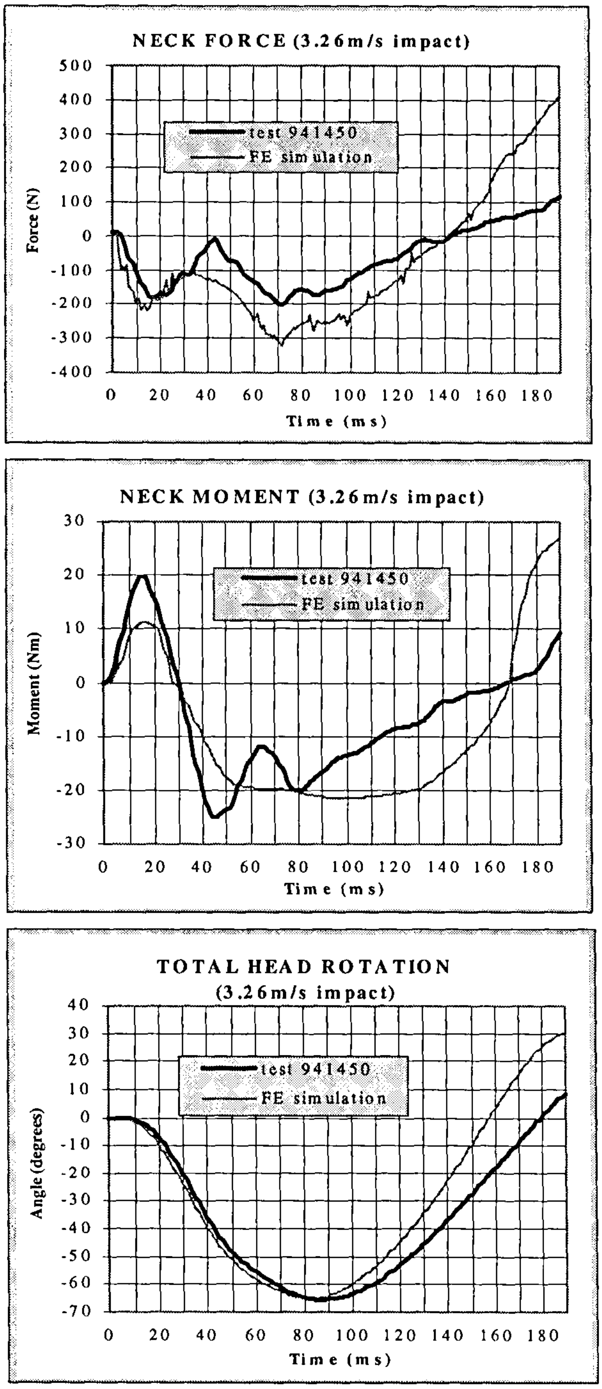

Figure 8. Correlation graphs of simulation 3.

Extension Calibration (low severity impact)

Pendulum Impact Velocity = 3.26 m/s

Nominal Neck Modulus = 10.75 MPa

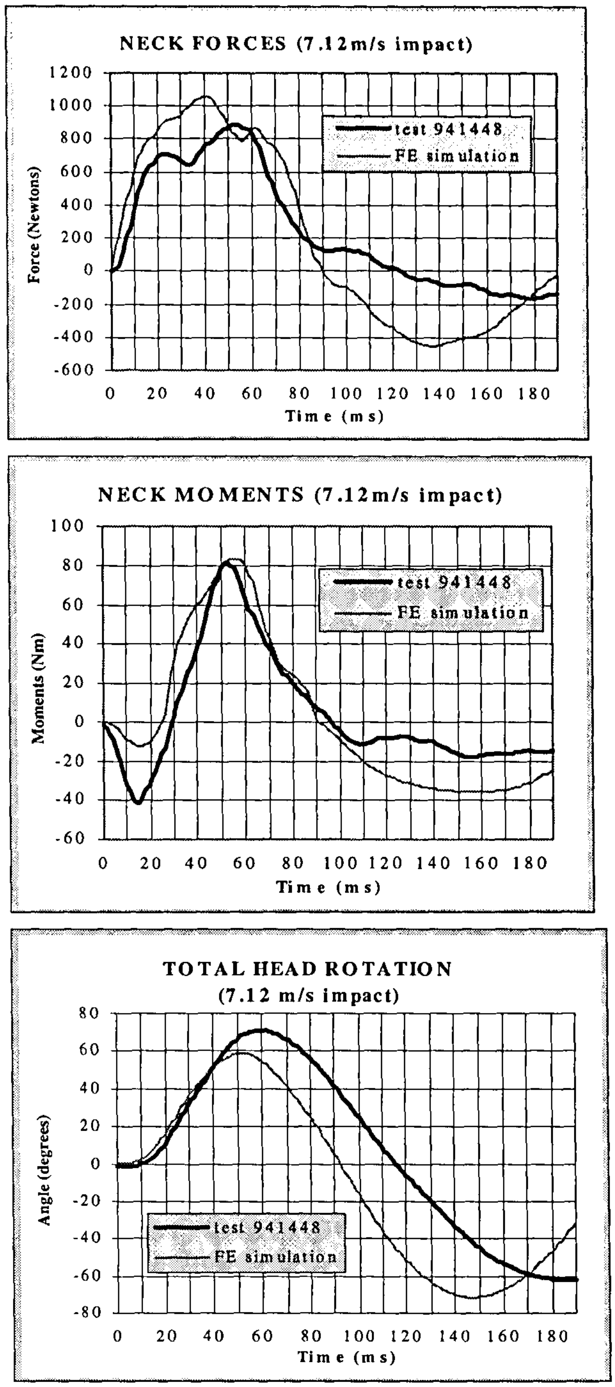

Figure 9. Correlation graphs of simulation 4.

Standard Flexion Calibration (high severity impact)

Pendulum Impact Velocity = 7.12 m/s

Nominal Neck Modulus = 16.5 MPa

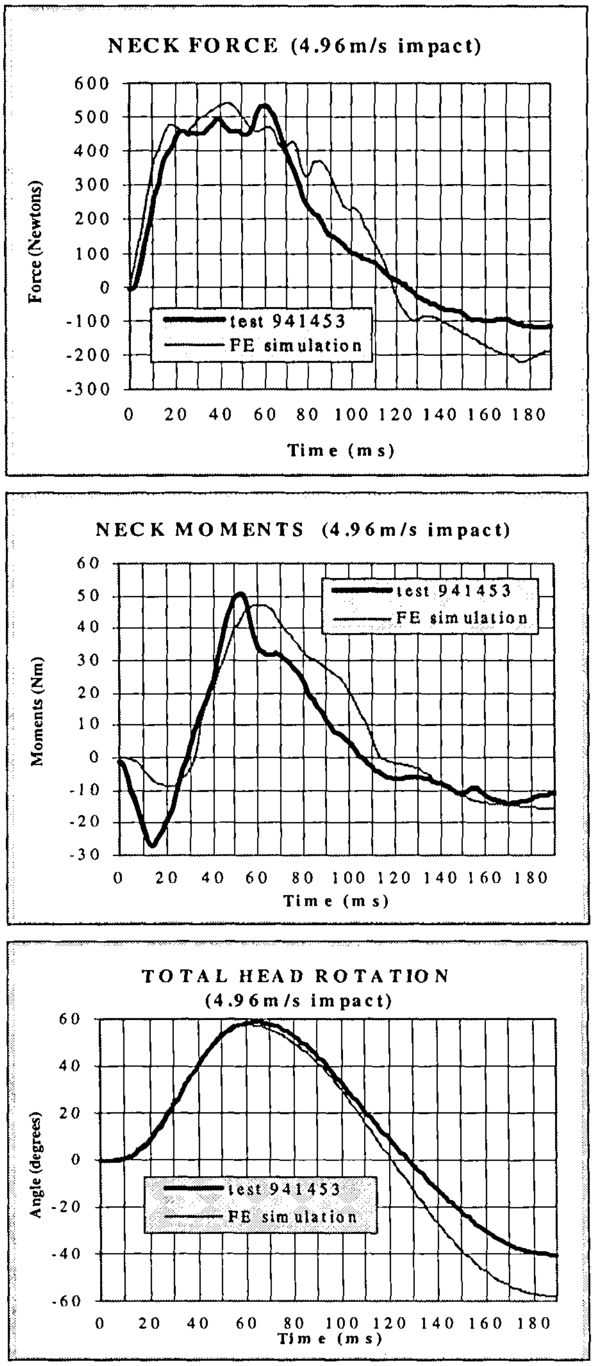

Figure 10. Correlation graphs of simulation 5.

Flexion Calibration (medium severity impact)

Pendulum Impact Velocity = 4.96 m/s

Nominal Neck Modulus = 8.5 MPa

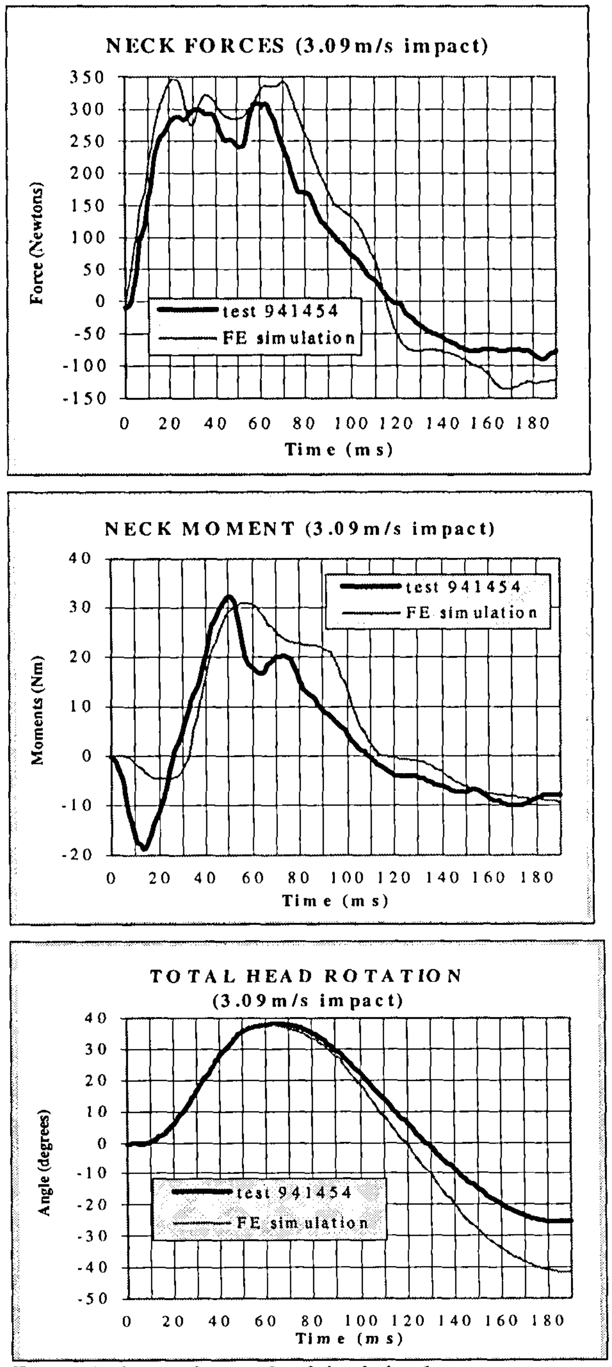

Figure 11. Correlation graphs of simulation 6.

Flexion Calibration (low severity impact)

Pendulum Impact Velocity = 3.08 m/s

Nominal Neck Modulus = 7.5 MPa

It was necessary to choose an NNM value for this Hybrid III neck model to best represent the neck rubber response according to the impact severity of a simulation. For the rear-impact simulations, an NNM value of 10.75MPa was used. This best represented the rubber material identified with the proposed acceleration pulse of the rear-impact simulation.

In general, head rotations, neck rotations and neck forces correlated very well with experimental results in both flexion and extension. Problems in matching the extension neck force and the moment responses were most likely due to insufficient definition of the occipital condyle joint resistance characteristics in extension and the material model response. Even though at times the peak extension neck forces and moments varied significantly in comparison to the experimental output, the phases of loading were well correlated and their peak outputs decreased consistently as a result of less severe input pendulum pulses. For these reasons, it was considered reasonable to utilise this deformable Hybrid III neck model for the FE rear-impact simulations. Neck forces and moments could be utilised for comparative assessment of neck loads while the good head and neck angular deflection responses provided improved kinematics for the dummy to seat interactions.

CREATION OF SEATED OCCUPANT MODEL FOR REAR-IMPACT SIMULATION

The creation of a seated occupant model for rear-impact and the correlation of its responses with experimental rear-impact data were required before parametric analyses could be applied to the model.

A FE model of a frontal-impact sled test created for the PAM-CRASH code was used for the rear-impact simulations. The FE Hybrid III dummy dataset for this model utilised rigid body representations. The FE frontal-impact simulation consisted of a 50th percentile Hybrid III male dummy model which was seated and restrained by a seatbelt in the standard passenger position. Its head, torso, and pelvis responses were validated by ESI (Engineering Systems International) against a series of frontal impact sled tests, conducted by the Ford Motor Company. Although validated for frontal-impact, the model was unsatisfactory for the rear-impact simulation requirements of this project. Modifications to this rigid body dummy model to incorporate a deformable FE neck component, a more realistic seat model, and application of a rear-impact acceleration load were required.

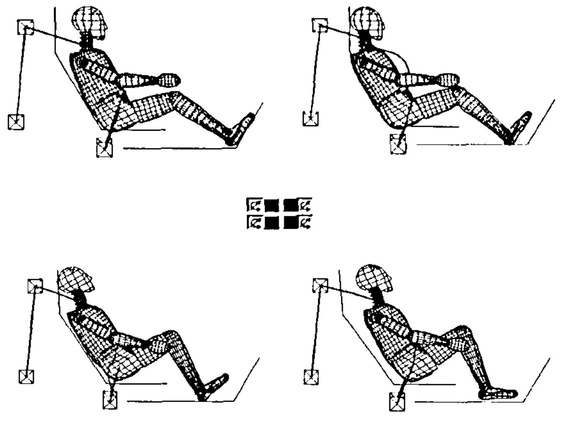

Figure 12. Rear-impact simulation incorporating the deformable finite element Hybrid III neck model.

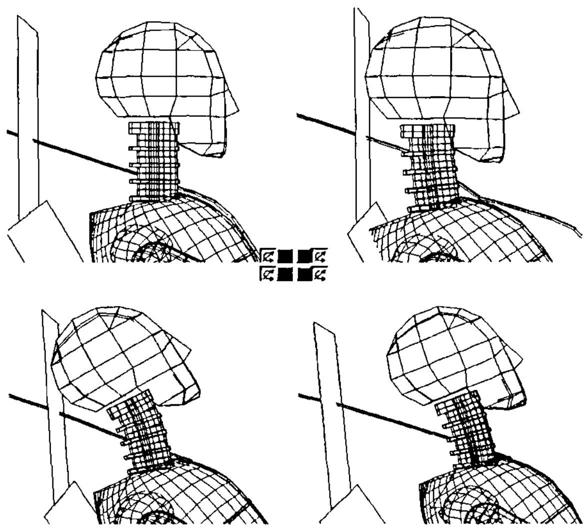

Figure 13. Animation of neck region during rear-impact loading.

Limitations Of Rigid Body Representations

The Hybrid III dummy model was modelled mainly by rigid bodies which were connected by joints with user defined mechanical characteristics. This representation is the most common technique used to model dummies in crash simulations as it is the least CPU intensive method. Dummy components are in most cases satisfactorily represented by rigid bodies as their deformations are negligible compared to the large joint motion. This method of modelling usually provides relatively good representation of full body dynamics and dummy component kinematics in impact simulations. The main disadvantage of using this method of modelling is that limited analysis can be performed on the rigid components of the model.

Even with acceptable kinematic data for the upper-torso and head accelerations, the mechanics of highly deformable regions such as the head-neck-torso interfaces are quite unrealistic. The neck representation used in the Hybrid III dummy model is that of a rigid cylindrical structure with movement between the head and the upper-torso governed by flexion-torsion joints at each end. This does not represent the true mechanics of the dummy head movement relative to the upper-torso. The Hybrid III head/neck motions are controlled by two mechanisms: the deformable characteristics of the neck structure and a pin joint at the occipital condyle joint. A fixed connection exists between the upper-torso and the neck base. Therefore the Hybrid III neck component required more detailed modelling than the rigid body representation to adequately simulate its highly deformable behaviour. To overcome the deficiencies of rigid body modelling, a method was adopted where the region of interest was modelled in more detail. Hence, the deformable finite element model of the Hybrid III neck was incorporated into the Hybrid III dummy model while maintaining the simplified rigid body representation for the rest of the dummy.

The previous flexion-torsion joint between the upper-torso and the base of the neck was replaced by a rigid connection. In addition, the moment-deflection characteristics of the head-neck joint was modified to simulate the Hybrid III occipital condyle joint resistance. As a result of the modifications made to the neck region, this geometrically and mechanically representative FE model of the Hybrid III neck was anticipated to provide better analysis data for the torso-neck-head system. Although the other dummy components consisted mainly of rigid body representations, it still provided useful end conditions for the deformable neck. The rigid body dummy model provided response to conditions such as dummy to seat and head to headrest interactions, and hence transferred these loads to the neck, when subjected to rear-impact loads.

By utilising a deformable FE neck model, previously unavailable data such as internal stresses or any other parameter dependent on deformation could be obtained. It could also be assumed that because the deformable FE neck modelled the physical system, a better head trajectory simulation was achieved providing more realistic torso/neck/head to seatback/headrest interactions. As a result, analysis variables like head-neck rotations, neck forces, neck moments, and head accelerations were considered more realistic that the old rigid neck model.

The Seat Model

Unlike frontal impact analysis, occupant to seat interaction is very important in rear-impact simulation. The seat and the headrest are the main restraining mechanisms in rear-end collisions. Dynamic responses of an occupant in rear-end collisions are governed principally by the vehicle seat and its mechanical characteristics. The way in which the seatback retards the rearward accelerating occupant greatly influences the conditions and magnitude of loading experienced by the occupant.

The seat model used in these simulations was a simplistic representation of a real seat, but it incorporated the main variables which defined the mechanical properties of a vehicle seat. It was modelled by three shell elements each of which represented the headrest, seatback, and seatcusion. Adjacent shell elements were connected by pin joints with only one rotational degree of freedom. By varying parameters, eg. the magnitude of seatback stiffness, their influence on neck loads could then be analysed. The simplicity of the model allowed such mechanical and physical parameter values to be easily changed with minimal influence on other variables.

Comparison Of FE Simulation Output And Experimental Sled Test Data

The responses of the rear-impact model was compared to experimental data to check the model's validity under the conditions tested. Reasonable outputs were obtained for the rear-impact model. Head-neck-torso responses compared very well with experimental tests although the torso-pelvis was much stiffer when compared to experimental results. The region of particular interest, the head-neck-torso system was satisfactorily simulated providing good acceleration responses. ie. the magnitude and phase difference of chest and head maxima were in relative agreement. The correlation between simulation and experiment is illustrated in the graphs of figure 14 and 15.

Although some discrepancies existed in the torso-pelvis interface, results obtained from this FE model remain useful, as it is the comparative behaviour of chosen neck loading variables which are of interest. Therefore, estimation of seat design variables for better rear-impact restraint was still possible, as it was the behaviour of the dummy rather than the actual response values which were of interest. A sensitivity analysis of head and neck responses to chosen seat geometrical and mechanical characteristics was carried out.

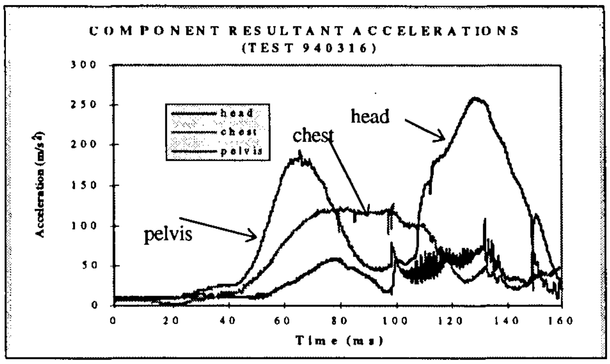

Figure 14. Resultant accelerations of experimental sled test.

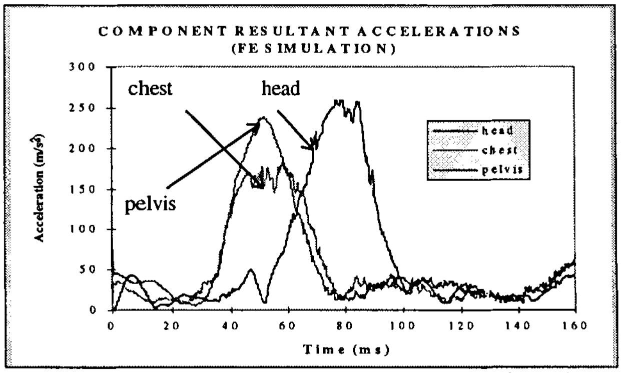

Figure 15. Resultant accelerations of FE rear-impact simulation.

PARAMETRIC STUDY

The objective of the parametric study was to determine which parameters in seat design effected neck loads in rear-impacts and as a consequence, influence the possibility of neck injuries. While many physical and mechanical parameters define the seat behaviour, they can all be placed into two basic categories, namely either the seat structural strength (or its resistance to deformation), or the seat geometry (or positioning of particular seating components). For the purpose of this parametric study, five possibly influential seat parameters were chosen. These parameters are outline in the proceeding section.

A univariate parametric study was necessary so that a single variable's role in rear-impact loading could be tested with minimal influence from the other input parameters. It was carried out by keeping all parameters unchanged in the baseline model, with the exception of the seating parameter value under analysis. A sensitivity analysis of resulting neck and head responses was then undertaken. For each of the seating parameters tested, approximately ten FE simulations of varying parameter values were executed. Parameter values were restricted to a realistic range to permit nonlinear aspects of the head-neck response to be studied.

Input Parameters

The input parameters selected for the analysis were:
1. initial seatback angle;
2. headrest stiffness;
3. head to headrest clearance;
4. seatback joint stiffness; and
5. the seatback upholstery stiffness.

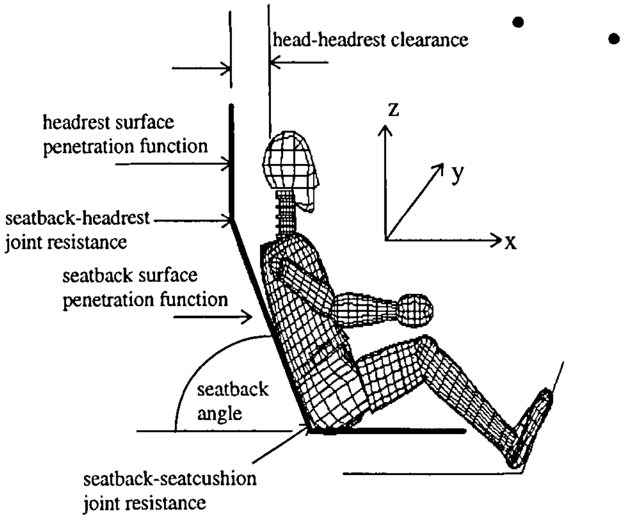

Figure 16. Locations of Input Parameters

These were the independent variables. Figure 16 illustrates where these parameters act. Each one of these parameters represented major characteristics which define the rear-impact restraint performance of vehicle seats.

Output Variables

Head and neck responses were used to analyse the effectiveness of each of the seating parameters. Selected output variables (dependent variables) were: neck rotation, head rotation, total head rotation, neck force, neck moment and the head resultant acceleration. The output variables were defined as follows.

1. Neck Rotation - angle of the neck relative to the upper torso
2. Head Rotation - angle of head cg relative to the neck.
3. Total Rotation - angle of head cg relative to the upper torso.
4. Neck Force - shear in local x-direction at the occipital condyle
5. Neck Moment - y-moment at the occipital condyle

6. Resultant Head Acceleration - resultant accel. of the head cg

These were the variables which were also chosen to verify the FE Hybrid III neck model. The sensitivity of these output variables to changes in a seat parameter were used as a guide to the amount of influence of each input parameter.

Recommendation of Seat Design Parameters For Reducing Neck Loads

A sensitivity analysis of the above described variables was carried out. The recommended seat and seating parameter values for reducing neck loads should only serve as a guide as to what are the desirable seat properties for improving rear-impact protection. What has been achieved in this parametric analysis is that risk factors in seat design for rear-impact protection have been identified.

Seatback joint stiffness and upholstery stiffness produced minimal changes in the head and neck responses in this numerical analysis. The seatback strength has been considered very important in rear-end impacts by many researchers. Experimental tests have shown that rebound from seatbacks and the effective energy absorbing characteristics of failing seatbacks influence very much the neck loads. It would therefore be desirable to conduct further simulations of this model over a wider range of seatback stiffnesses to verify that the low sensitivities calculated are consistent.

The crucial seat design parameters for reducing head-neck loads during rear-impacts were the initial seatback angle, headrest stiffness and the head to headrest clearance. The head-neck extension responses were found to be most sensitive to the head to headrest clearance distance. This seat parameter acted to restrain the head in the rearward direction greatly defining the extension responses of the head and neck.

On the other hand, flexion responses of the head and the neck were most influenced by the initial seatback angle. Head and neck responses as a result of these two geometric input parameters suggest that great improvement can be achieved through geometric design of the seat alone.

The headrest stiffness was the only seat mechanical property which produced significant influence to output head-neck responses. It was most effective in controlling the resultant head acceleration response and also effected considerably the peak extension responses.

From these preliminary simulations of a 70kg, 50th percentile, male, anthropomorphic test dummy (Hybrid III), three seat parameters were identified as having a significant influence on neck loads. They were the initial seatback angle, headrest stiffness, and the head to headrest clearance. The following recommendations for seat parametric values are suggested for reducing head-neck output responses in rear-impact.

Initial Seatback angle ----- (70 to 75 degrees)
Headrest Stiffness --------- (10 to 20 kN/m)
Head to Headrest Clearance -- (0.05m or less)

A more comprehensive set of simulations looking at other combinations of these seating parameters as well as other seating parameters would be desirable.

The findings suggest that significant improvements for rear-impact protection can be achieved by increasing seat geometric variability. Seatback angle variability exist in all vehicle seats. Vertical variability of headrests also exist in most vehicle seats but horizontal variability has not yet been incorporated into head restraints. From the simulations, because seatback angle and headrest clearance were the major factors influencing neck responses, a lot could be done to improve rear-impact protection through geometric modifications. Such modifications to seat design to improve rear-impact protection may include a horizontally adjustable headrest. However, the effectiveness of such modifications would only be beneficial if used in the correct manner. If the variability of such parameters are incorrectly applied, the result of having increased variability can in fact produce worse neck loads. The study by Nygren et al. found that head supports were usually adjusted to the lowest position, and as a result fixed head supports were more effective in reducing neck injuries. It would therefore be necessary to educate vehicle occupants on the correct use of the head restraint and seatback incline adjustment. Incorporating such variability to a seating system would only be effective if the seat was correctly adjusted to the optimum position for individual occupants.

An alternative to increasing the variability of seat geometric parameters would be to engineer a seat with minimal variability encompassing an optimum seat configuration for reducing neck loads. The main disadvantage of such a seating system is that the size and posture of every occupant is different, making it very difficult to design for the broad range.

CONCLUSION

A study was undertaken using finite element methods to examine the influence of seatback and head restraint design parameters on neck loads in rear-end collisions. To achieve these objectives, a deformable finite element model of the Hybrid III neck was developed and correlated with calibration test data. This new neck model was then incorporated into an existing occupant model, seated and belt-restrained for rear-impact simulations. The rear-impact simulations were reasonably correlated with experimental sled test data. The rear-impact model was then utilised to conduct parametric studies of seating parameters possibly influential to neck loads.

The Hybrid III neck was not an ideal representation of a neck in low-speed rear-impact as it was very stiff, but it was sufficient for providing a comparative assessment of neck responses. Correlation of the deformable finite element Hybrid III neck was obtained for low to high severity impact conditions.

The rear-impact model allowed the study of dummy interactions with the seat structure. A sensitivity analysis, used to predict how certain seatback/headrest parameters should be modified to reduce possible injury causing head/neck loads and hence reduce the risk of whiplash neck injury, yielded the following conclusions.

1. The head and neck responses are very sensitive to seatback and headrest positioning.
2. The neck flexion responses and positive neck force and moment are strongly influenced by the initial seatback angle.
3. The extension responses and negative neck force and moment are strongly influenced by the head to headrest clearance.
4. The resultant head acceleration is strongly influenced by headrest stiffness.
5. The head-neck responses are influenced very little by the seatback joint stiffness and the seatback upholstery stiffness.

To reduce neck loads, recommended values for the critical seat parameters were:

Initial seatback angle - 70 to 75 degrees from the horizontal
Headrest stiffness - 10 to 20 kN/m
Head to headrest clearance - 0.05m or less

The sensitivities of neck responses to the seatback stiffness will require further analysis. This seat parameter has been widely reported as also having an influence on whiplash injuries but yielded very low neck response sensitivities in the simulations conducted.

Generally, further development of the FE rear-impact model is required. The response of the FE Hybrid III dummy model in rear-impact and dummy to seat interaction needs to be improved to achieve more accurate simulation output. At present, the pelvis-upper torso is very stiff and does not adequately match Hybrid III responses in rear-impact loading. Also, with the introduction of two large-strain rubber material models into the PAM-CRASH analysis code (Mooney-Rivlin and Hart-Smith material models), the Hybrid III neck model response can be improved. Such large-strain material models may end the need to choose a Nominal Neck Modulus for different severity loadings.

ACKNOWLEDGMENTS

Many thanks to the RTA's Vehicle and Equipment Safety Branch for providing the computing facilities for this study.

REFERENCES

T. B. Khalil and T. C. Lin, *Simulation Of Hybrid III Dummy Response To Impact By Non-Linear Finite Analysis*, 38th Stapp Car Crash Conference Proceedings, 1994

Ake Nygren, Han Gustafsson, and Claes Tingvall, *Effects of Different Types of Headrests in Rear-End Collisions*, 12th International Experimental Safety Vehicles Conference, 1989

King H. Yang and Jialiang Le, *Finite Element Modelling Of The Hybrid III Head-Neck Complex*, The 36th Stapp Car Crash Conference Proceedings, 1993

DEVELOPMENT OF AN INSTRUMENTED BIOFIDELIC NECK FOR THE NHTSA ADVANCED FRONTAL TEST DUMMY

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ABSTRACT

This paper sets forth the needs of an advanced instrumented neck for the NHTSA advanced frontal dummy, which is intended to duplicate the response of a human neck during dynamic impact in the fore and aft and lateral directions. Previous efforts to develop a suitable biofidelic mechanical neck for human surrogates are briefly discussed in order to outline their limitations in the dynamic impact environment. Human response of the head/neck system under various dynamic impact conditions, to which the new neck simulation system was designed, are presented and the goals of the development effort outlined.

The evolution of the new biofidelic neck design is presented and the final neck design that has been incorporated into the advanced ATD is discussed in detail. A series of evaluation tests of the neck response under various dynamic impact loadings were conducted to evaluate the success of the dummy head/neck response in duplicating the responses obtained from the volunteer tests. The results of these evaluation test are presented and discussed.

INTRODUCTION

Since the development of the first dummies for evaluating the effectiveness of various crash safety devices in automobiles, representation of the mass and stiffness characteristics of the human neck to simulate the dynamic response of the head/neck system to impact loadings has been a challenge. Many different neck designs have been undertaken with various degrees of success but none have been considered to meet the desired goals. Mertz, Patrick, and Chou [1,2,3] developed criteria that correlated the moments around the occipital condyle pin with angle that has become the standard acceptance criteria for necks to be used in crash dummies. The criterion specifies a corridor within which the resistive torque at the occipital condyle for a given head angle should fall for a specified impact pulse. The boundaries, developed by Mertz, et al, were derived from data obtained during tests of a volunteer for a series of dynamic loadings in the fore, aft and lateral directions. The neck used in the current standard crash dummy, Hybrid III, meets these corridors.

The Naval Biodynamics Laboratory, NBDL, conducted a series of tests with a number of volunteers in which the dynamic response of the human head/neck system was measured at various g levels in the fore and aft as well as in the lateral and oblique directions [4-9]. Wismans and Spenny [10-15] performed detailed analyses of the data. On the basis of this data a new set of biodynamic kinematic response requirements for the human head/neck system has been developed. The characteristics of the restraint system have raised some questions regarding the acceleration and rotation of T1, and these have been studied and resolved by analyses conducted by Wismans [16]. Additional analyses have been conducted to resolve the concerns regarding the effect on the response due to the mass of the instrumentation held in the mouth of the volunteers during the tests [24]. A significant result obtained during these tests [17], was the lag of the head rotation in time with respect to the rotation of the neck. A series of controlled sled tests conducted by NHTSA's Vehicle Research and Test Center (VRTC), indicated that the Hybrid III neck is too stiff relative to the NBDL volunteer data. In particular, it does not produce the desired head lag motion in flexion seen in the volunteers under the same loading

conditions. Proper simulation of the trajectory is necessary to represent the time and location of the head impact with the vehicle structure. While the NBDL tests did not investigate the dynamic response to the human head/neck system in the extension direction, there is some data obtained by JARI with a volunteer and reported at the 1993 IRCOBI conference [18]. It is noted that while the tests were conducted at relatively low g levels, it is realistic data which can be used as a guide in evaluating the dynamic response of dummy necks.

The new neck development that is discussed in this paper has used the NBDL and JARI volunteer data to establish the dynamic response requirements for neck design. However, the Mertz corridors have also been utilized as secondary requirements.

HUMAN DYNAMIC RESPONSE REQUIREMENTS

Figures 1 through 6 present plots of the NBDL volunteer test sled pulses and the associated head/neck dynamic response in the flexion, lateral, and extension directions [17-19]. These data are presented in the laboratory coordinate system. It is noted that the data presents mean head/neck response data and does not include the corridor boundaries. The data in Figures 7 through 9 are the JARI volunteer extension test results. It can be seen in the data presented in Figure 2 that the head rotation angle lags (in time) the rotation angle of the neck by approximately 30 ms for the 15 G flexion response to impact loads applied in the fore and aft direction. This time lag results in the head remaining roughly horizontal while the neck rotates during the initial 30 ms. It is important that the CG of the head also follows the X and Z displacements measured on the humans as a function of time if the correct kinematics of the head is to be obtained with the simulated neck. It is noted that the head angle is the relative angle between a vertical line passing through the occipital condyle and a line joining the CG of the head and the occipital condyle.

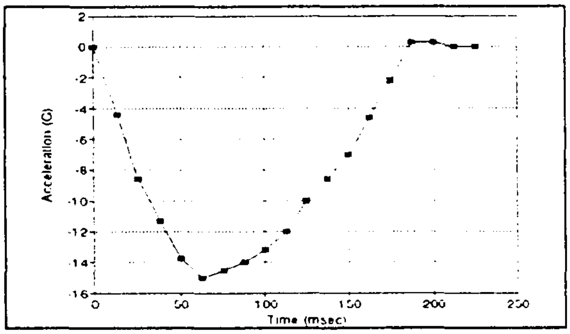

Figure 1. Sled acceleration time history for 15 G for frontal flexion test.

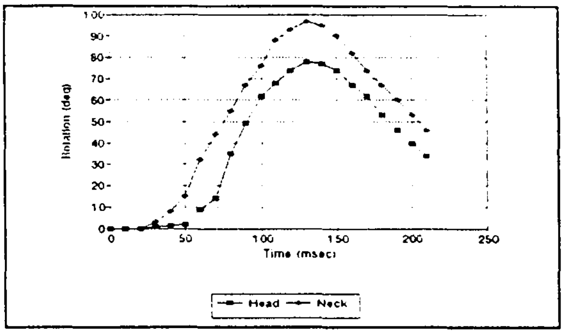

Figure 2. Head and neck rotation angle vs time NBDL tests in frontal flexion.

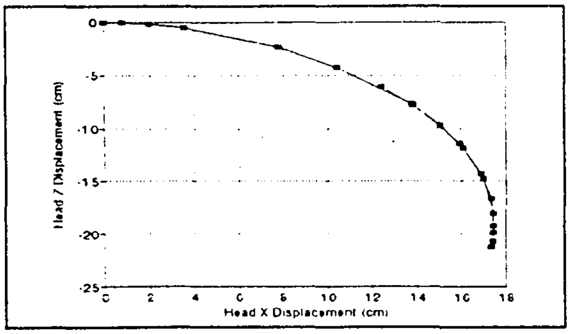

Figure 3. Head CG displacement in Z - X plane in flexion test.

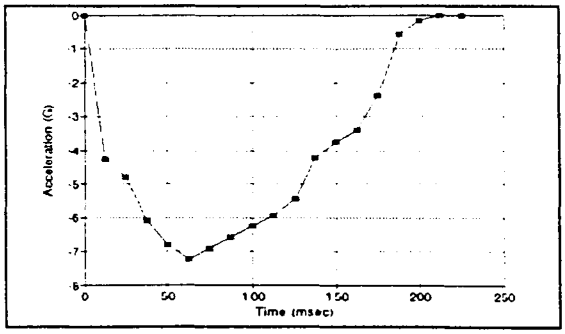

Figure 4. Sled acceleration time history for 7 G lateral flexion test.

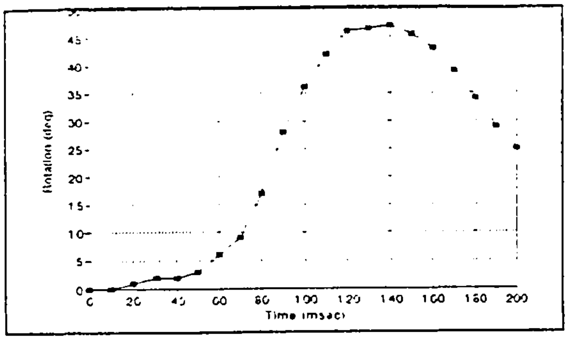

Figure 5. Head rotation angle vs time for NBDL tests in lateral flexion.

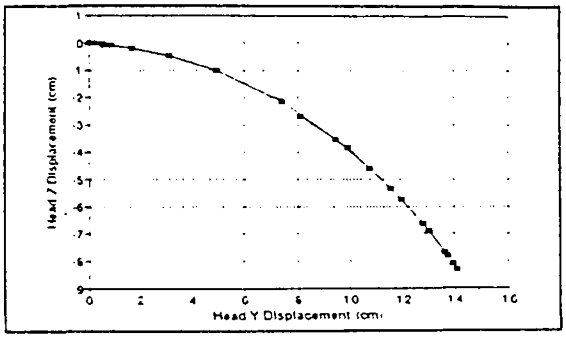

Figure 6. Head CG displacement in Y - Z plane for NBDL tests in lateral flexion.

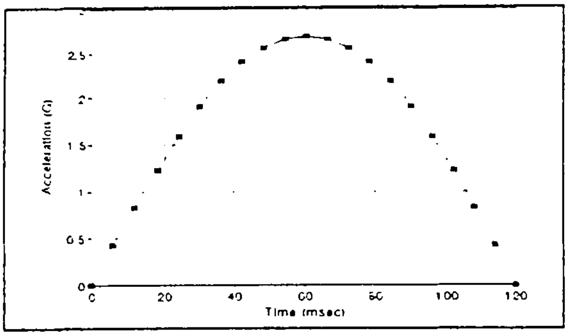

Figure 7. Sled acceleration time history for 2.7 G extension test.

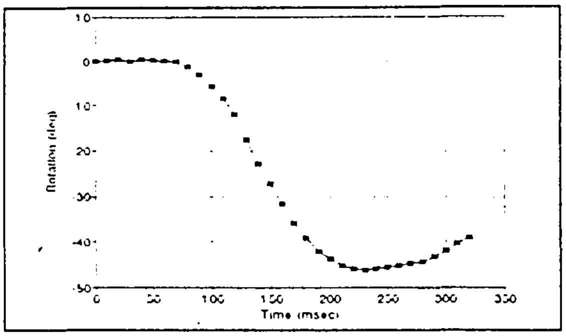

Figure 8. Head rotation angle vs time for volunteer extension test.

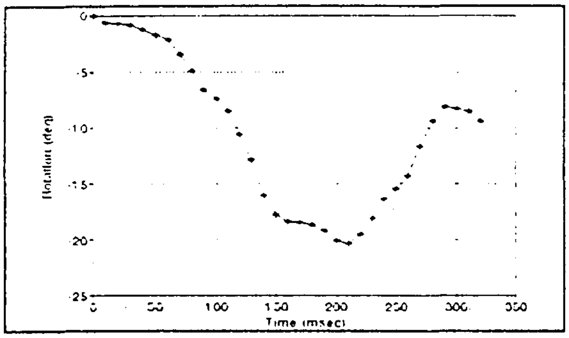

Figure 9. Neck rotation angle vs time for extension test.

PREVIOUS DEVELOPMENT EFFORTS

The National Highway and Traffic Safety Administration (NHTSA) has been investigating the requirements for and the mechanical simulation of the human neck for a number of years. In 1985 the Vehicle Research and Test Center (VRTC) of NHTSA reported on an initial effort in the development of a new concept for a Head/Neck simulator [20]. A report on the initial development and tests of a new concept of mechanically simulating the response of the human neck was presented at the Twelfth International Conference of ESV [21]. In this development effort they concluded that Hybrid III neck stiffness had to be reduced and a spring/cable exterior to the neck should be incorporated to obtain the proper excursions and lag developed by the volunteers in the NBDL tests. Following this earlier work, VRTC researchers developed several additional neck design prototypes to address expanded design goals that included achieving a biofidelic response in frontal flexion, lateral flexion,extension, and axial compression. To formalize these goals, they developed a set of performance criteria for biofidelic dummy necks [19]. Based upon these performance criteria, NHTSA contracted with EASi Engineering to develop a new design based upon finite element analysis. This neck (BNN-3) was constructed and tested at VRTC and showed promising results relative to the performance criteria, although It was not suitable for inclusion in a test dummy. In 1995, this prototype neck was delivered to GESAC,who was assigned the task of modifying the prototype to fit in the NHTSA advanced frontal dummy.

DEVELOPMENT EFFORT CONDUCTED BY GESAC

Figure 10 presents a drawing of the concept that NHTSA developed for testing and the concept that GESAC was tasked to modify for incorporation into the advanced ATD. As can be seen the NHTSA developed neck consists of five rubber pucks that are separated by aluminum disks. At the top of the neck is located a six component load cell that incorporates the condyle pin to attach the Hybrid III head. In the anterior and posterior of the neck column there are cables attached to the head and at the base of the neck to compression springs. The compression springs developed a force when the head flexed in either the flexion or extension directions and thus provided the restraint needed to develop a suitable lag with respect to the neck rotation motion. The guides incorporated in the third aluminum disk kept the cables from interacting with the neck during extreme excursions of the head as well allowing the cable to act along the arc of the neck. The lateral stiffness of the neck is completely defined by the stiffness of the rubber pucks and is not effected by the fore and aft springs. It is noted that the effective T1 location is at the first disk from the base due to the addition of the fifth puck in the neck. While the neck is longer than the human neck,this difference in the length was found to be required to properly simulate the X,Y,Z location of the head CG during impact.

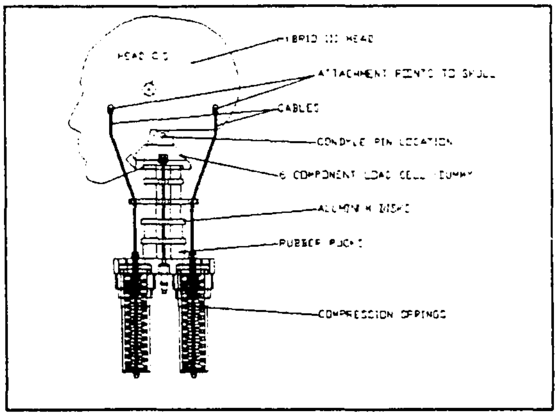

Figure 10. Side view of VRTC conceptual design of simulated neck.

Test data obtained with this neck design, while indicating the proper type of head lag with respect to the neck, did not yield the proper total response that was desired to meet the criteria set forth in Reference [19]. In addition, because of the large external spring mechanism at the base of the neck, the design of the assembly developed by NHTSA was not immediately adaptable to the new dummy.

INITIAL INVESTIGATIONS

The initial investigations conducted by GESAC were concerned with determining the physical characteristics of the neck developed by NHTSA and in formulating a suitable simulation analysis procedure for investigating the effects of various parameters on the dynamic response of the neck assembly. DYNAMAN, a lumped mass,3-D occupant simulation model, developed by GESAC, was used to conduct modelling studies. Physical characteristics of the NHTSA neck were obtained through static testing at the Armstrong Laboratories at Wright-Patterson AFB. In these tests, the neck was fixed at the bottom and flexion and lateral bending loads were applied at the top of the neck. Applied torque and bending angle were measured to characterize the response of the neck.

A lumped mass model of the NHTSA neck was developed and exercised using the impact pulse used to test the NHTSA neck. The model was validated by comparing simulation output with test results. In addition, the model's response to static loading was obtained and compared with the applied torque-bending angle data obtained from the tests conducted at Armstrong Laboratories. Simulation results compared well with the test results during the loading phase.

The validated DYNAMAN model was then exercised using the NBDL volunteer T1 pulse to conduct a parameter sensitivity study. The aim of this study was to explore the effects of variation of the following system parameters on the dynamic response of the NHTSA prototype neck:

1. Dimensions of the major and minor axes of the ellipsoidal rubber puck,their elastic and damping characteristics,and thickness of the pucks
2. Stiffness of the fore and aft springs,effect of spring pre-load, and location of the spring attachment points
3. Magnitude of frictional torques applied about the occipital condyle pin
4. The stiffness characteristics of the soft stops located on the head and neck

The results of the parametric studies can be briefly summarized as follows:

a. Elastic pucks

1. The dimensions in the lateral and the fore and aft directions were very important in establishing the relative stiffness in the flexural and lateral directions. The elliptical shape of the pucks permitted the desired stiffness to be obtained in both the lateral and the fore and aft directions.
2. Both urethane and rubber elastic materials were investigated for use in the necks. While both materials could be manufactured to obtain the desired durometer, it was found that the urethane was stiffer in compression than desired and had less hysteresis than required. The rubber material was superior as it met all the desired properties. The pucks were therefore designed using a natural rubber having a durometer of 78 shore A.
3. Since the characteristic length of the NHTSA neck had been established, it was not altered in the GESAC design and therefore the same number of pucks and thickness were used.

b. Spring characteristics

1. It was found that the front spring was not required to provide the proper motion of the head in the flexion direction and it was removed in the design of the first prototype neck. While the NHTSA neck had springs having a stiffness of 168 lb/in it was shown that a spring stiffness of 104 lb/in was adequate to provide a good simulation of flexion in the forward direction.

2. The NHTSA neck design specified that the spring should be preloaded after the head had been properly positioned. Simulations conducted by GESAC determined that the small preload specified by NHTSA had almost no effect on the dynamic response of the head and therefore provisions for spring preload were not provided in the GESAC design.

3. The location of the spring/cable restraint in the fore and aft direction relative to the condyle pin had a significant effect on the flexion response of the head. Since there was not very much room to change the location of the attachment point, a location that provided the best compromise for construction, load application, and relative head/neck rotation was picked and held constant during the various parametric investigations that followed.

c. Effect of frictional torque about the condyle pin

1. Prior to the construction of their first prototype, the NHTSA evaluated the effect of applying a friction moment of approximately 460 cm-kg about the condyle pin. The dynamic response of the head was affected significantly. Since the GESAC design does not have a spring forward of the condyle pin to balance the moment applied by the aft spring during setup, the effect of providing a friction moment about the condyle pin to help maintain the head position during setup was investigated. It was found that placing a friction moment of approximately 17 cm-kg about the condyle pin did not have a noticeable effect on the dynamic response of the head/neck system. This amount of friction moment about the condyle pin was found to be sufficient to maintain the head in a position relative to the neck during setup.

d. Effect of soft stop stiffness

1. Stops to soften the impact of the head on the neck during extreme motions were found to be required to prevent sharp impact loads at extreme deflections. In addition, mechanical stops with a soft stop feature were placed behind the lower two disks to stiffen the elastic neck in extension. On the basis of the simulation studies it was found that placing the stops between the lower two disks was the optimum location to achieve the desired stiffening effect.

DESIGN OF FIRST PROTOTYPE NECK

On the basis of the above simulation analyses, a design of a mechanical neck system was undertaken. Figure 11 presents a system drawing of the first prototype design. The head/neck system is instrumented with six component load cells mounted at the top and bottom of the neck. The top load cell is located below the occipital condyle pin. The bottom load cell is mounted on a pitch change mechanism. This mechanism was included so that the angle of the neck can be altered as required to simulate humans seated in various seated postures. Since the neck constructed for testing was only a prototype, an

injection mold was not used to mold the entire neck at one time. The natural rubber pucks were manufactured in separate molds and then the assembly was bonded together by a process developed by GESAC. Static proof tests of the flexible neck were conducted prior to the dynamic testing to insure the integrity of the neck. It was found that this construction technique proved to be successful as there was no debonding during the static or dynamic testing that was conducted on the neck system.

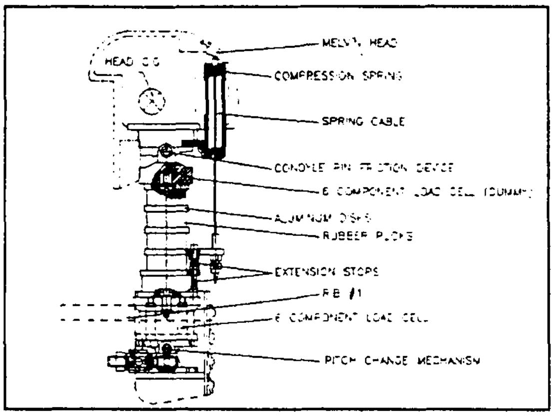

Figure 11. First prototype neck design.

DYNAMIC TESTING OF THE FIRST PROTOTYPE NECK

The dynamic testing of the first prototype neck was conducted on the mini-sled pendulum equipment developed at the Medical College of Wisconsin Neuroscience Laboratories. The instrumentation used in the tests to measure the pertinent accelerations and loads were the following:

a) A uniaxial accelerometer attached to the rear face of the pendulum for measuring the input accelerations
b) A uniaxial load cell attached to the leading face of the impactor to measure the input longitudinal force time history
c) A triaxial accelerometer and a triaxial angular velocity sensor attached to the head
d) A six component load cell attached to the head/neck to measure the force and moment time histories
e) A six component load cell at the base of the neck to measure the force and moment time histories
f) An accelerometer at the base of the neck to measure the acceleration along the sliding direction of the sled.

In all, there were 21 channels of data recorded for each of the test conditions which was recorded on a digital data acquisition system at a sampling rate of 12,500 HZ. In addition a high-speed video camera operating at 2250 full frames per second recorded the impact event. Retroreflective targets were placed on the head as well as on every metal disk so that the head rotation angle and deflection of the neck along its length could be measured. Figure 12 shows a side view of the head/neck complex which illustrates how the targets were viewed by the video camera.

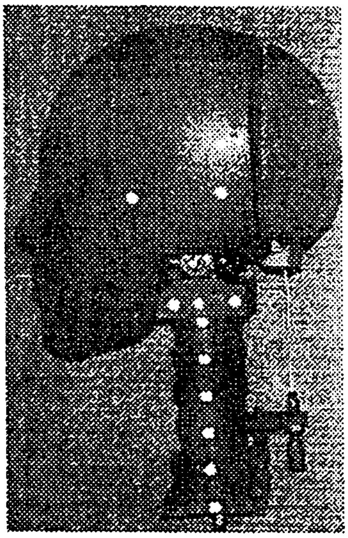

Figure 12. Side view of neck showing reflective targets.

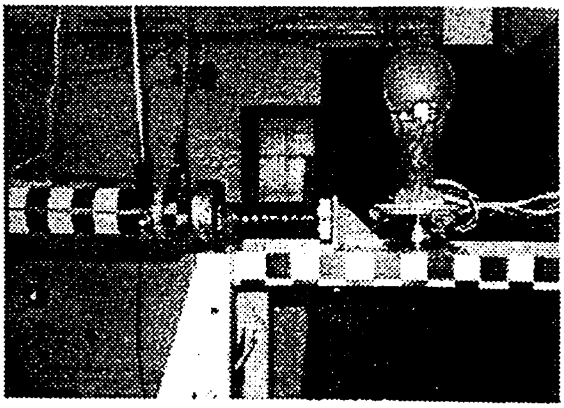

Figure 13. Test setup for lateral impact tests.

The head/neck assembly was rigidly fixed at the base of the neck to the plate on the sled in a manner that

The head/neck assembly was rigidly fixed at the base of the neck to the plate on the sled in a manner that the head/neck system could be rotated to apply the impact pulse in the flexion, extension, or lateral direction. The impact pulses that were selected for the tests corresponded to impacts at 5 mph, 7.5 mph, and 10 mph and had a duration of approximately 100 ms. This pulse width is about one half the time for the pulse used in the NBDL volunteer tests. The pulse widths used in the test were the longest that could be generated by the test equipment. Figure 13 shows a photograph of the test set up for a lateral impact.

TEST RESULTS

The primary purpose of the mini-sled tests were to evaluate the integrity of the system, to develop data that could be utilized to evaluate the adequacy of the DYNAMAN model, and lastly to obtain some indication of how well the physical features of the simulated neck produced the response that was desired in the flexion, extension, and lateral directions. It was realized that the change in velocity would be about one-half of that seen in the volunteer tests and thus the input energy during impact would be only about one quarter of the energy of the volunteer tests. It was believed the test results that were obtained however, could be analyzed and extrapolated to obtain an idea of how well the neck duplicated the human response in the NBDL tests.

Flexion Tests

The impact pulse applied to the base of the neck is presented in Figure 14. As can be seen, a fairly clean pulse having a maximum acceleration of approximately 13.3 g's was generated and the pulse width was approximately 100ms. This pulse was used to drive the lumped mass model. In the next section, the test response of the neck will be first compared with simulation results. Then the test results will be extrapolated and compared with target human response.

Comparison of model and prototype responses - The head rotation angle versus time of the flexion response is presented in Figure 15 and is compared to the results of the simulation analysis. It is seen that the correlation between the simulation and experimental results is very good. A plot of the Z vs X displacements is presented in Figure 16 and the experimental results are compared to the simulation results. It can be seen that there is a big difference between the experimental results and the results predicted by the simulation program. The reason for this difference, particularly in the Z direction, is not known.

Comparison of prototype and human volunteer responses - The maximum head rotation angle observed in the test is only about 61 degrees as compared to approximately 78 degrees rotation seen in the volunteers. Also, peak rotation angle occurred approximately 15 ms earlier in the test than that measured for the volunteer. Both of these differences are believed due to the slightly smaller magnitude of the impact pulse and the shorter pulse duration. It was also noted that the head lag angle in the tests was only about 10 degrees or about one third of that obtained with the human volunteers. This result indicates that the aft spring is not sufficiently strong to produce the desired head lag angle.

It is noted that the maximum Z deflection is 6 inches less than that of the volunteer. The maximum X deflection is about 2.5 inches less than that observed in the volunteer tests. It is believed that a reason for these differences is the much smaller energy in the experimental impact pulse. If the input energy were raised to human volunteer test levels, it is believed that the effect would be to significantly increase the deflection in the Z direction while increasing the X deflection by a smaller amount. On the basis of the test results and the above analysis, it was concluded that the stiffness of the neck was approximately correct but the aft spring stiffness needed to be increased in order to achieve the desired head lag. In viewing the video tapes recorded during the mini-sled tests, it was determined that the rebound of the head/neck system was significantly greater than that of the human and therefore a spring restraint was probably needed forward of the condyle pin in order to limit the rebound.

Figure 17 presents a comparison of the test data and the Mertz corridor for the frontal impact. It can be seen that a significant portion of the test data lies within the corridor. When the head neck system is incorporated with the dummy and neck-chest impact occurs, as it does with the human, it is expected that all of the test data would lie with the corridor. In addition, when a stiffer spring is placed behind the condyle pin, the increased torque produced by the spring should raise the data further into the Mertz corridor

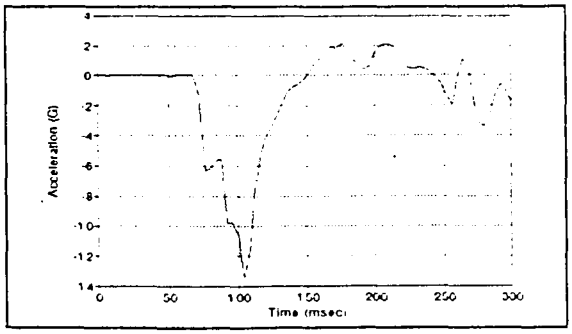

Figure 14. T1 acceleration for frontal flexion at 10 mph.

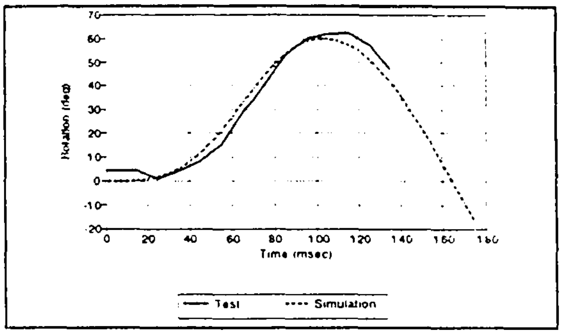

Figure 15. Comparison of head rotation angle test from test and simulation for frontal flexion.

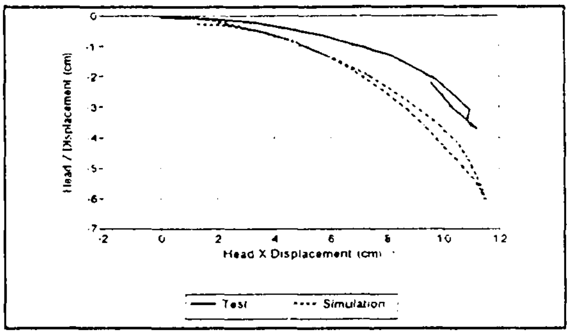

Figure 16. Comparison of head CG displacement in Z-X plane from test and simulation for frontal flexion test.

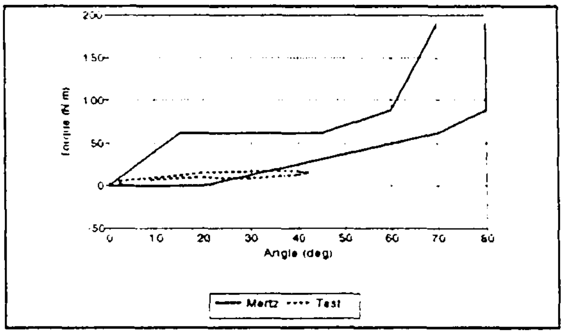

Figure 17. Comparison of test data and Mertz corridors for frontal flexion test.

Lateral Bending Tests

The impact pulse for the lateral tests is presented in Figure 18. It can be seen that the pulse is relatively clean and has a maximum value of 7 G's and a width of approximately 100 ms, again one half of that of the NBDL tests. This pulse was used to drive the lumped mass model. In the next section, the test response of the neck will be first compared with simulation results. Then the test results will be extrapolated and compared with the target human response.

Comparison of test and simulation results - The rotation of the neck is presented in Figure 19 and it can be seen that the predicted head rotation angle does not predict the magnitude of the head rotation angle but does closely predicts the variation of the experimental result with time. The plots shown in Figure 20 shows that the predicted y and Z deflections compare well with the test results.

Comparison of prototype and human volunteer responses - It is noted from Figure 19 that the peak rotation angle is approximately 40 ms earlier than that which was measured for the human. It is also noted that the head rotation angle is significantly less than the 55 degrees measured for the volunteer for a 7 G impact loading. The differences in the magnitude and timing of the head rotation angle are believed to be caused partly by the narrower pulse width and lower energy of the test pulse, and partly by excessive neck stiffness in the lateral direction.

The Z vs Y deflection, presented in Figure 20 also indicates that the neck is too stiff in the lateral direction as the Y deflection is approximately only one half of that measured for the volunteer and the Z deflection is only on tenth of the measured deflection. Comparison of the measured kinetic results with Mertz corridors is presented in Figure 21 for the lateral impact. As can be seen, the data indicates that the experimental results are within the corridor.

Analysis of test films revealed that there was a significant rebound of the neck. While the human data also indicated a large rebound it was not as severe as that noted during the tests of the simulated neck. As previously mentioned, while some of this difference is probably due to the difference in the energy level in the two pulses, it is obvious that the neck must be weakened in the lateral direction. If the neck is weakened it is expected that the results obtained with the altered neck will still be within the corridors even though the head rotation angle is increased significantly,

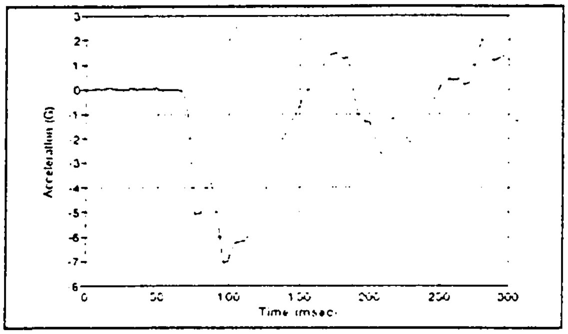

Figure 18. T1 acceleration for lateral flexion test at 7.5 mph.

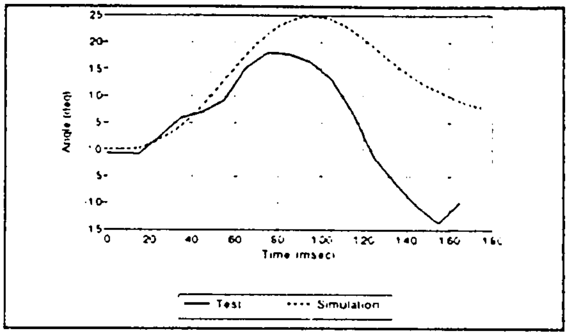

Figure 19. Comparison of head rotation angle from test and simulation for lateral flexion.

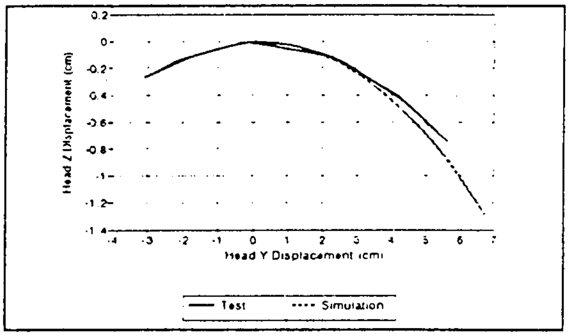

Figure 20. Comparison of head CG displacement in Y - Z plane from test and simulation for lateral flexion test.

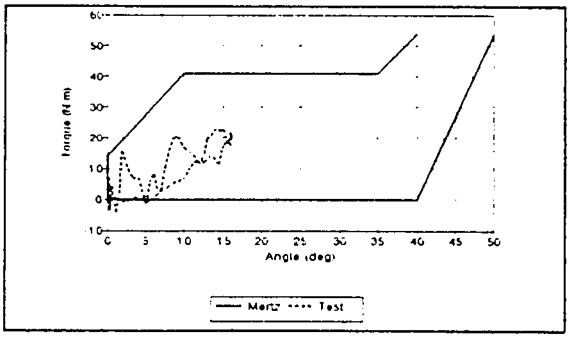

Figure 21. Comparison of test data and Mertz corridors for lateral flexion.

Extension Tests

Figure 22 presents the plot of the impact pulse vs. time for the extension test. As can be seen the pulse is somewhat distorted and does not have the relatively clean pulse shape that was obtained in the flexion and lateral tests. The reason for the distorted pulse is not known but it might have been caused by the interaction of the head stop with the neck which occurred at approximately 70ms. However, a maximum G force of approximately 7 G's was obtained and the width of the pulse was about 100 ms, as it was with the other test pulses. As before, this pulse was used to drive the lumped mass model. In the next few paragraphs, the test response of the neck will be first compared with simulation results. Then the test results will be extrapolated and compared with the target human response.

Comparison of test and simulation results - Figure 23 presents a time history plot of the head rotation angle obtained in response to the impact loading. It can be seen that the simulation results compare very favorably with the experimental results. The impact of the head stop on the neck rotation angle can be observed in the experimental data at about 80 ms while the simulation results indicates a smaller effect.

Figure 24 presents a plot of the time history of the neck rotation angle as a result of the impact loading.

The effect of the impact of the head stop on the neck response is very obvious in the experimental data, as it is in the results of the simulation which predicts the response fairly well.

Comparison of test results with target human response - The maximum rotation angle achieved by the head was approximately 60 degrees which is approximately 12 degrees more than that measured for the human volunteer. This increased response is not too surprising since the maximum G loading is approximately three times that applied to the human volunteer. Since the time of the impact pulse is approximately only one half of that used for the volunteer test, the effect is to minimize the increase of the head rotation from that which might be expected if only the increased G loading was considered.

The maximum neck angle achieved is only 14 degrees, which is approximately 6 degrees less than that measured for the human volunteer. This result is somewhat surprising when the characteristics of the impact pulse are considered. It would be expected that, like the head rotation angle, the neck rotation angle seen in the test would be higher than that observed in human volunteer tests. Comparing the ratio of the neck rotation angle to the head rotation angle, the results obtained with the volunteer are approximately twice that obtained from the test of the simulated neck. It is believed the reason for this difference is the increased stiffness of the neck in extension due to the motion stops placed at the rear of the neck between disks one and two.

It is noticed that there is very little head lag in the response to the impact loading for the simulated neck which is in contrast to that obtained for the volunteer. This result suggests again that a spring restraint system needs to be placed forward of the condyle pin so that the proper lag response can be obtained. Figure 25 compares the experimental data with the corridors of kinetic response developed by Mertz. It can be seen that during rebound the experimental data falls outside of the corridor. It is expected that the addition of the spring restraint forward of the condyle pin will increase the torque and the data measured with the modified head/neck system will fall within the corridor.

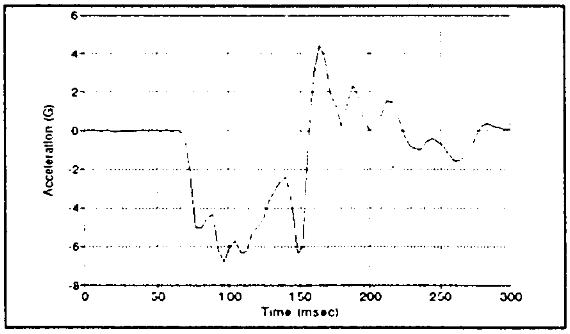

Figure 22. T1 acceleration for extension test at 7.5 mph.

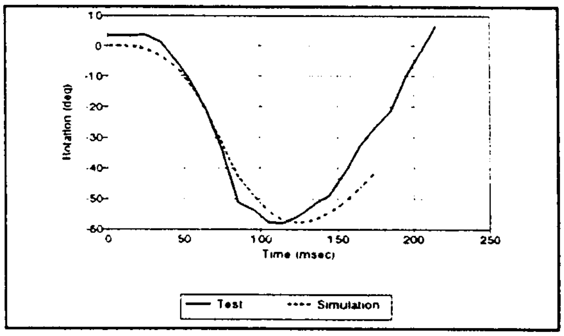

Figure 23. Comparison of head rotation angle from test and simulation for extension test.

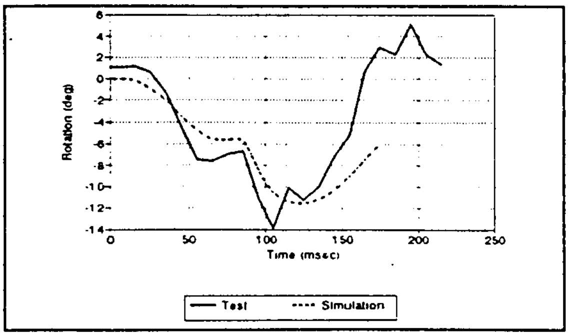

Figure 24. Comparison of neck rotation angle from test and simulation for extension test.

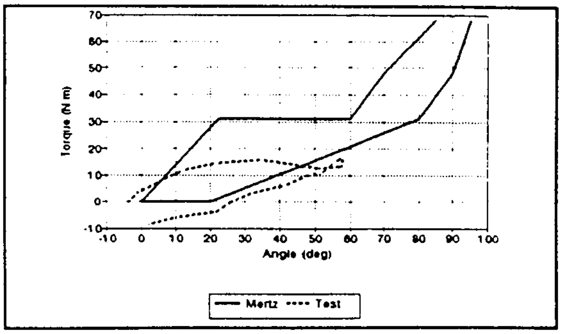

Figure 25. Comparison of test data and Mertz corridors for extension test.

Neck Compression Stiffness

On the basis of results obtained with an Instron testing machine,the axial stiffness of the new neck was determined to be approximately 4000 N/cm which compares to approximately 1590 N/cm for the cadaver and approximately 5600 N/cm for the Hybrid III neck. The results indicate that the new neck is a little more than twice the stiffness of the cadaver but only 70% of that of the Hybrid III. While the new neck is much closer to the cadaver stiffness than the Hybrid III, it does not meet the goal of matching the stiffness of the cadaver neck.

As a result of the tests that were conducted the following observation were made:

1. The simulation analysis based on DYNAMAN predicts the experimental results fairly well.
2. A spring must be incorporated forward of the condyle pin to develop a restraining moment to increase the head lag during flexion response, as well as, to limit the head rotation during rebound.
3. The lateral stiffness of the neck must be reduced in order to obtain a better correlation with the target human volunteer response.
4. In order to obtain the proper head lag response in extension a spring restraint system needs to be placed forward of the condyle pin.

DESIGN OF THE SECOND PROTOTYPE NECK

On the basis of the results obtained during the tests of the first prototype neck, a second prototype neck was designed to resolve the problems and obtain responses closer the those measured by NBDL for the human volunteers. Figure 26 presents a side view drawing of the second prototype neck. It is anticipated that a head with features described by Melvin [23], and developed to test for facial injuries, will be used in the second prototype neck design. The main differences in the two prototype head/neck systems, is the addition of a restraining spring attached to the head forward of the condyle pin. This spring was added to help alleviate the rebound problem and improve the head/neck response in extension. The spring housings are fabricated of plastic and the springs are coated to minimize any possibility of spring noise due to their motion inside the housing. In order to adjust the cable/spring length for zero slack, an adjustment nut is located in the base of each spring housing. The soft stops in the fore and aft locations have been redesigned so that when they are impacted an increasing force is generated in a more gradual manner than in the first prototype design. The cross-section of the rubber pucks have also been slightly altered in order to provide a more realistic stiffness distribution in the lateral direction. In addition to these changes, a new neck shroud has been designed to mimic the contour of the human neck and to prevent parts of an airbag from intruding into the gap between the head and neck. The shroud should also eliminate the possibility of the airbag interacting with the mechanical parts of the neck. It is believed that the changes incorporated in the second prototype neck will adequately eliminate the problems noted with the first design and result in a good simulation of the volunteer data.

At the present time the new neck is being fabricated. It will be tested in the near future to evaluate if the above noted desired changes produce a head/neck system that mimics the human response in the flexion,lateral and extension motions during impact.

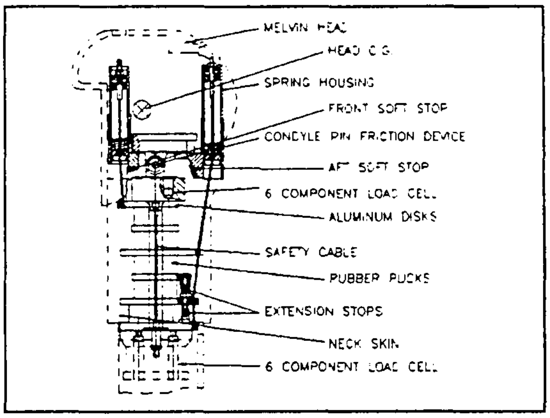

Figure 26. Second prototype head/neck design.

CONCLUSIONS

GESAC has designed and tested a prototype neck that shows great promise in its ability to meet the goal of duplicating the impact response of the human neck in frontal, lateral and aft directions. The success in developing a computer simulation program to use as a guide in the design of a suitable neck, has been invaluable in facilitating the development effort. The test results that were obtained during the evaluation of the first prototype neck design indicated that a suitable neck can be developed for incorporation into the NHTSA advanced frontal test dummy. The second prototype neck now being fabricated for evaluation testing was designed using

the proven simulation program: therefore, the improvements incorporated in the second prototype neck should result in a dummy neck that will adequately duplicate the response of the human neck during impact loadings.

ACKNOWLEDGEMENT

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REFERENCES

1. Mertz,H.J., Neathery.R.F., Culver,C.C., "Performance Requirements and Characteristics of Mechanical Necks." Human Impact Response: Measurement and Simulation.ed by King.W.F..and Mertz.H.J. Plenum Press.New York,1973

2. Mertz.H.J., Patrick,L.M., "Strength and Response of the Human Neck," Fifteenth Stapp Car Crash Conference Proceedings, SAE 710855,1971

3. Patrick,L.M., Chou, "Response of the Human Neck in Flexion, Extension, and Lateral Flexion," Vehicle Research Institute Report No.YRI-7-3,SAE,1976

4. Ewing,C.L., Thomas,D.J., Beeler.G.W., Patrick,L.M., Gillis,D.B., "Dynamic Response of the Head and Neck of the Living Human to -Gx Acceleration," Twelfth Stapp Car Crash Conference Proceedings SAE 680792, 1968

5. Ewing,C.L., Thomas,D.J., Patrick.L.M., Beeler,G.W., Smith,M.J., "Living Human Dynamic Response to -Gx Impact Acceleration. Part II-Accelerations Measured on the Head and Neck," Thirteenth Stapp Car Crash Conference Proceedings, SAE 690817 1969

6. Ewing,C.L., Thomas,D.J., "Torque vs. Angular Displacement Response of Human Head to -Gx Impact Acceleration," Seventeenth Stapp Car Crash Conference Proceedings SAE 730976,1973

7. Ewing,C.L., Thomas,D.J., Lustick,L., Becker,E., Williams,G., Muzzy III,W.H. " The Effect of the Initial Position Of the Head and Neck on the Dynamic Response of the Human Head and Neck to -Gx Impact Acceleration," Nineteenth Stapp Car Crash Conference Proceedings, SAE 751157,1975

8. Ewing,C.L.,Thomas,D.J.,Lustick,L. Muzzy,W.H.,Williams,G.,Majewski,P.L., "The Effect of Duration,Rate of Onset and Peak Sled Acceleration on the Dynamic Response of the Human Head and Neck," Twentieth Stapp Car Crash Conference Proceedings,SAE 760800 ,1976

9 Ewing,C.J.,Thomas,D.J.,Majewski,P.L.,Black,R.,Lustick,L., "Measurement of Head,T1,and Pelvic Response to -Gx Impact Acceleration," Twenty-first Stapp Car Crash Conference,SAE 770927, 1977

10. Spenny.C.H., "Analysis of Head Response to Torso Acceleration," DOT-HS-807-159,DOT-TSC-NHTSA-86-5 December 1987

11. Wismans,J. "Preliminary Development-Head-Neck Simulator," DOT-HS-807-034 August,1986

12. Wismans.J., Spenny,C.H., " Head-Neck Response in Frontal Flexion," Twenty seventh Stapp Car Crash Conference Proceedings, SAE 841666,1984

13. Wismans,J., Spenny,C.H. " Performance Requirements for Mechanical Necks in Lateral Flexion," Twenty-seventh Stapp Car Crash Conference Proceedings, SAE 872194,1987

14. Wismans,J., et al., "Comparison of Human Volunteer and Cadaver Head-Neck Response in Frontal Flexion," Thirty-first Stapp Car Crash Conference Proceedings,SAE 872194 1987

15. Wismans,J., van Oorshot,H., Woltring,H.J., "Omni-Direction Human Head-Neck Response," Thirtieth Stapp Car Crash Conference Proceedings , SAE 861893,1986

16. Thunnissen,J., Wismans,J., Ewing,C.L., Thomas,D.J., "Human volunteer Head/Neck Response in Frontal Flexion: A New Analysis," 39th Stapp Car Crash Conference, SAE Paper No.952721, 1995

17. Klinich,K.D., Beebe,M.S., "Comparison off TAD and Hybrid III Dummies in NBDL Sled Test Configuration," Event Report VRTC-88-0108. Vehicle Research and Test Center, May 1994

18. Happee,R., Twisk,D., Beusenberg,M.C., "Analysis of Volunteer Experiments to Define Neck Response

Requirements for Low Severity Forward and Rearward Loading," TNO Report #95 ORBV 008.1/RHA. TNO Road-Vehicles Research Institute,1995

19. Klinich,K., Beebe, M., Pritz,H., Haffner,M., "Performance Criteria for a Biofidelic Dummy Neck," NHTSA technical report, 1995

20. "Head/Neck Simulator Development, "Progress Report,SRL-59, April 1985/May 1986, National Highway Traffic Safety Administration, Vehicle Research and Test Center, East Liberty, Ohio

21. Mendis,K., Stalnaker,R.L., Pritz,H.B., "Multi-Directional Dummy Neck Prototype," Twelfth Internal Conference on ESV,1989

22. Yoganandan,N., Sances, A.,Jr. Pintar,F.A., "Biomechanical Evaluation of the Axial Stiffness of the Human Cadaveric and Manikin Necks," Journal of Biomechanical Engineering, 111 (3), pp 250-255, 1989.

23. Melvin,J., Shee,T., "Facial Injury Assessment Techniques". 12th International Technical Conference on ESV, pp 608-617, 1989.

24. Eppinger,R.E. and Kleinberger,M. .1995 Personal communication

A COMPARISON OF SENSOR SYSTEMS FOR MEASURING THREE DIMENSIONAL CRASH DUMMY MOTION

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ABSTRACT

Tracking angular motion of dummy components, such as the head, is important in understanding body response during violent force exposures. This paper compares four methods of measuring angular motion of a Hybrid III dummy head during a series of tests using a horizontal accelerator sled and a head/neck pendulum. The Hybrid III head was instrumented with three orthogonal magnetohydrodynamic (MHD) angular rate sensors and with nine linear accelerometers arranged in a 3-2-2-2 array. The motion of the head was monitored using a Selspot optical target tracking system and a high speed video camera during the horizontal accelerator sled tests. A two-potentiometer device and a high speed camera were used to monitor the head motion during a series of head/neck pendulum flexion and extension tests. Software routines were written to calculate the head rotation and angular velocity from the head mounted sensors. Comparisons of the angular velocity and rotation, determined using the MHD, nine accelerometer array, and Selspot system, were made for each of the horizontal accelerator sled tests. For each pendulum test, the two-potentiometer data were differentiated to determine the angular velocity and these data were compared to the angular velocity determined using the MHD sensors and the nine accelerometer array. The angular rotation of the head from the three sensor technologies was also compared for each pendulum test. Rotational motion of the head in the principal direction of motion using all four sensing technologies compared well for each of the horizontal sled tests and for the head/neck pendulum tests in which there was no head impact. When the head, attached to the base of the pendulum, was subjected to impact against a wooden board, analysis of the accelerometer array resulted in calculated rotations greater than those which actually occurred. The MHD angular rate sensors proved to be the superior of the tested techniques in determining the three-dimensional angular velocity of a rigid body.

INTRODUCTION

The ability to measure the rotational motion of a rigid body during impact testing is critical to understanding the response of the human body to violent force exposures. This understanding may provide insights that lead to the development of new and better criteria for determining the potential for injuries and consequently provides guidance for the design of safer vehicles. In order for measured data to be of significant value, the evaluation technique must provide a rapid, accurate, and repeatable means to determine the dynamic response of the body. Traditionally used techniques, such as high speed photography, target tracking, and linear accelerometer arrays, provide reliable results, but demand a significant amount of time and data collection effort.[1] New technologies, such as magnetohydrodynamics, may provide accurate results without the inconvenience associated with these other methods.[2,3] To verify the performance of rotational motion sensing techniques, a Hybrid III head was instrumented with three orthogonal magnetohydrodynamic (MHD) angular rate sensors and with nine linear accelerometers arranged in a 3-2-2-2 array and a series of horizontal accelerator sled and head/neck pendulum tests were performed.

EXPERIMENTAL APPROACH

A three dimensional digitizer was used to define a head structural axis system with which the head mounted sensors could be aligned. The axis system was defined using four bolt hole locations on the flat, rear surface of the aluminum Hybrid III skull. The y axis was defined such that it originates at the origin, specified as the point midway between the bottom two bolt holes, and is directed toward the bottom left bolt hole. The z axis originates at the origin and is directed upward, toward the midpoint of two upper bolt holes. The x axis direction is defined as the cross product of the y and z axes. The center of gravity location of the instrumented head was measured with respect to the head structural axis system using the mass properties measurement procedure developed at the Armstrong Laboratory.[4]

The MHD sensors were mounted orthogonally near the center of gravity of the head and aligned with the structural axis system of the head. The nine linear accelerometers were arranged in a 3-2-2-2 configuration within the head to permit angular acceleration to be derived. Three of the accelerometers were aligned with the structural axis system of the head and were mounted near the head's center of gravity. Two accelerometers, oriented to sense acceleration along the y and z axes, were mounted 2.2 inches from the CG along the positive x axis. Two accelerometers were positioned 1.9 inches from the CG along the positive y axis and oriented to measure acceleration along the x and z axes. Two accelerometers, oriented to measure x and y accelerations, were mounted 3.2 inches from the CG along the positive z axis.

Small, light weight, infrared light emitting diodes (LEDs) were secured to the forehead, mouth, jaw, and upper

surface of the head using glue and Velcro. The positions of the LED targets were determined with respect to the head structural axis system using the three dimensional digitizer.

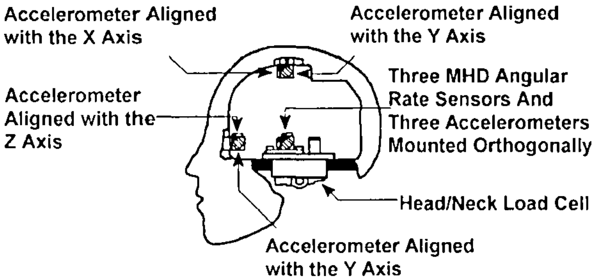

Figure 1. Position of the Instrumentation with the Hybrid III Head.

Horizontal Accelerator Sled Tests

Six horizontal accelerator sled tests were performed with the instrumented head attached on an Advanced Dynamic Anthropomorphic Manikin, ADAM.[5] Three acceleration pulses, varying from an 8g, 270 msec pulse to a 10g, 240 msec pulse, were applied to the sled. The tests were performed using a standard ACES style ejection seat bucket and head rest. An aircrew style harness was used to secure the manikin within the seat. For two of the tests, the right harness was intentionally loosened prior to testing to allow for non-planar motion of the head. To generate a head strike during rebound, an aluminum plate was bolted to the front of the head rest for two of the tests.

Two Selspot cameras were mounted on the horizontal accelerator sled during testing. One camera was positioned to achieve a lateral view of the dummy head and the other was mounted at an oblique angle. A photodetector unit within the cameras registered light pulses from the LED targets on the dummy head. At .002 second intervals, the x-y coordinates of the LED locations were digitized by the cameras. The Selspot data were transferred to a computer and processed by the Selspot MULTILab system software. A software program corrected the raw camera image coordinates for sled vibration, filtered the data using an FFT filter with a cutoff of 120 Hz, transformed the digitized data from both cameras into three dimensional LED positions, and output the LED positions with respect to the sled coordinate system.[6]

A sampling rate of 1000 Hz was used for the MHDs and linear accelerometers. The Selspot LED target data were collected at a 500 Hz sampling rate. A 360 Hz analog filter was used for all instrumentation.

Head/Neck Pendulum Tests

Twelve tests were performed with the instrumented head attached to a Hybrid III dummy neck and mounted to the base of a head/neck pendulum which was built to meet SAE part 572 specifications for dummy neck certification.[7] The head/neck pendulum consists of an instrumented pendulum arm, velocimeter, power supply, data acquisition system, and a computer.

During operation, the pendulum arm is raised, using an electric hoist, to a predetermined height to produce the desired impact velocity. When released, low friction bearings allow the pendulum arm to swing freely into a block of aluminum honeycomb, imparting a near square wave deceleration pulse to the base of the neck. The velocity of the pendulum arm immediately prior to impact is measured with a velocimeter, and a linear accelerometer, mounted on the pendulum arm, measures the pendulum deceleration.

Ten tests were performed with the head mounted on the end of the pendulum arm in a configuration to produce a flexion response and two tests were performed with the head mounted to produce an extension response. A two-potentiometer device was mounted to the side of the head, attached at the base of the neck and at the occipital condyl pin, to measure the head and neck rotation angles.

For six of the twelve tests, a 2 inch by 4 inch wooden board was clamped to the pendulum frame to produce a direct impact to the head. The board was mounted perpendicular to the direction of motion for four of the tests, producing nearly planar motion of the head at impact. Two of the tests were performed with the board angled to produce an impact that would result in yaw motion of the head.

Data were collected at a 10 kHz sampling rate with a 5 kHz analog filter. A digital butterworth low pass filter with a 100 Hz cut-off frequency was applied to the data from all sensors except the MHD angular rate sensors. A digital recursive filter, provided by the manufacturer to compensate for the low frequency corner of the MHD, was used to filter the angular rate sensor data. High speed film, at a film rate of 500 frames per second, was taken of each pendulum test.

ANALYSIS METHODOLOGY

Data from the two-potentiometer device and the Selspot position measurement system were used to derive the angular displacement of the head. The MHD angular rate sensors and the nine accelerometer array measured angular velocity and angular acceleration, respectively. The angular position was determined by numerically integrating the output from the sensors.

Because the head rotates in three dimensional space, the internal measurements achieved with the MHD sensors and the accelerometer array provide angular motion with respect to the rotating and translating head structural axis system. To compute the angular position of the head in the inertially fixed axis system it is necessary to track the angular position and, for the accelerometer array data, angular velocity as well, and to use output from the sensors to compute the change in angular position at each time increment.

MHD Data

The MHD sensor data were first zeroed by averaging data points immediately prior to the acceleration event and subtracting this value from the remainder of the data. Twenty data points prior to time zero were used for the sled tests and approximately fifty data points prior to impact were averaged for the pendulum tests. The MHD sensor data were then given an initial offset equal to the initial angular velocity of the head. For the sled tests the initial angular velocity of the head was zero but for the pendulum tests it was assumed to be equal to the initial angular velocity of the pendulum. This was calculated by recording the linear velocity of the pendulum arm using a slotted light wand mounted on the pendulum arm, and dividing this velocity by the distance from the pendulum pivot to the light wand.

If it is assumed that the inertially fixed axis system is aligned with the structural axis system of the head at time zero, then the transformation matrix from the inertially fixed axis system to the head structural axis system at time zero, $\underline{A}_{10}$, is equal to the identity matrix. A transformatin matrix from the head orientation at time t to the orientation at time t+1 can be expressed in terms of three sequential rotations about the head z, y, and x axes.

$$A_{21} = R_x^T \, R_y^T \, R_z^T \tag{1}$$

The individual matrix rotation operators are given by

$$R_z^T = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$R_y^T = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \tag{3}$$

$$R_x^T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix} . \tag{4}$$

If the rotation is small between time steps, Δt, the rotation angles are given by

$$\theta_x = \frac{\omega_1(t) + \omega_1(t+1)}{2} \Delta t \tag{5}$$

$$\theta_y = \frac{\omega_2(t) + \omega_2(t+1)}{2} \Delta t \tag{6}$$

$$\theta_z = \frac{\omega_3(t) + \omega_3(t+1)}{2} \Delta t \, , \tag{7}$$

where ω_1, ω_2, and ω_3 are the MHD measured angular velocity data about the x, y, and z axes, respectively.

Transformation matices were calculated every .002 sec and the transformation matrix to the orientation at the n-1 time increment from the initial position was calculated using

$$A_{n0} = A_{n(n-1)} \, A_{(n-1)(n-2)} \ldots A_{10} \, . \tag{8}$$

The three Euler angles, yaw, pitch, and roll, were calculated from the elements of the $\underline{A}_{n0}$ matrix. The pitch angle was calculated from

$$\theta_y = -\sin^{-1}(A_{13}) \, . \tag{9}$$

For a pitch angle not equal to 90 degrees, the yaw and roll angles were calculated from

$$\theta_z = \tan^{-1}\left[\frac{A_{12}}{A_{11}}\right] \tag{10}$$

and

$$\theta_x = \tan^{-1}\left[\frac{A_{23}}{A_{33}}\right] , \tag{11}$$

respectively.

For a pitch angle of 90 degrees, the roll angle is equal to zero and the yaw angle was determined by using,

$$\theta_z = \tan^{-1}\left[\frac{-A_{21} - A_{13}\,A_{32}}{A_{22} - A_{13}\,A_{31}}\right] . \tag{12}$$

These equations are valid for rotations less than or equal to 90 degrees. No head rotation greater than 90 degrees was achieved in any of the horizontal accelerator or head/neck pendulum tests.

Accelerometer Array Data

The outputs from the accelerometers were zeroed using the same technique described for the MHD data and the initial angular velocity was similarly assigned. The linear accelerometer array, arranged with three linear accelerometers mounted in an orthogonal configuration at the origin and three pairs secured in the head with the sensitive axis of each aligned with one of the orthogonal directions,

was used to compute the angular acceleration components about the body-fixed axes. This configuration is shown in Figure 2.

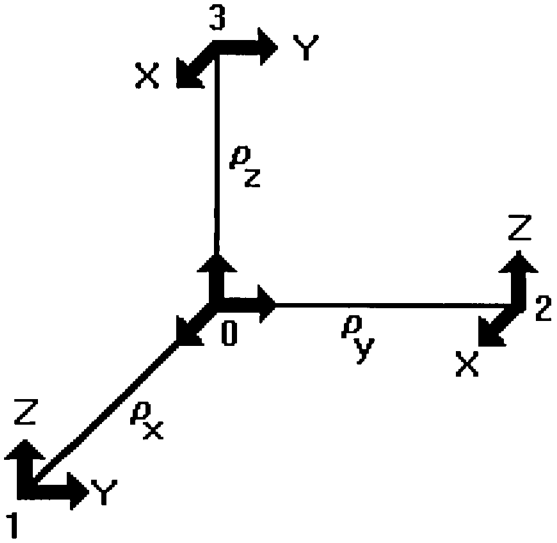

Figure 2. Linear Accelerometer Arrangement

The nine accelerometer array data were converted to angular accelerations using the formulas

$$\alpha_1 = \frac{(A_{Z2} - A_{ZO})}{2\ \rho_y} - \frac{(A_{Y3} - A_{YO})}{2\ \rho_z} \tag{13}$$

$$\alpha_3 = \frac{(A_{YI} - A_{YO})}{2\ \rho_x} - \frac{(A_{X2} - A_{XO})}{2\ \rho_y} \tag{14}$$

$$\omega_1(t) = \omega_1^{(s)}(t) + \alpha_1(t+1) * \Delta t \tag{15}$$

where A_{ij} is the acceleration sensed in the i direction at the j location. ρ_k is the distance of the accelerometers from the origin along the k axis.

The angular accelerations, measured with respect to the rotating structural axis system, were used to calculate angular velocities

$$\alpha_2 = \frac{(A_{X3} - A_{XO})}{2\ \rho_z} - \frac{(A_{ZI} - A_{ZO})}{2\ \rho_x} \tag{16}$$

$$\omega_3(t) = \omega_3^{(s)}(t) + \alpha_3(t+1) * \Delta t \tag{17}$$

$$\omega_2(t) = \omega_2^{(s)}(t) + \alpha_2(t+1) * \Delta t \tag{18}$$

where $\vec{\omega}^{(s)}$ is the angular velocity about the inertially fixed axis system. The angular position was similarly determined by integrating the angular velocity.

The process for calculating the angular velocities and displacements with respect to the inertial coordinate system was the same as for the MHD data using equations 1 through 8.

Selspot/MULTILab System

Since transformations can be calculated between any two coordinate systems that have been formed from three noncolinear points, three of the four Selspot LED targets were used to define a coordinate system and to provide a transformation, $\underline{A}_{LS}$, from the sled axis system to an intermediate LED axis system. The forehead, jaw, and upper head LED targets, on the surface of the dummy head, were used to form the LED intermediate axis system. A vector $\vec{Z}$ was defined such that it originates at the location of the forehead target and points in the direction of the upper head target. The vector $\vec{Y1}$ was defined such that it originates at the forehead target and is directed toward the jaw target. The $\vec{Y1}$ vector is not necessarily orthogonal to the $\vec{Z}$ axis. The component of the $\vec{Y1}$ vector in the $\vec{Z}$ direction is given by

$$\vec{Y1} \cdot \hat{Z}_n = |\vec{Y1}| \cdot |\hat{Z}_n| \cos\theta\ , \tag{19}$$

this is subtracted from $\vec{Y1}$ to produce a vector, designated as $\hat{Y}$, that is orthogonal to $\vec{Z}$,

$$\vec{Y} = \vec{Y1} - |\vec{Y1}|\ \cos\theta\ \hat{Z}_n\ . \tag{20}$$

The cross product of vectors $\hat{Y}_n$ and $\hat{Z}_n$ defines the vector $\hat{X}_n$.

The transformation matrix, $\underline{A}_{LH}$, from the head structural axis system to the LED intermediate axis system, was obtained from the LED positions digitized using the three dimensional digitizer.

The transformation matrix, $\underline{A}_{SH}$, from the head structural axis system to the sled axis system was obtained from

$$A_{SH} = A_{LS}^T\, A_{LH} = A_{SL}\, A_{LH} \tag{21}$$

and was calculated at every .002 time increment.

The matrix $\underline{A}_{SH}$ is a 3 X 3 array with elements Aij, that are calculated every .002 seconds, represents a spatial orientation and is expressed as

$$A_{SH} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} . \tag{22}$$

Each of the spatial orientations can be defined by a sequence of rotations consisting of yaw, pitch, and then roll. The net transformation for these rotations is given by

$$\begin{bmatrix} Cos\theta_z\ Cos\theta_y & Sin\theta_z\ Cos\theta_y & -Sin\theta_y \\ Cos\theta_z\ Sin\theta_y\ Sin\theta_x - Sin\theta_z\ Cos\theta_x & Sin\theta_z\ Sin\theta_y\ Sin\theta_x + Cos\theta_z\ Cos\theta_x & Cos\theta_y\ Sin\theta_x \\ Cos\theta_z\ Sin\theta_y\ Cos\theta_y + Sin\theta_z\ Sin\theta_x & Sin\theta_z\ Sin\theta_y\ Cos\theta_x - Cos\theta_z\ Sin\theta_x & Cos\theta_y\ Cos\theta_x \end{bmatrix} . \quad (23)$$

By equating this matrix to $\underline{A}_{SH}$, the rotation angles can be determined as shown in equations 8 through 11.

The head angular velocity was calculated using the following method. There is a coordinate rotation operator, corresponding to the transformation $\underline{A}_{SH}$, that rotates the inertial axis system to the orientation of the head structural axis system. This rotation operator is given by,

$$R^{(S)} = A_{SH}^{T} . \quad (24)$$

For two adjacent orientations, produced by $\underline{R}_0^{(S)}$ and $\underline{R}_1^{(S)}$, and separated by .002 seconds, the rotation operator from the 0 orientation to the 1 orientation was calculated using

$$R_{0\to1}^{(S)} = R_O^{(S)T} R_1^{(S)} . \quad (25)$$

The similarity transformation,

$$R^{(H)} = R_0^{(S)T} R^{(S)} R_0^{(S)} , \quad (26)$$

was used to determine the rotation operator in the head structural axis system and was applied to $R_{0\to1}^{(S)}$ to find

$$R_{0\to1}^{(H)} = R_0^{(S)T} R_{0\to1}^{(S)} R_0^{(S)}, \quad (27)$$

which can be expanded to

$$R_{0\to1}^{(H)} = R_0^{(S)T} R_0^{(S)T} R_1^{(S)} R_0^{(S)} . \quad (28)$$

By substituting equation 24 into equation 28, but omitting the H subscript for convenience, the rotation operator was defined by

$$R_{0\to1}^{(H)} = A_{0S} A_{0S} A_{S1} A_{S0} . \quad (29)$$

This rotation, in the head structural axis system, produces a rotation of the head from the 0 orientation to the 1 orientation.

The corresponding angle of rotation, $\Delta\theta$, is calculated from

$$\Delta\theta = \cos^{-1}\frac{(r_{11}+r_{22}+r_{33})-1}{2} \quad (30)$$

where r_{ij} are the elements of the rotation matrix.

The rotational velocity components about the x, y, and z axes of the head structural axis system were determined from the relationships

$$\omega_x = \frac{r_{21} - r_{12}}{2\sin\Delta\theta}\frac{\Delta\theta}{\Delta t} \quad (31)$$

$$\omega_y = \frac{r_{13} - r_{31}}{2\sin\Delta\theta}\frac{\Delta\theta}{\Delta t} \quad (32)$$

$$\omega_z = \frac{r_{32} - r_{23}}{2\sin\Delta\theta}\frac{\Delta\theta}{\Delta t} . \quad (33)$$

RESULTS

Comparisons of the angular velocity and rotation, determined using the MHD sensors, nine accelerometer array, and Selspot MULTILab system, were made for each of the horizontal accelerator sled tests. For each pendulum test, the two-potentiometer data were differentiated to determine the angular velocity and these data were compared to the angular velocity determined using the MHD sensors and the nine accelerometer array. The angular rotation of the head, determined using the two-potentiometer device, MHD sensors, and nine accelerometer array, was also compared for each pendulum test.

Horizontal Accelerator Sled Tests

No Head Impact Comparisons of the angular velocity about the x, y, and z axes, respectively, computed using the MHD angular rate sensors, nine accelerometer array, and Selspot optical target tracking method for a 9 g sled test with a 255 millisecond pulse duration are shown in Figures 3, 4, and 5, respectively. The shoulder harness was tight during the test so that minimal out-of-plane motion of the head would occur. As shown in Figures 3 through 5, the differentiation technique used to obtain angular velocity from the Selspot data resulted in a very noisy signal that is difficult to compare to the other rotation measurement techniques.

Figure 3 shows that, for angular velocity about the x axis, the accelerometer array and MHD derived results have a similar shape, but that the accelerometer derived angular velocity tends to diverge with time.

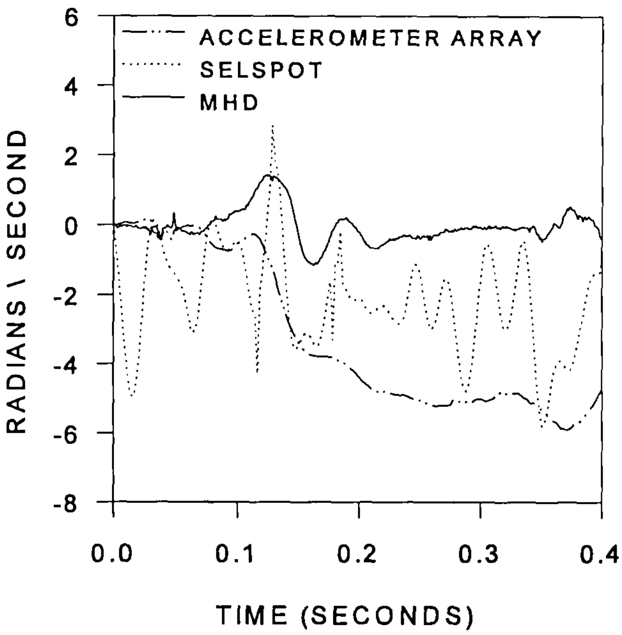

Figure 3. Angular Velocity about the x Axis

For angular velocity about the y axis, all three methods compare very well in shape, amplitude and phase, as shown in Figure 4.

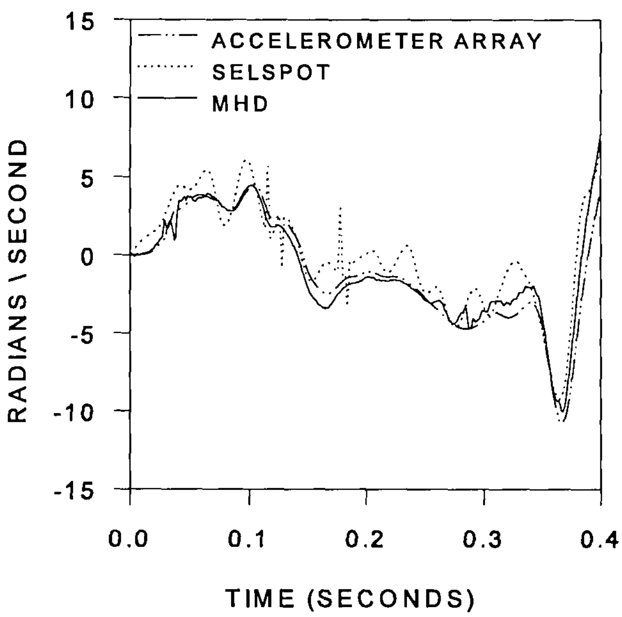

Figure 4. Angular Velocity about the y axis

Figure 5 illustrates that the accelerometer array and MHD derived angular velocity about the z axis have a similar shape. However, there is some divergence and a slight phase shift in the accelerometer derived results.

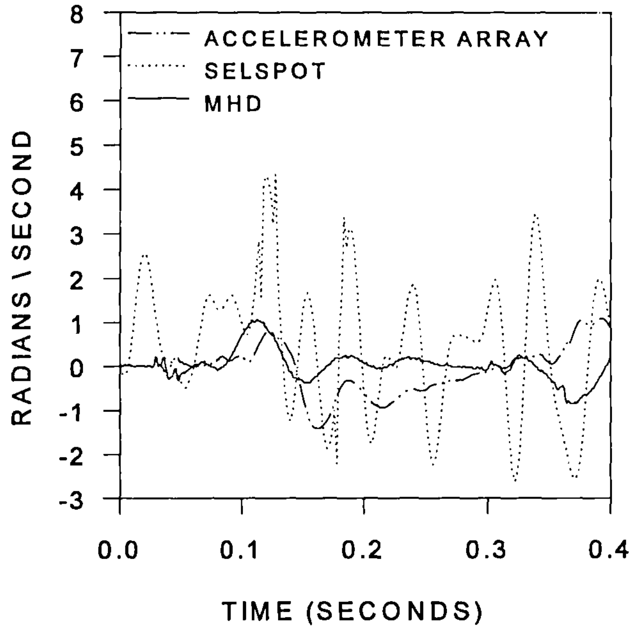

Figure 5. Angular Velocity about the z axis

Comparisons of the head rotation about the x, y, and z axes for the same horizontal accelerator sled test are shown in Figures 6, 7, and 8, respectively. The head rotation about the x axis computed using the Selspot optical target tracking method, MHD angular rate sensors, and nine accelerometer array is initially similar in shape but the accelerometer array derived results diverge after about 250 milliseconds.

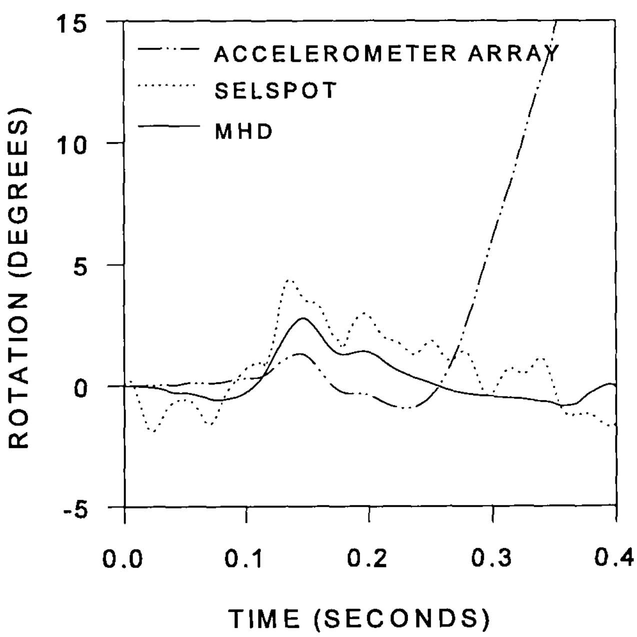

Figure 6. Angular Rotation about the x axis

The Selspot targets and nine accelerometer array result in rotations about the y axis that are slightly higher than the angular rate sensor derived rotations. However, the peak amplitudes are within approximately 2 degrees, the shapes of the three curves are very similar and no phase differences were noted.

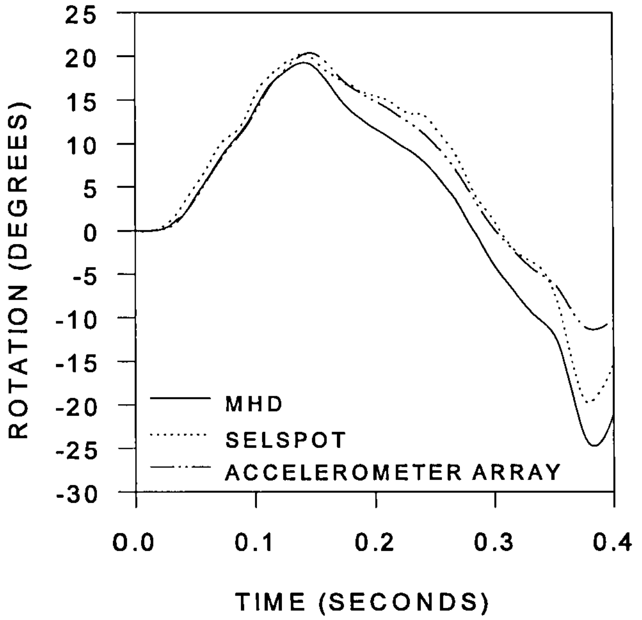

Figure 7. Angular Rotation about the y axis

Although comparisons of the head rotation about the z axis show an initial similarity between the three results, the accelerometer derived results show divergence after approximately 150 milliseconds.

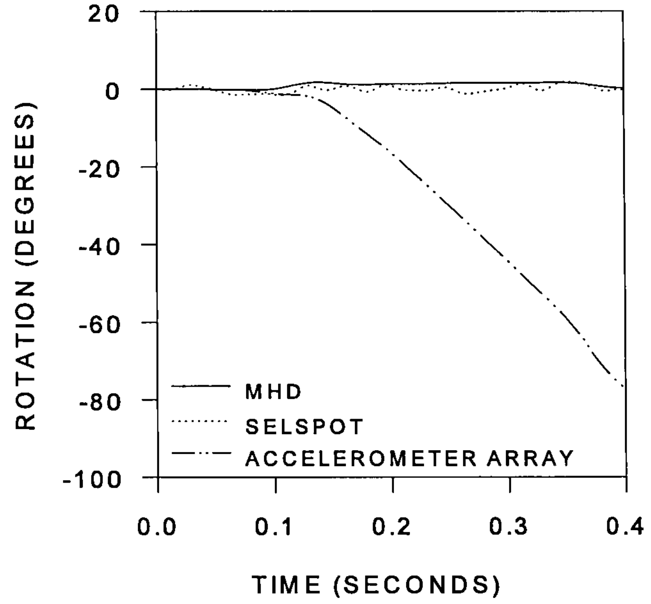

Figure 8. Angular Rotation about the z axis

Comparison of the results of this sled test with a similar 10 g sled test with a 240 millisecond pulse duration showed similar results for the angular velocity response about the x, y, and z axes. Also, similar results were obtained for the angular rotation comparisons about the x and z axes. The angular rotation about the y axis derived from the Selspot targets and the MHD sensors compare well in shape and phase and have a peak amplitude difference of only about 2 degrees. However, the accelerometer array analysis results in a curve that is more broad than the Selspot and MHD derived rotation curves and has a peak amplitude of approximately 7 degrees greater than the peak rotation derived from the other techniques. Figure 9 shows comparisons of the angular rotation about the y axis computed using the MHD angular rate sensors, nine accelerometer array, and Selspot optical target tracking method for the 10g sled test.

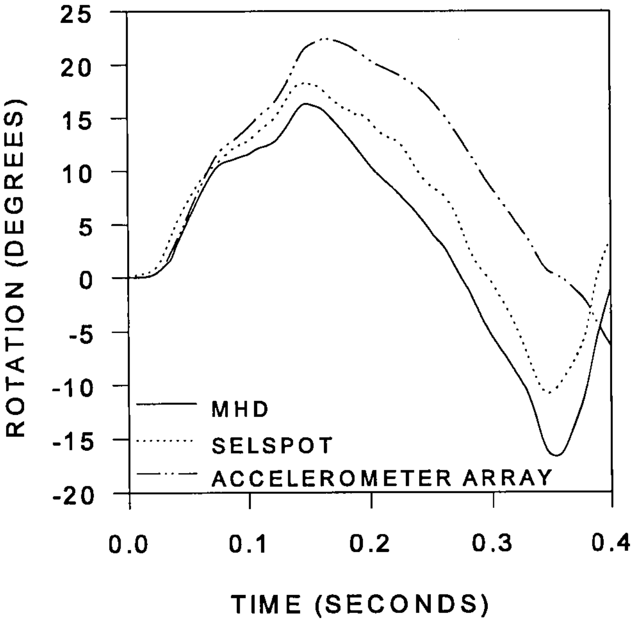

Figure 9. Angular Rotation about the y Axis

Comparisons were made of the rotational velocity and angular rotation about the x, y, and z axes for a test 10g sled test with a 240 millisecond pulse duration in which the right shoulder strap of the harness was loosened to produce non-planar motion of the head. Similar to the results of the tight harness sled test, the angular velocity about the x axis obtained from the MHD angular rate sensors and Selspot optical target tracking method are similar in shape despite a noise component in the differentiated Selspot data. The angular velocity determined from the accelerometer array tends to diverge with time. The angular velocity about the x axis is shown in Figure 10.

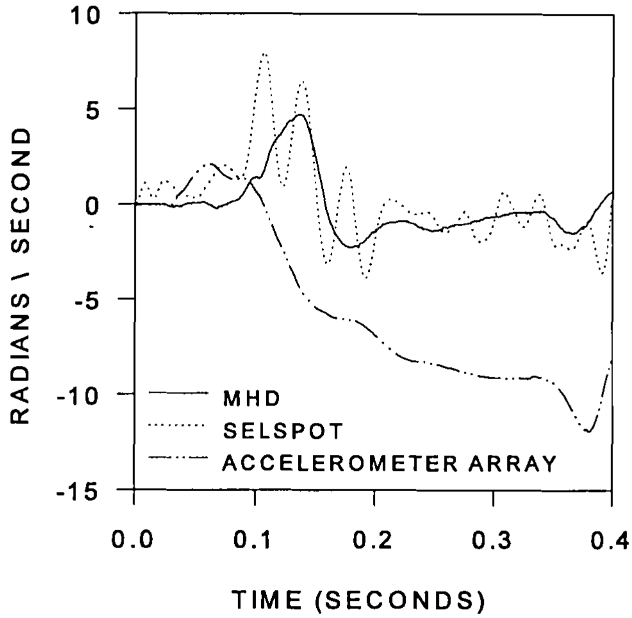

Figure 10. Angular Velocity about the x Axis

The comparison of the angular velocity about the y axis, shown in Figure 11, illustrates that the three measurement techniques produce results that are very close in amplitude, shape, and phase.

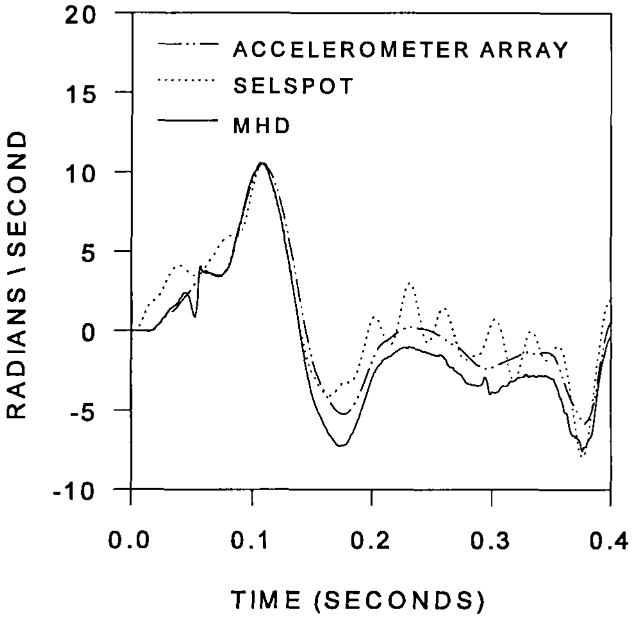

Figure 11. Angular Velocity about the y Axis

Figure 12 shows the angular velocity about the z axis obtained from the MHD angular rate sensors, the nine accelerometer array and determined using the Selspot optical target tracking method. This figure shows that the angular velocity obtained from the nine accelerometer array is similar in shape to that derived from the MHD angular rate sensors and Selspot targets. There is also a slight divergence and a phase shift of approximately 50 milliseconds in the accelerometer array derived angular velocity.

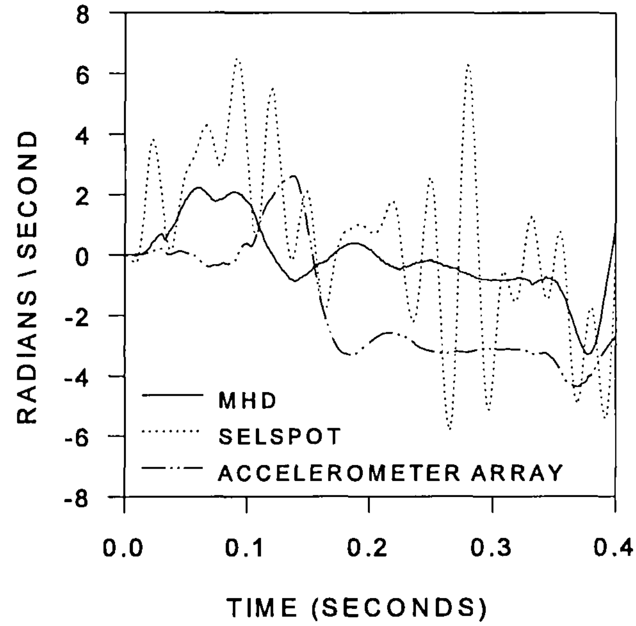

Figure 12. Angular Velocity about the z Axis

Comparisons of the head rotation about the x, y, and z axes for the same horizontal accelerator sled test are shown in Figures 13, 14, and 15, respectively. Again similar to the tight harness test, the head rotation about the x axis computed using the Selspot optical target tracking method and derived from the MHD angular rate sensors are very similar in shape, amplitude, and phase. Although the rotation derived from the nine accelerometer array is initially similar in shape to the curves determined from the MHD sensors and optical target tracking method, the results of the accelerometer array diverge after about 150 milliseconds.

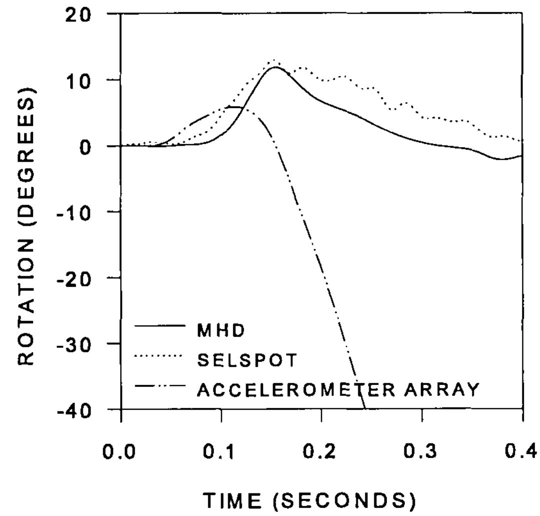

Figure 13. Angular Rotation about the x Axis

As illustrated in Figure 14, the rotations about the y axis obtained using the Selspot targets, nine accelerometer array, and MHD angular rate sensors are very similar in phase and shape. The difference in peak amplitude determined by the three different methods is within 2 degrees.

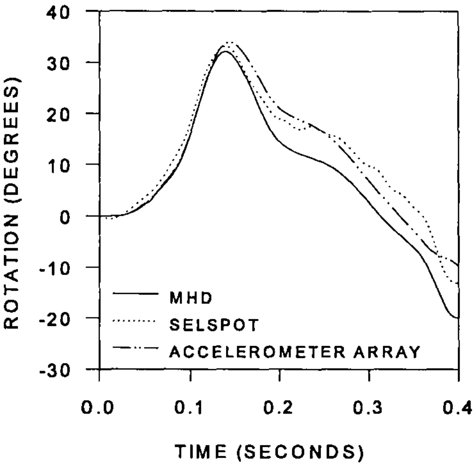

Figure 14. Angular Rotation about the y Axis

Figure 15 shows that although the nine accelerometer derived angular rotation about the z axis is similar in shape and within 2 degrees in peak amplitude to the results obtained using the MHD angular rate sensors, there is a phase shift in the results of the accelerometer array data of approximately 50 milliseconds. The nine accelerometer curve is also less broad than the MHD and Selspot derived curves and the nine accelerometer results diverge with time.

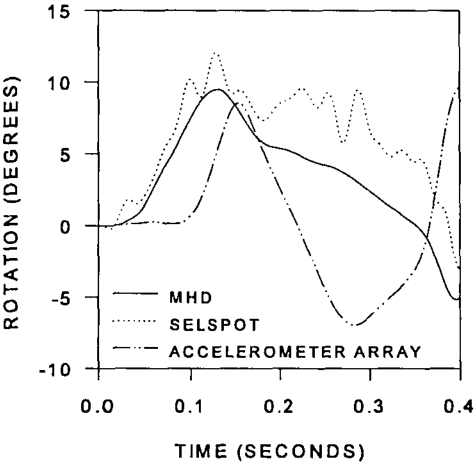

Figure 15. Angular Rotation about the z Axis

Head Impact Figures 16, 17, and 18 show comparisons of the angular velocity about the x, y, and z axes, respectively, computed using the MHD angular rate sensors, nine accelerometer array, and Selspot optical target tracking method for a 10g sled test with a 240 millisecond pulse duration in which the head was allowed to strike an aluminum beam during rebound. Figure 16 shows that, similar to the results of tests in which there was no head impact, the results obtained using the optical target tracking method are noisy due to the differentiation process, but are similar in shape and phase to the MHD derived results and the nine accelerometer array data diverge with time. The head impact event is illustrated by a sharp spike in the data at approximately 340 milliseconds as shown in the curve derived from the MHD angular rate sensors and the curve determined from the nine accelerometer array.

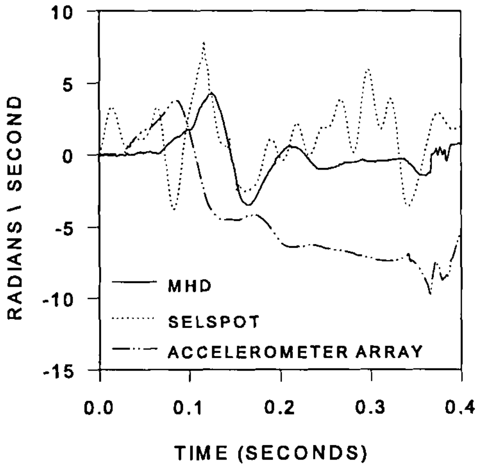

Figure 16. Angular Velocity about the x Axis

Angular velocity about the y axis, as shown in Figure 17, illustrates a very good comparison between the three measurement techniques in the curves' shape, phase, and amplitude.

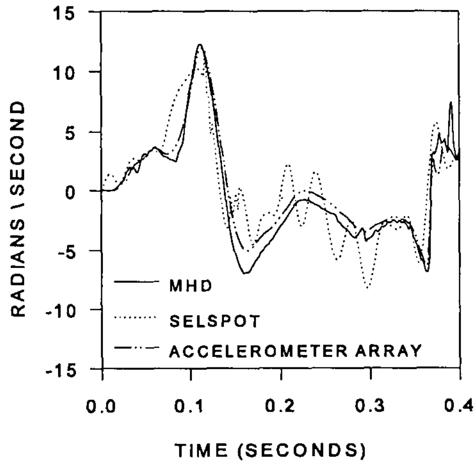

Figure 17. Angular Velocity about the y Axis

Figure 18 shows that the differentiation technique used to obtain angular velocity from the Selspot data resulted in a very noisy signal that is difficult to compare to the data from the other rotation measurement techniques. Similar phase and shape results were obtained from the MHD sensors and accelerometer array. A slight divergence in the accelerometer array results was noted. Similar to the results shown in Figure 15, the head impact event is represented by a sharp spike in the MHD sensor and accelerometer array curves at approximately 340 milliseconds.

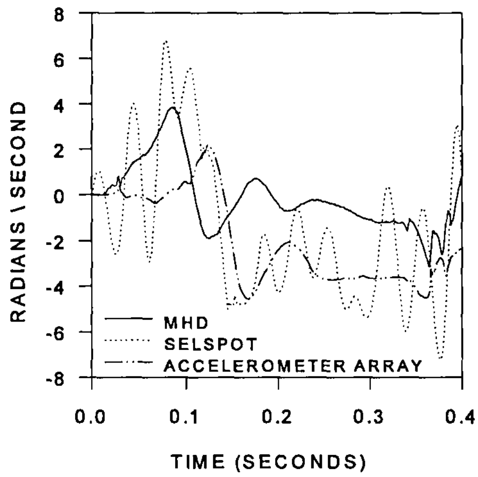

Figure 18. Angular Velocity about the z Axis

The angular rotation of the head about the x and z axes for the same horizontal accelerator sled test, shown in Figures 19 and 20, respectively, show a good comparison between the angular rotation determined using the MHD angular rate sensors and that determined using the optical target tracking technique. The results obtained from the nine accelerometer array show a divergence with time.

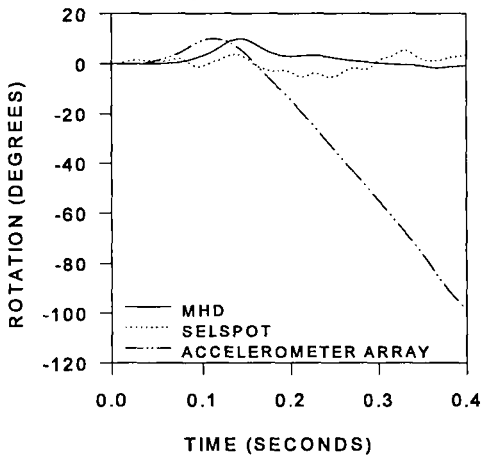

Figure 19. Angular Rotation about the x Axis

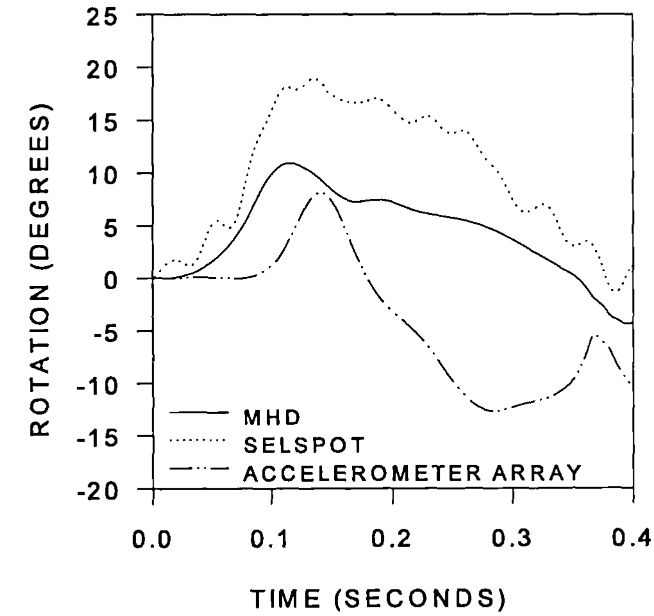

Figure 20. Angular Rotation about the z Axis

The comparison of the rotation of the head about the y axis, Figure 21, obtained from the three measurement techniques show similar results in shape, phase, and amplitude. The slight rotation caused by the head impact is shown by the results of the optical target tracking technique and by the MHD derived results as a small peak that occurs at approximately 340 milliseconds.

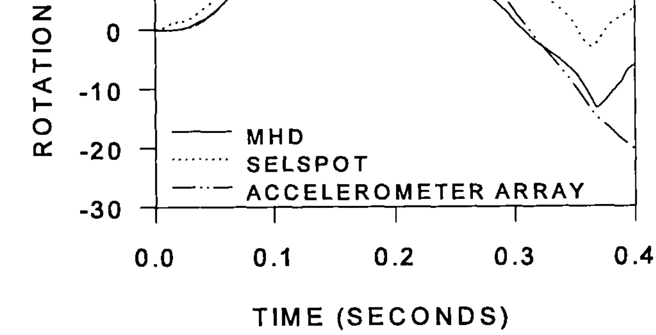

Figure 21. Angular Rotation about the y Axis

Head/Neck Pendulum Flexion Tests

No Head Impact Figures 22, 23, and 24 show the angular velocity about the x, y, and z axes of the head, respectively, for a head/neck pendulum flexion test with an initial pendulum impact velocity of 23 feet per second. Although the impact event was symmetric, some unsymmetric responses were measured. This is most likely due to the additional mass of the two-potentiometer device, mounted on one side of the head. This conclusion is supported by the fact that the pendulum test performed without the two-potentiometer device did not show evidence of unsymmetric head rotation.

A comparison of the angular velocity about the x axis determined from the MHD angular rate sensor and calculated from the nine accelerometer array show a similarity in shape and phase and an amplitude difference of approximately 2 radians/second.

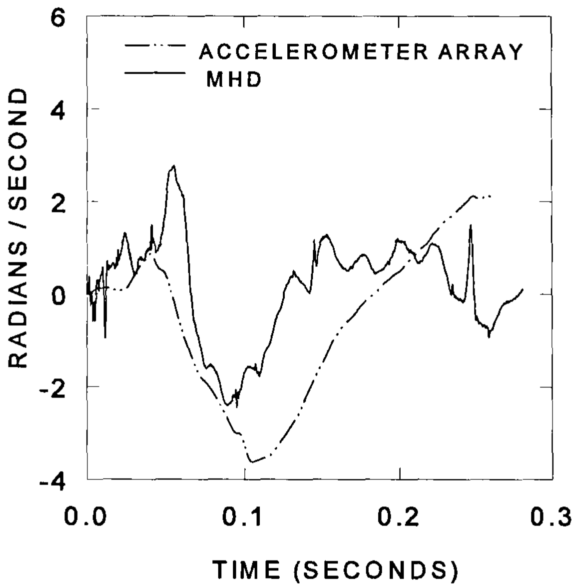

Figure 22. Angular Velocity about the x Axis

Figure 23 shows the angular velocity about the y axis determined from the two-potentiometer device, angular rate sensor, and nine accelerometer array. Although the three measurement techniques result in curves that are similar in shape, there is a slight difference in phase between the MHD obtained results and those derived from the two-potentiometer device and nine accelerometer array. The plot also shows that the peak amplitude determined using the accelerometer array is approximately 4 radians/second lower than that determined using the two-potentiometer device and MHD sensors.

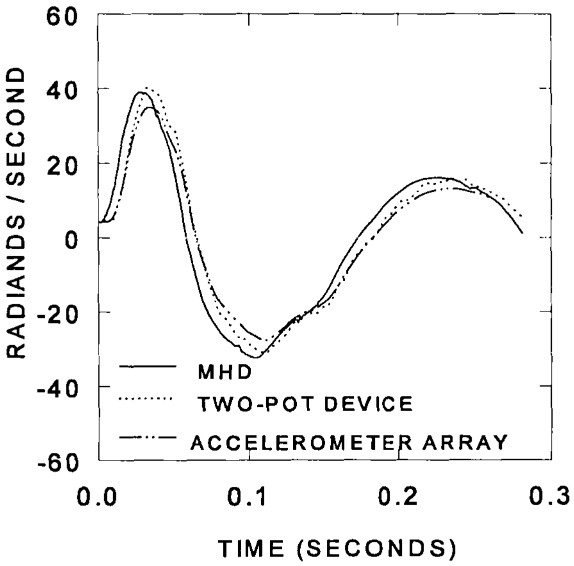

Figure 23. Angular Velocity about the y Axis

Figure 24 shows that the angular velocity about the z axis obtained from the MHD sensors is not similar to that determined from the nine accelerometer array. The MHD derived angular velocity appears to oscillate about the initial position and the nine accelerometer array results initially oscillate slightly but diverge with time.

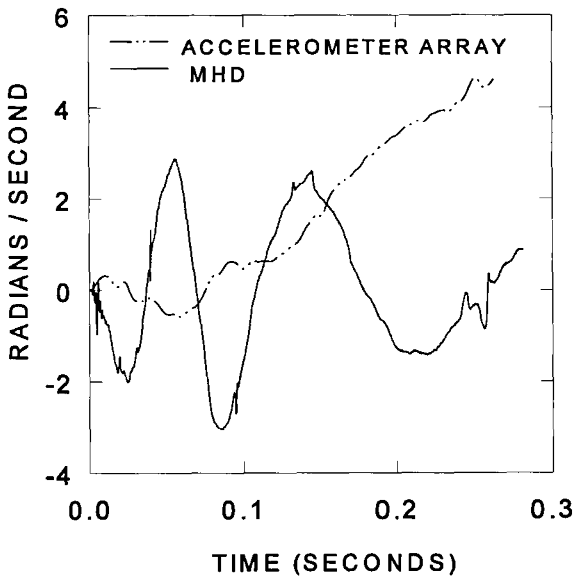

Figure 24. Angular Velocity about the z Axis

As seen in the horizontal accelerator sled tests, comparisons of the rotation about the x and z axes, Figures 25 and 26, respectively, computed using the nine accelerometer array and MHD angular rate sensors show an initial similarity in the curve shapes but the nine accelerometer array data tend to diverge with time.

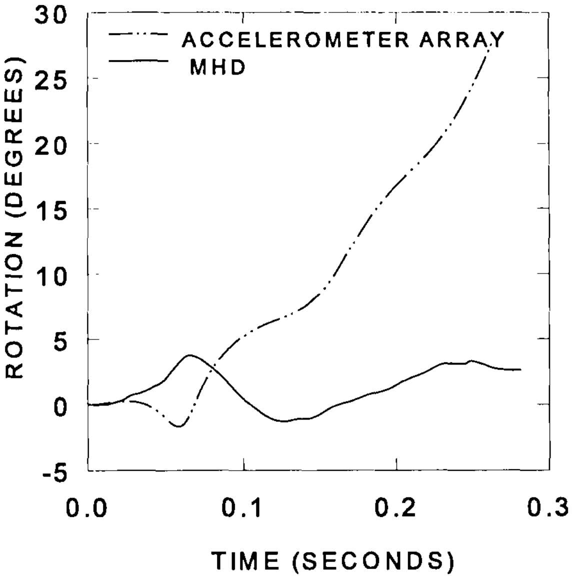

Figure 25. Angular Rotation about the x Axis

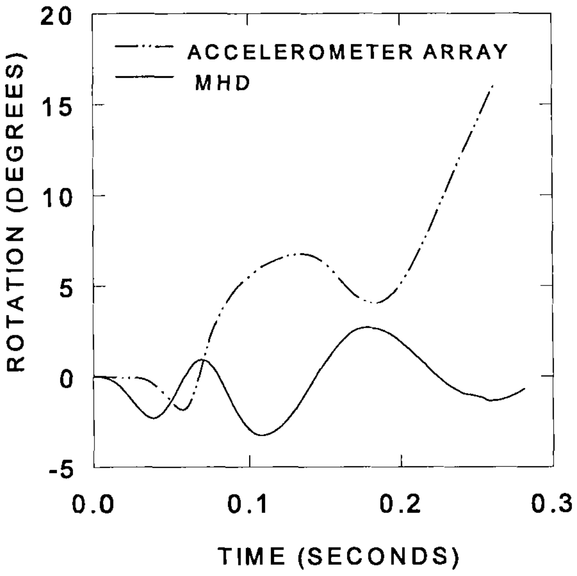

Figure 26. Angular Rotation about the z Axis

Figure 27 shows that the head rotation about the y axis computed using the two-potentiometer device, angular rate sensors, and nine accelerometer array result in curves of similar shape. Comparison of the peak amplitudes shows a slight difference in the three techniques. The peak rotations obtained from the two-potentiometer device and accelerometer array occur slightly after the peak rotation obtained from analysis of the MHD angular rate sensors.

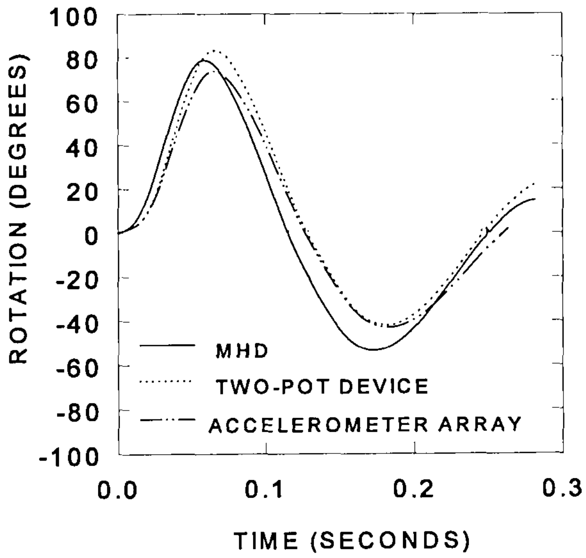

Figure 27. Angular Rotation about the y Axis

A comparison of this test with two similar head/neck pendulum tests showed that the angular velocity about the y axis results were similar for all three tests. Although differences in the amount of unsymmetric head motion were noted, the angular velocities about the x and z axes results of the other two tests also compared very well. All three head/neck pendulum tests showed that the MHD angular rate sensors, two-potentiometer device, and accelerometer array track the motion of the head about the y axis with acceptable accuracy and that the data obtained using the nine accelerometer array diverge with time.

Head Impact Comparisons of the angular velocity of the head about the x, y, and z axes obtained from the MHD sensors, two-potentiometer device, and accelerometer array are shown in Figures 28, 29, and 30 respectively. The head/neck pendulum test was performed with a pendulum impact velocity of 22.92 feet per second and a board mounted at an angle to the direction of impact. Figure 28 shows the comparison of the angular velocity about the x axis of the head obtained from the MHD sensor data and determined using the accelerometer array. Although the curves are similar in shape, the compensation filter used to

filter the angular rate sensor data did not eliminate the noise spikes caused by the head impact.

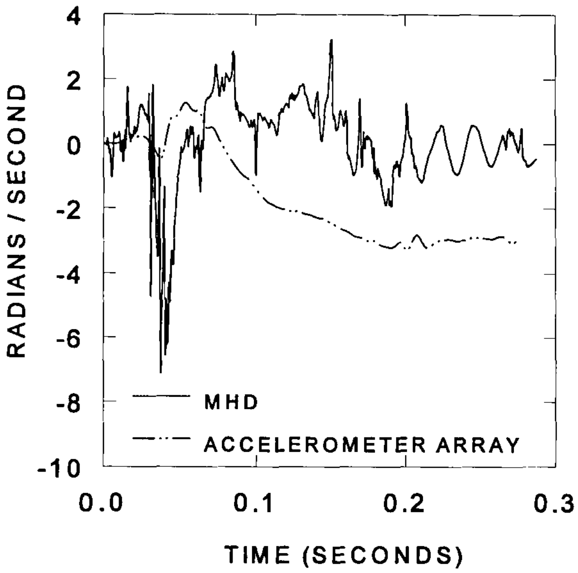

Figure 28. Angular Velocity about the x Axis

The angular velocity about the y axis is shown in Figure 29. This plot shows that there is a good correlation between the shape, phase, and amplitude of the results obtained from differentiation of the two-potentiometer device data and that measured by the MHD sensors. The accelerometer array results in a curve that has a similar shape and phase but is dissimilar in amplitude when compared to the results obtained from the MHD sensors and two-potentiometer device.

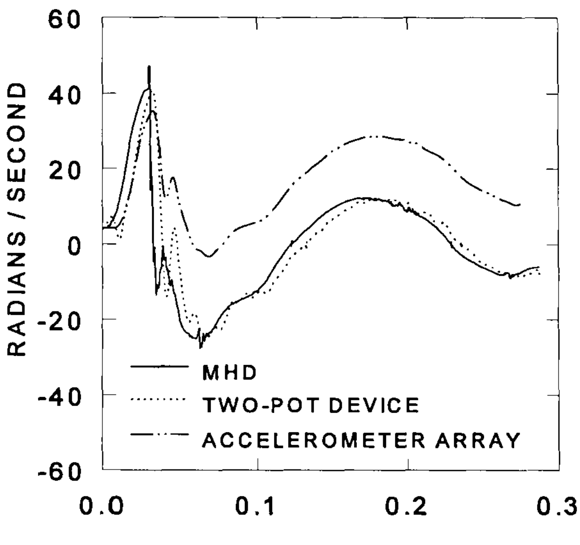

Figure 29. Angular Velocity about the y Axis

Similar spikes to those shown in Figure 28 are shown in the angular rate sensor measurement of the angular velocity about the z axis, as illustrated in Figure 30. This plot also shows a dissimilarity between the curve shapes and amplitudes.

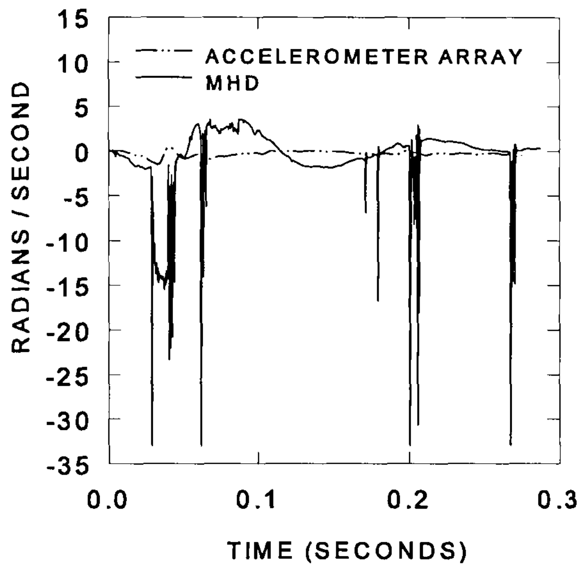

Figure 30. Angular Velocity about the z Axis

Figures 31, 32, and 33 show comparisons of the angular rotation about the x, y, and z axes, respectively, computed using the MHD sensors, accelerometer array, and measured with the two-potentiometer device for the same head/neck pendulum test. As shown in all three plots, the nine accelerometer array data result in unrealistic head rotations that are not consistent with standard head/neck pendulum flexion test results. As expected, the results obtained from the MHD sensors show very little rotation about the x axis and about 15 degrees rotation about the z axis. The rotation about the z axis, however, appears to diverge slowly with time. The comparison of the rotation about the y axis, shown in Figure 32, computed using the angular rate sensors and measured with the two-potentiometer device, show similar results in shape and amplitude. This plot also shows a phase difference of about 25 milliseconds between the angular rate sensor data and the two-potentiometer device.

A comparison of this pendulum test with other head/neck pendulum tests in which there was a head impact shows an inconsistency in the noise content of the MHD data. The MHD obtained angular velocities and rotations about the x and y axes, measured during two pendulum tests that had a head impact against a board mounted

perpendicular to the direction of motion, were similar to those illustrated above. Also, the noise spikes in the angular velocity data about the z axis for these tests did not decrease with time. Very sharp spikes in the data, on the order of 25 to 35 radians per second, were consistent throughout the tests. These two tests also show that, similar to Figure 33, the angular rotation about the z axis, obtained from the MHD data, gradually diverges with time. The angular velocity and rotation results obtained from using the accelerometer array and two-potentiometer device were similar for all head/neck pendulum tests in which there was a head impact.

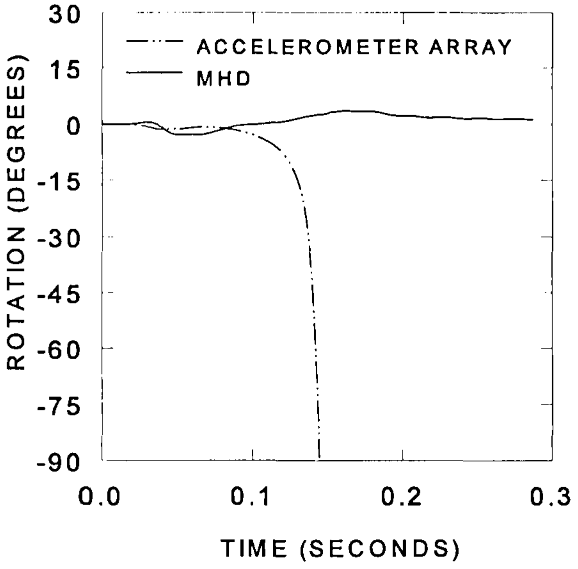

Figure 31. Angular Rotation about the x Axis

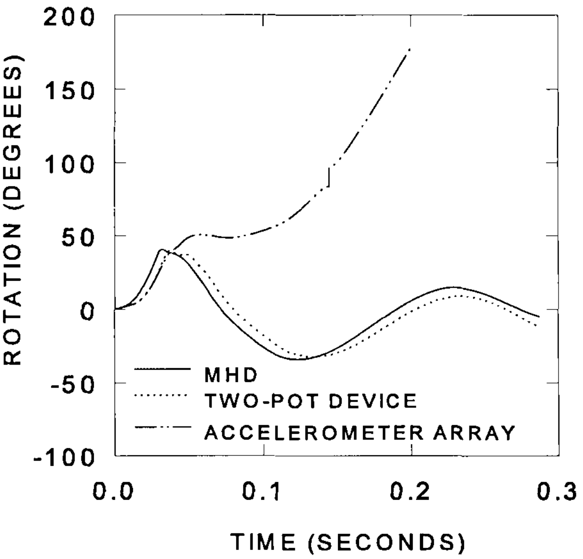

Figure 32. Angular Rotation about the y Axis

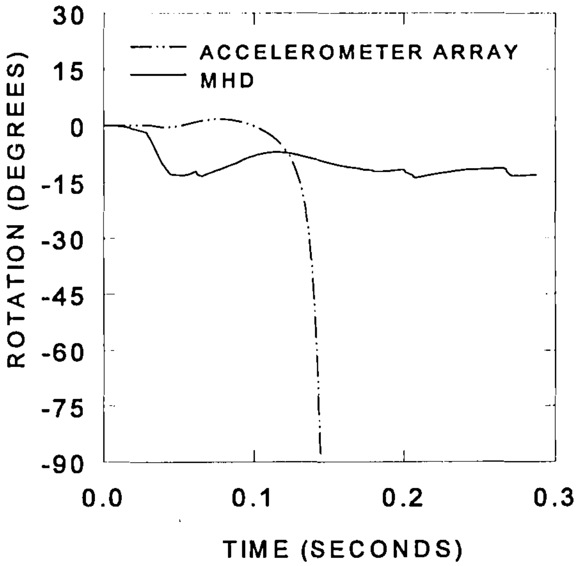

Figure 33. Angular Rotation about the z Axis

CONCLUSIONS

Comparisons of the angular velocity and rotation of the head during a series of horizontal accelerator sled tests and non-impact head/neck pendulum tests revealed that, although there were differences in the peak amplitude of the responses, the general phase and shapes of the head rotation and rotational velocity profiles obtained from the MHD angular rate sensors, nine accelerometer array and optical target tracking technique were similar. For small rotations about the other axes, the MHD angular rate sensors appear to be superior to the other methods for measuring the angular velocity of the head. The differentiation technique used to determine the angular velocity from the optical target data resulted in a highly noisy signal that was difficult to compare to the other responses. The angular displacements calculated using the optical target tracking technique, however, compared well to those obtained from the angular rate sensors. The accelerometer array data initially appeared to be similar to the MHD and Selspot obtained data but showed a tendency to diverge rapidly with time due to the accumulation of error caused by integrating the angular acceleration to determine angular velocity and rotation. The data show that small errors in the accelerometer array response become amplified as the data are integrated.

Evaluation of the head motion during a series of head/neck pendulum tests in which the head impacted a wooden board revealed that both the MHD sensors and the nine accelerometer array are susceptible to errors when exposed to large linear accelerations. The nine accelerometer data resulted in a head rotation response that was not physically realistic. Inconsistent noise spikes in the

MHD sensor data illustrates that the sensor may be sensitive to large linear accelerations.

MHD data which contained large, sharp, noise spikes within the first 50 to 100 milliseconds of the test and decreased in amplitude with time resulted in realistic angular displacement results, but tests in which the noise spikes were consistent throughout the test resulted in a head rotation that gradually diverged with time.

This study has shown that the MHD angular rate sensors, nine accelerometer array, optical target tracking technique, and two-potentiometer device provide reliable capabilities for tracking the angular motion of a rigid body about the primary axis of motion when the body is not subjected to a direct impact. For impact events that result in small rotations over a long duration, the MHD sensors and Selspot optical target tracking technique provide superior results to the nine accelerometer array, which tends to diverge with time.

It has been shown that although each of the sensors provides an acceptable means for tracking the angular motion of a rigid body about the primary axis of rotation, the MHD angular rate sensor is superior to all other methods analyzed in this report when comparing small angular velocities of a rigid body.

ACKNOWLEDGEMENT

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REFERENCES

1. Padgaonkar, A. J., Krieger, K. W. , King, A. I. , "Measurement of Angular Acceleration of a Rigid Body Using Linear Accelerations", Journal of Applied Mechanics, The American Society of Mechanical Engineers, March, 1975.

2. Laughlin, D.R., "A Magnetohydrodynamic Angular Motion Sensor for Anthropomorphic Test Device Instrumentation", Proceedings of the Thirty Third Stapp Car Crash Conference, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warendale, PA, October, 1989.

3. Willems, G. C., Knouse, D. R., "A Detailed Evaluation of the ATA Angular Motion Sensor in Realistic Simulated Crash Environments", Proceedings of the Thirty Fifth Stapp Car Crash Conference, Society6 of Automotive Engineers, Inc., 400 Commonwealth Drive, Warendale, PA, November, 1991.

4. Albery, C.A., Obert, A., Whitestone, J., Lephart, S.A., "The Automated Mass Properties Measurement System Testing Procedure", Harry G. Armstrong Medical Research Laboratory, Report No. AAMRL-TR-89-300, Wright Patterson Air Force Base, Ohio, October 1989.

5. Bartol, Aileen M., Hazen, Vernon L., Kowalski, Joseph F., Murphy, Brian P., White, Richard P., "Advanced Dynamic Anthropomorphic Manikin (ADAM) Final Design Report," AAMRL-TR-90-023, Wright-Patterson AFB OH, March 1990.

6. Graf, P.A., Mohlman, H.T., "Techniques and Procedures Applied to Photometric Methods for the Analysis of Human Kinematic Responses to Impact Environments", AFAMRL-TR-80-61, October, 1980.

7. Department of Transportation, Part 572E Dummy Performance Calibration Test Procedure, Code of Federal Regulations.

A Standardized Motorcyclist Impact Dummy for Protective Device Research

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ABSTRACT

A specialized impact dummy for research into the feasibility of motorcycle mounted devices which are intended for protection of riders has been developed and is specified in ISO 13232. The ISO motorcyclist dummy specification is based on a Hybrid III dummy with modified capabilities and characteristics for comparative tests involving motorcycle/car impacts and considering the tendency for three dimensional dummy motions and forces. Special characteristics include: 32 channel internal data recording system; instrumented frangible upper and lower leg bones; three degrees of freedom frangible knees; helmet compatible head form; a neck torsional module; and other modifications to provide for motorcycle compatibility. Technical requirements and the research basis for the key components are presented and discussed, along with suggestions for possible future refinements.

INTRODUCTION

Over the last three decades, research into the feasibility of the rider crash protection devices has occurred in Great Britain, the United States, Japan and Germany. Such research has involved a wide variety of test methods and equipment, much of which was borrowed or adapted from the passenger car field.

A main element of such research methodology is the impact dummy. Recently, as car crash dummy technology has continued to advance and as the key factors in motorcycle impact research have emerged, more specialized dummies for use in motorcycle research have evolved. Specialized features of these have included, for example, frangible or crushable dummy legs, used to evaluate leg injury potential.

Recently, the need for different researchers worldwide to be able to evaluate the same or similar protective devices, and to get comparable results, has led to the need for a standardized motorcyclist research dummy.

This paper reviews the background and technical features and specifications of the motorcyclist dummy which has been standardized internationally in ISO 13232.

BACKGROUND

History

Use of anthropomorphic tests devices in motorcycle impact research has involved a wide range of devices borrowed or adapted from the automotive and aviation fields, including for example:

- Anthropomorphic manikin (Inuoe, et al, 1969);
- Alderson CG-50 dummy and parachutist dummies (Bothwell, 1971, et al op);
- 50th percentile male anthropomorphic dummy (Bartol and Livers, 1973);
- Modified Ito 3DGM-AM50-70 standing dummy (Uto, 1975);
- Modified Humanoid Hybrid II dummy (Tadokoro, 1985);
- OPAT 50th percentile male manikin (Chinn, 1981, et al op);
- Combined Hybrid II and Hybrid III standing dummy (Rogers, 1991);

In general, these devices which were developed for other purposes (eg, simulating restrained car occupants in frontal impacts) had limited means to assess some of the key factors in motorcycle accidents - for example, rider leg injury potential in lateral impacts - and also tended to have biofidelity characteristics which were specialized for their original intended function.

To try to account for such limitations, in some cases dummy mechanical or electronic modifications were made. For example, several means of assessing leg injury potential were attempted during the 1970's and 1980's, as reviewed by Sakamoto (1990), including various combinations of force measurement, on both rigid and breakable leg bones, and even

rectangular energy absorbing metallic honeycomb legs.

In 1986, the motorcycle industry proposed that further research was needed to obtain a basic understanding of actual rider leg injury mechanisms via accident analysis, and clinical and laboratory studies, with the goal being an improved dummy, dummy leg and overall methodology for motorcyclist secondary safety research (BPICM, 1986).

Work on several aspects of such secondary safety methodology proceeded in 1985, supported from within the industry. A progress report on some of this work (IMMA, 1988) described several interim efforts to upgrade the knowledge and technology base, and along with longer term efforts this included:

- Accident and clinical analyses, in an attempt to further elucidate leg injury mechanisms, and relevant impact test conditions;
- Development of several different approaches toward an injury indicating dummy leg (as also reviewed by Sakamoto, 1990);
- Development of a motorcyclist impact dummy;
- Development of injury indices and criteria applicable to riders;
- Development of a dummy internal data recorder (no external cables which can distort dummy motions); and
- Refined test procedures including impact conditions and measurement methods.

Subsequently, with regard to the dummy, these efforts led to a prototype Motorcyclist Anthropomorphic Test Dummy (MATD-1) (St. Laurent, et al, 1989; Newman, et al, 1991) which had some improvements in biofidelity with respect to motion and injury indication. These included:

- Instrumented, frangible, composite material femurs and tibias, with bending and torsional strengths and stiffnesses corresponding to human bones;
- Frangible knee ligaments in two axes (torsion and lateral bending);
- Internal 64 channel digital recording system in order to eliminate motion distortion caused by external cables;
- Modified head form (chin and neck areas) to accommodate a motorcycle helmet;
- Modified hands which allow gripping of the handlebars.

This prototype dummy was used in a series of leg protector feasibility evaluations (eg, Rogers, 1991b).

A number of refinements to this dummy were identified as desirable for evaluating the feasibility of head and upper body protective devices (eg, airbags) (Biokinetics, 1991; Gibson, et al, 1992). These were integrated to form the MATD-2 dummy prototype, which included, in addition:

- Several modified neck versions (summarized by Zellner, et al (1994)), in order to improve biofidelity (ie, reduced initial torsional stiffness) and increase the head and neck adjustment range to accommodate motorcycle riding positions;
- A more compact 16 channel internal recorder, in order to retain Hybrid III chest compression measurement capabilities;
- Additional head accelerometers to measure angular as well as linear head motions;
- A straight lumbar spine with improved biofidelity (decreased stiffness); and
- A frangible abdominal insert to record lower torso forces.

This dummy was used in a series of airbag feasibility studies (Zellner, et al, 1994).

An International Leg Protector Seminar (IMMA, 1992) resulted in the conclusion that a common internationally accepted motorcyclist dummy and methodology were needed before there was further progress in protective device research. This led through a series of steps (Van Driessche, 1994) to the drafting and approval of an International Standard for research methods applicable to motorcycle protective device research (ISO, 1996). The Standard was based upon existing technology and refinements of the MATD-2 dummy described previously.

Requirements for motorcyclist dummies

Comprehensive requirements for motorcyclist impact dummies had been previously compiled by Biokinetics (St. Laurent, et al, 1989a; Biokinetics, 1991). Each of these compendia comprise several hundred pages, which include reviews of the relevant biomechanics literature and compilations of detailed anthropomorphic and biofidelity requirements. Some

of the main requirements for motorcyclist dummies addressed include:

- Suitability for motorcycle/car impacts, which typically include relatively large rotations of the motorcycle during impact (yaw, pitch, and roll); relatively large, unrestrained motions of the dummy; dummy contact with rigid car structures; and therefore exposure of the dummy to many possible directions and locations of impact;
- Relation between human anthropometry and response, and existing, available ATD specifications and biofidelity (including anthropometry, geometry, range or motion, joint characteristics, biofidelity, flesh compliance, and mass characteristics);
- For the head, compatibility with helmets (which is not available in car impact dummies); and ability to sense both linear and angular motions related to brain injury potential;
- For the neck, as related to airbag research, the possibility of oblique, forced motion of the head, leading to asymmetric (eg, torsional) loading of the neck; the greater exposure of the neck to bag contact, due to the more extended orientation of the rider's neck in comparison to car occupants; and the need for a greater range of head and neck adjustment to accommodate various riding positions;
- For the chest, also as related to airbag research, biofidelity for and ability to sense forces acting on the torso;
- For the lower extremities,
  - ability to monitor for injury potential along the length and around the circumference of the femur and tibia;
  - stiffness and strength similar to human tibia, femur, and knee joints; and
  - in the event of bone fracture or knee dislocation, realistic dummy motions following failure;

  none of which are included in existing car impact dummies;
- Motorcycle compatibility, with respect to hand grips, foot pegs or rests, seats, realistic riding posture, and dummy stability on the motorcycle;
- Absence of external electrical cables, which can distort dummy motions;
- Repeatability and reproducibility;
- Durability, particularly with regard to use in motorcycle/car impacts;
- Repairability;
- Certification and calibration procedures;
- Instrumentation compatibility.

DESCRIPTION OF ISO 13232 MOTORCYCLIST DUMMY

Figures 1 and 2 illustrate the special mechanical and electronic features of the ISO 13232 motorcyclist dummy specification. The detailed geometric and/or performance specifications for each component is given in the Standard itself (ISO, 1996).

Following is a description of some of the main rationale and technical basis for each component.

Basis dummy

The basis dummy is the Hybrid III 50th percentile male dummy, with sit/stand construction, head/neck assembly compatible with the specified six axis upper neck load cell, and standard non sliding knees. The basis dummy components are modified or replaced as described in the Standard and summarized below.

As a result of a detailed review of the above requirements, the Hybrid III 50th percentile male dummy was identified in 1989 as being, on a worldwide basis, the most thoroughly researched, contemporary, biofidelic, well documented, available dummy as a starting point for a motorcyclist dummy.

The Hybrid III is, in effect, a public domain dummy specification (USA, 1993) and dummies which are intended to meet this specification are produced by several manufacturers and are available worldwide. A 50th percentile male dummy was considered to be appropriate for the target rider population.

The sit/stand (pedestrian) construction allows the dummy to be positioned on a conventional motorcycle. In the passenger car (sitting) version of the Hybrid III the upper legs do not rotate sufficiently with respect to the pelvis, in view of the large range of motion encountered in motorcycle impacts.

A head/neck assembly which is compatible with an upper neck 6 axis load cell is necessary in view of the potential importance of the neck in motorcycle airbag feasibility research.

Non sliding knees are specified because the passenger car occupant sliding knees tend to bind in

lateral impacts, which are relatively common in motorcycle impacts.

Special Mechanical Components

Motorcyclist dummy head skins - Head skin extensions are required because the standard Hybrid III head skin does not provide surfaces for the helmet retention strap (under the chin) or for rear helmet seating.

Neck shroud - A special neck shroud provides an appropriate reaction surface for external objects, in particular, for head protective devices such as airbags; and covers the exposed metal plates protruding from the standard Hybrid III neck. The standard Hybrid III neck may distort the interaction between the dummy and airbags because of its surface irregularities. A special neck shroud was needed because the commercially available shroud had significant "gapping," due to the wide range of head/neck adjustment, and due to the fact that it was stiffer than desirable.

Lower neck mount - A modified lower neck mount is needed to increase the range of neck extension adjustment so as to be compatible with typical forward leaning rider postures, which are different from typical semi-supine car occupant postures.

Motorcyclist neck - Recent research (Rogers, 1991c; Zellner, Newman, and Rogers, 1993, Ramet, el at, 1994) into motorcycle airbag feasibility has indicated that the potential exists for serious neck injury as a result of motorcycle airbag deployment. For example, the necks of out-of-position cadaver subjects were observed to be fractured by airbags deployed from the fuel tank region of a motorcycle. This may relate to the significantly different seating and airbag positions on motorcycles, as contrasted with cars and, in particular, the more fully extended angle of the head relative to the torso. For these and other reasons, it is considered to be very important to measure and to evaluate neck forces and moments in a realistic manner, in researching the feasibility of motorcycle airbag systems.

In order for such measurements and evaluations to be realistic, it is important that the dynamic response of the neck meet some minimum biofidelity requirements. The Hybrid III head/neck juncture was modified in order to incorporate improved biofidelity in the head/neck torsional response (Surowiak and Gibson, 1992). The modifications provided a closer match to published biomechanical response data described by Wismans and Spenny (1983) for volunteer torsion response and by Myers, et al. (1989) for cadaver torsion response.

The Hybrid III neck structure was modified to include a torsional element which allows the neck to respond similarly to the mean human neck response corridor shown in Figure 3. A two-phased response of the human neck would create a large increase in the design complexity. Therefore, the neck design target remained as a simple one-phased linear response with an initial ramp. This linear response lies substantially within the human response corridor and passes through the point of 110° rotation, 37 N·m + 3 N·m, - 4 N·m moment.

The example modified neck has mass properties which are different from those of the standard Hybrid III neck as indicated in Table 1. However, with the exception of the improved torsional response, the modified neck response has been verified to meet all Hybrid III response and performance envelopes. This indicates that the mass changes have had very little effect on the response of the head/neck assembly; and this would be even less so when a helmet is fitted to the headform, which is the case in the Standard.

Replacement nodding blocks - The initial alignment of the dummy head in pitch will affect the orientation of the head on impact with the OV. This impact orientation will also affect the response properties of the head/neck subsystem. The replacement nodding blocks, in combination with the modified lower neck joint, provide maximum adjustability for positioning the dummy head in an initial position which is as close to horizontal as possible, as defined by the procedure in Part 6 of the Standard.

Replacement thoracic spine - In general, a replacement thoracic spine box is needed which is compatible with the internal data acquisition system. It is intended that it maintain the same neck and lumbar structural attachment points and the same fore/aft sternum deflection capability as the standard Hybrid III component, and that it is compatible with standard Hybrid III ribs. A 120 mm width is specified as a boundary that would be compatible with at least one existing feasible design of an internal data acquisition system. With regard to mass and inertial

Table 1
Comparison of mass characteristics of the standard Hybrid III neck and the modified neck

	Standard	Modified
Mass, kg	1,173	1,881
Mass, including head and upper neck load cell, kg	5,194	5,903
Center of gravity height above base, mm	68,7	94,5
Moment of inertia: whole assembly (head, neck, and load cell), kg·m^2	0,188	0,246
Moment (≡ ^{nt} to 1 g) whole assembly about upper torso, N·m	9,68	11,83

properties, the Hybrid III specification only specifies mass and cg location for the upper torso assembly as a whole. The mass, cg, and moments of inertia of the spine box assembly are not specified and may vary as long as the upper torso mass and cg specifications are met. The existing feasible design of an internal data acquisition system meets the Hybrid III upper torso mass and cg requirements.

Modified chest skin - A slightly modified chest skin is required to allow use of the upper torso inclinometer, specified in Part 6 of the Standard, in order to measure the upper torso angle during motorcycle test set up.

Modified straight lumbar spine - A modified straight lumbar spine is required in order to: provide an upright seating position on a motorcycle; be compatible with the Hybrid III total height specification; provide proper biofidelity with respect to published human force-displacement properties; provide a mounting system for the abdominal insert described below; and provide appropriate weight for maintaining the proper Hybrid III center of gravity and mass. The static moment vs. thoracic angular displacement curve of this modified lumbar spine and cable assembly falls within the corridors for human volunteers (Melvin and Weber, 1985) as shown in Figure 4.

The lumbar load cell simulator is specified in order to provide the proper lower torso dimensions and weight when the optional lumbar load cell is not used.

Motorcyclist dummy abdominal insert - The frangible abdominal insert is based upon research by General Motors (Rouhana, et al., 1989). It allows quantification of potential abdominal injuries as a result of penetration into the polystyrene material. Compared to the original Rouhana design the specified component is of single piece construction without fins (which would not be biofidelic in lateral impacts), and has twice the force/deflection stiffness of the original design, in order to account for the space available in the dummy lower thorax. The very light mass lies within the limits of the Hybrid III mass and center of gravity specifications. The specification of a test method provides a performance standard for this component.

Sit/stand pelvis - Part of the internal data acquisition system may be contained in the pelvis, and if so, then the requirement is that the listed Hybrid III sit/stand pelvis characteristics remain unchanged. Note that the pelvis moments of inertia of the Hybrid III itself are not specified, and may vary within and among Hybrid III manufacturers.

Modified elbow bushing - The Delrin elbow bushing requires a score mark on the outside diameter to indicate the position for an elbow angle of 10°, required for motorcycle test set up, as specified in Part 6 of the Standard. This prevents over center locking of the elbow joint, which would distort dummy torso motion.

Motorcyclist dummy hand components - The special dummy hand components are necessary in order to provide realistic seating position and dummy-to-handlebar force properties. The hands are anthropomorphic and are constructed of deformable aluminum wires covered with a silicon skin material. They are designed to wrap around the hand grips as described in Part 6 of the Standard; to hold the dummy in position in a realistic manner during the run up to impact; and to allow release of the hands under inertial loads after impact.

Frangible femur bone and mounting hardware - Frangible leg bones which have human-like stiffness and strength are necessary in order to provide: human-like (biofidelic) impact force magnitudes up to the fracture level; human-like trajectory after fracture; and continuous monitoring for fracture potential along the length and around the circumference of the bone. In

addition, such a bone should have adequate repeatability and be compatible with the mechanical, geometric, and mass properties of the crash dummy. The ability to measure, electronically, the loads at several points should be included, not as an injury indicating means (for which such electronic sensors are inadequate, as discussed below), but as a means to trace sources of fractures.

For these reasons, frangible leg bones have been utilized in past and current motorcyclist and pedestrian research (Uto, 1975; Nyquist, et al., 1985; Tadokoro, et al., 1985; Miyazaki, et al., 1989; Sakamoto, 1989; St. Laurent, et al., 1989a; Newman, et al., 1991; Rogers, 1991a; Gibson, et al., 1992; Mayer and Hochgeschwender, 1993). These have varied in their material composition and the axes in which they simulate human bone stiffness and strength. The bones incorporated in the Standard are the composite bones described by St. Laurent, Newman, Rogers, and Gibson, cited above.

Leg bones for car crash dummies are rigid and non-frangible (e.g., the metal bones used in the Hybrid III dummy). These are inappropriate for motorcycle crash research because:

- They were designed for a different purpose and crash environment. In particular, Hybrid III leg bones are intended for frontal impacts, usually to the knees, against padded or relatively deformable car interiors, with a dummy which is usually restrained by lap and torso belts and/or airbag. Motor cyclist legs can be exposed to multiple frontal and lateral impacts to the knees, lower and upper legs; the impacted objects are often rigid; and the rider is typically not restrained.
- Mid-span impacts to a fleshed metal Hybrid III lower leg bone with a rigid impactor result in greatly distorted (i.e., magnified) forces, compared to those recorded for a human cadaver lower leg or the feasible frangible lower leg design (see Figures 5 to 9). This rigid/rigid interaction can result in more than 100% overestimation of impact forces, and therefore, of fracture potential.
- The fact that the metal leg bone does not fracture can, in some cases, distort the dummy motion compared to the motion with frangible human or dummy leg bones. This distortion was measured by Tadokoro (1987) and Miyazaki, et al (1989). Another occurrence of this is illustrated in Figure 10, which is from an Articulated Total Body three-dimensional computer simulation of an impact to the rider's knee by the front corner of a car, with and without frangible femur and tibia leg bones, with characteristics as defined in the Standard, with all other parameters held constant. As can be seen, there are large differences in the head, shoulder, hip, knee, and ankle trajectories when frangible vs. non frangible bones are used. This large difference in trajectory is verified by the full-scale test pelvis trajectory results shown in Figure 11, for an offset frontal impact with Hybrid III legs and with composite frangible leg bones, as defined in the Standard.
- Force monitoring with load cells only measures the loads at the specific load cell location, and not at other potential fracture sites. This may be suitable for monitoring knee frontal impact in cars; but is not adequate for the multiple impacts and impact directions in motorcycle crash tests. This method can result in underestimation of fracture potential in many cases. An example is the three point loading impact to the lower leg, illustrated in Figure 12. The lower leg is supported near the upper and lower tibia load cells, while the 50 kg mass impacts the mid tibia. A practical example of this would be an impact to the mid tibia by a car bumper, while the lower leg is resting against the fuel tank at the upper end and engine case at the lower end. The sensed loads indicate little or no bending moment applied to the bone, whereas in fact, the loads are sufficient to fracture human or frangible dummy leg bones. The result is a nearly 100% underestimation of the bending moment, and therefore, injury potential.

The composite femur and tibia bones, geometry and performance requirements which are given in the Standard, have been validated against the Yamada (1970) and Martens, et al. (1980) cadaver data, as well as more recent cadaver testing. For example, Figure 13 shows mid tibia impactor force for three point dynamic tests with a sample of nine wet tibia specimens (mostly 55 years and older) as reported by Fuller and Snider (1989). As is typical, there is considerable scatter in the responses, but for most of the specimens, the fracture pulse is over within

0,001 s. Figure 14 shows envelopes which bound the time responses for all nine specimens and for the weakest six specimens (after correction for support length variation). Also shown are impactor force time histories for two composite tibia bones. The latter show:

- A high level of reproducibility;
- A waveform which is similar to the envelopes for the cadaver data, and which lies between the weaker and the stronger specimens (closer to the stronger specimens). This is not unexpected since the design target, as noted below, was the young adult male cadaver properties described by Yamada (1970).

Another validation example is shown in Figure 15, which is a two point (i.e., pivoted at the knee) impact test with fully fleshed wet cadaver lower leg, and fully fleshed composite dummy bone lower leg. Again, the time history waveform is similar; and the composite bone forces are somewhat larger than those for the embalmed and approximately 60 year old cadaver specimen.

The conclusion of the above is that frangible leg bones which have human like stiffness and strength are appropriate for use in motorcycle crash research; and standard Hybrid III rigid leg bones are not appropriate for use in motorcycle crash research.

The mounting of the frangible femur bone and the specification of its mass are intended to provide compatibility with the remaining Hybrid III leg components.

Static and dynamic performance tests are specified for leg bone design certification and quality control purposes. Of these procedures, the dynamic laboratory tests provide conditions which are most relevant for the leg bone's intended use, while the static measurements are more convenient to perform.

The characteristics which are specified for the femur are bending, torsion, and axial characteristics, as these are the types of loads which have been observed in past motorcycle impact testing and in motorcycle clinical studies. The specified static and dynamic properties are for an existing feasible leg bone design which is consistent in its characteristics with the published biomechanical data, as defined below. The specified values are provided as references in order to standardize dummy component performance to those achieved in one feasible design. The feasible design is based upon (and achieves to within a few percent) published biomechanical data.

The biomechanical data for bending strength and stiffness are based upon data reported by Yamada (1970), measured by Motoshima (1960). The static bending deflection is based on static measurements of a sample of young adult male cadavers. The dynamic bending strength of the femur is also based on the Motoshima statically measured young adult male samples increased by a factor of 1,4 to account for dynamic stiffening. The 1,4 factor is based upon a literature review by St. Laurent, et al., (1989) which included the available biomechanical data of McElhaney (1966) and others. The static torsion deflection is based on the work by Martens, et al. (1980). The dynamic torsion strength is based on the Motoshima statically measured young adult male samples increased by a factor of 1,4, again to account for dynamic stiffening.

For axial loading, the upper leg stiffness and strength properties are heavily dependent on the bending properties, due to the presence of eccentricity in the human and dummy hip joints. The static axial peak strength is specified so as to maintain consistency with the available biomechanical data and also to assure similarity to the existing feasible leg bone design.

Femur load cell simulator - This component is specified in order to provide for proper leg dimensions and weight when the optional femur load cells are not used.

Motorcyclist dummy frangible knee assembly - A frangible knee assembly has been specified in order to monitor for knee ligament injuries in lateral bending and torsion relative to the tibia (M_X, M_Z); to provide for appropriate knee joint rotations and dummy motions when the lower leg is restrained; to provide appropriate forces and structural "fusing" between the lower and upper legs (i.e., realistic rotations and moments); and to be compatible with existing biomechanical data (St. Laurent, et al., 1989). In addition, prior research (Tadokoro, et al., 1985) had indicated the potential for large torsional loads in the femur. The frangible knee was intended to provide enhanced biofidelity in this regard.

The frangible knee assembly has been specified to be compatible with the remaining Hybrid III leg components and masses.

Static tests are used to confirm knee designs and provide quality control for frangible knee components because the existing biomechanical data is static in nature. The prefailure and at failure moment and rotation values for valgus (lateral bending) and torsion are based on cadaver measurements (St. Laurent, et al., 1989), and upon the measured properties of the existing feasible knee design which are consistent with these biomechanical data.

For this frangible knee concept, a failure of an internal shear pin is interpreted as an injury of the respective knee ligaments. "Prefailure" refers to a loaded condition prior to fracture of the shear pin.

Leg retaining cables - Retaining cables are necessary to prevent the separation of dummy legs from the dummy upon fracture of the frangible element. Loss of a leg during a test could affect overall dummy motion. Traumatic loss of a limb is a rare event in accidents, and in any case the dummy leg does not otherwise have sinew, muscle, and other tissues which retain the limb. The cable has a weight limit and is installed with slack so as not to affect the fracture force of the bone itself.

Frangible tibia bone and mounting hardware - The same considerations apply here as in the case of the frangible femur bone and mounting hardware noted above, with the exception of the tibia axial characteristics, as these were judged to be unimportant for typical motorcycle impact situations. For both the upper and the lower leg bones, the specified static deflections are approximately 50% of the deflection at peak strength, to provide a measurement in the linear material behavior range. The static and dynamic characteristics of the tibia bones are based upon the corresponding Yamada (1970), Martens, et al., (1980) and McElhaney (1966) data for tibia bone samples.

Modified lower leg skin - Modified lower leg skins are specified in order to provide for installation and removal of the skin from the frangible leg bones, which is not feasible with the standard Hybrid III leg skins. The internal contour of the leg skin has been modified to conform to the frangible knee assembly. The masses are consistent with the standard Hybrid III specification.

Sampling of frangible components - The purposes of frangible component sampling and measurement are to: allow for performance specification of potentially different frangible component designs and to ensure that the variability in frangible components is controlled to a feasible minimum.

Initial conformity of production - A sample of 10 frangible components is specified because this is the approximate minimum number needed to establish a usable mean and standard deviation. Since the tests are destructive in nature, separate samples of 10 are needed for each characteristic. A relatively tight bound of 5% for the sample mean for specified strengths (and abdominal insert static forces) is given because these values are crucial in injury assessment. Also, this number is relatively small compared to run-to-run variability in other dynamic measurements such as maximum resultant head acceleration, for example. A broader range of 20% for the static deflections is specified because these values affect injury assessment in a more indirect manner. Likewise, a relatively tight specification on the allowable standard deviation is given in order to control variation of leg samples used in evaluating injuries. A standard deviation less than 7% of the sample mean is specified for all strengths (and abdominal insert static forces) and less than 10% for all static deflections because this reflects the relatively tight bounds that have been achieved with the existing feasible designs. Data in the Standard indicate that the feasible designs of the femur, tibia, abdominal insert and knee compliance elements meet the criteria.

Subsequent conformity of production - The purpose of the subsequent conformity of production (CoP) tests is for lot checking and quality control of components, once the bone design, material, and manufacturing processes have been certified by the manufacturer. Here a compromise between the cost of quality control sampling and the reliability of the sampling process has been reached. For typical past production runs of 30 to 60 bones, a sample of three bones represents 5% to 10% destructive sampling, which is relatively costly. For a sample of three bones, assuming a normal distribution and the same mean, it would be expected that one of the bones would exceed one standard deviation in its properties. Therefore, if none of the components deviates by more than two standard deviations (14%) the lot is considered to be normally distributed and acceptable for impact testing. If one or more of the samples deviates by more than two standard deviations, this exceeds the bounds of a normal distribution, and a larger sample is then used to improve the reliability of

the estimate. This involves three more components from the same lot. Then, again, if one third of the total test sample (of six components) deviates by more than two standard deviations from the established means, the lot is considered to exceed the bounds of a normal distribution with the specified standard deviation and is rejected for full-scale impact testing purposes.

Electronic Configuration

The electronic configuration of the ISO 13232 dummy includes:

- Up to 31 required, electronically recorded variables (including 5 required for head protective device research and 10 required for leg protective device research);
- Up to 25 additional, optional, electronically recorded variables;
- A recommendation not to record chest and pelvis accelerations;
- Sensor specifications for the required and optional variables;
- Internal data acquisition and recording system specifications; and
- Data reduction requirements.

The following summarizes some of the features and rationale for these.

Electronically recorded variables (required) - Nine linear accelerometers are used to measure head linear and angular accelerations, according to the method developed by Padgaonkar, et al (1975). This involves a triaxial central sensor and three biaxial sensors aligned with each of the triaxial axes.

The nine variables from the sensors are arithmetically combined to produce three linear accelerations and three angular accelerations. The six components are then combined to calculate the head injury indices described in Part 5 of the Standard.

Chest upper and lower sternum displacement relative to the thoracic spine box is recorded to enable calculation of the chest compression and chest velocity compression as defined in Part 5 of the Standard. Left and right triangulated displacements are sensed. This has several advantages. First, it enables installation of the frangible abdominal insert which would normally interfere with the location of the standard Hybrid III rotational potentiometer in the lower thorax. Second, placing the potentiometers on either side of the spine box allows for full travel of the sternum plate. Third, the use of separate left and right measurements allows for later analysis of asymmetric sternum displacement, although this effect is not currently included in the chest injury indices.

The measurement of upper and lower displacements allows the worst values from the two potential injury sites to be used in calculating injury costs.

Five neck forces and moments are recorded for head protective device evaluation to enable evaluation of neck injury indices. The forces and moments are sensed in the region of the atlanto-occipital juncture. The neck lateral flexion moment ($M_{x,n}$) is optional due to the lack of an injury criterion for this variable at the time of the drafting of this International Standard.

Three upper femur forces and moments are recorded for each leg for leg protective device research. These are not directly used in injury prediction but are used to help trace sources of frangible leg damage. The lateral and antero-posterior bending moments are recorded because these are the primary likely axes of femur failure based on past tests and clinical data. The axial force is also recorded because this can contribute to potential bending failure for the upper leg. Also, torsion moment is optional because the femur tends to be isolated in torsion by the hip ball joint and varus degree of freedom at the knee.

Two upper tibia bending moments are recorded for each leg for leg protective device research and as with the upper femur, variables are used primarily to trace sources of potential bone fracture rather than as an injury index.

The lateral and antero-posterior bending moments are recorded because these are the primary likely axes of tibia failure. Additional tibia and femur forces and moments may be recorded as permissible variables, as described below.

Not recommended variables - It is recommended that chest acceleration not be recorded in Motorcycle impact research tests, because for rigid, distributed, three dimensional impacts to the motorcyclist dummy, these measurements are potentially misleading and could result in erroneous conclusions. Existing chest acceleration criteria evolved from early, simplified studies of dynamic effects on injuries. Chest acceleration criteria assumed that the thorax acts as a

rigid body subjected to whole body decelerations. The limitations associated with the application of these criteria and associated measurements include: a lack of sensitivity to impact location, i.e., accelerations registered in the thorax cannot be isolated from load paths through the knees, legs, pelvis, hips, shoulders and head; dynamic force amplification due to rigid impacts to the exposed rigid Hybrid III shoulder; the inability to account for the effect of chest deformation on injury causation; and the over sensitivity of the criterion to the impact test set up.

Likewise, measurement and recording of pelvic accelerations are considered to be potentially misleading in the case of motorcycle impacts, and therefore, are not recommended. Early pelvic acceleration criteria were based on whole body motion concepts. They did not consider rigid impacts to the ischia and other pelvic structures to which motorcycle riders may be exposed; nor did they consider the gross differences in stiffness between the human pelvis and the cast aluminum Hybrid III pelvis. The human pelvis is relatively flexible, with the deflection at fracture being as much as 50 mm in some regions. The Hybrid III pelvis, on the other hand, is metallic and essentially rigid, and this results in dynamic force amplification (compared to forces on cadavers) when it is contacted by other rigid structures not typically found in car frontal impacts, but quite common in motorcycle multi-directional crashes. This force amplification is potentially misleading, and could result in erroneous conclusions.

Permissible variables - The permissible variables are, in general, those variables for which injury criteria were not available at the time of the drafting of the Standard, and/or which may supplement the required variables for purposes of tracing potential injury sources. They include: all six axes of upper neck forces and moments; the six axes of lumbar forces and moments; and the forces and moments acting on the femur and tibia, which may be useful, for example, for tracing the sources of leg fractures.

In general, the lower femur and lower tibia variables are permissible rather than required because they are in the frangible region of the respective bones. This requires the use of strain gauges which are destroyed in the fracture event. The upper tibia sensors are also in the frangible region, but are required for leg protective device evaluation because they give some general indication of loads and timing of loads occurring at the knee and also at the upper tibia.

Head accelerometers - The specified accelerometers are compatible with the defined accelerometer mount and with the interior space, measurement range, durability, and accuracy requirements of the specified head form. The specified accelerometer mount is compatible with the space limitations of the Hybrid III head form. The spacing and alignment of the nine accelerometers need to be standardized to ensure that the same angular accelerations and similar signal-to-noise ratios are measured for the same inputs, at all test facilities. The spacing and skewed alignment with respect to the head axes give minimum cross axis sensitivity across the full range of angular motions encountered.

Upper neck load cell - The specified sensor is compatible with the special Hybrid III head form and upper neck mounts and with the accuracy, ruggedness, range, and cross axis sensitivity requirements of the Hybrid III dummy.

Chest potentiometers - The standard Hybrid III rotary chest displacement transducer has been replaced by a chest deflection instrumentation assembly. This assembly consists of four string potentiometers, an upper one and a lower one, on either side of the thoracic spine box of the dummy. The use of this array is compatible with the provision of the load sensing abdomen, as the mounting brackets for the frangible abdominal insert preclude the use of the standard Hybrid III displacement transducer.

The string potentiometers are Space Age Control, Inc. 160-321V units which are specially modified for use in measuring rib deflection in frontal impact testing and have a maximum response rate of 1,5 m/s ± 0,5 m/s at a tension of 15,6 N. In this application this rating is further increased by the angled mounting of the potentiometer strings. As a result, a sternal velocity of up to 13,5 m/s (which is equivalent to a chest impact velocity of 50 km/h) is able to be measured.

Chest impact tests at an impact speed of approximately 3 m/s were conducted with both string pots and the original rotary pot installed in the chest of MATD. The results indicated that there was no apparent phase difference in the response of the string pots as compared to the rotary pot.

Lumbar load cell - The specified sensor is compatible with the special straight lumbar spine

assembly and with the accuracy, range, ruggedness, and cross axis sensitivity requirements of the Hybrid III dummy.

Upper femur load cells - The specified sensor is specially designed for the motor cyclist dummy and has a much smaller outer diameter than the standard Hybrid III upper femur load cell. This is to help reduce rigid/rigid interaction with impacting structures and the resulting force magnification that may occur. Such magnification due to direct sensor impact may still occur, but it is less severe than with the standard load cell. Otherwise, the specified load cell is compatible with the geometry, accuracy, range, ruggedness, and cross axis sensitivity requirements of the frangible femur bones and Hybrid III leg components.

Frangible leg bone strain gauges - The locations for the femur and tibia strain gauges are specified in order that comparable measurements will be made by different test facilities. The specific gauge and installation details are also specified because these will influence the accuracy, drift, and comparability of measurements made at different test facilities. The specifications lie within what is considered common strain gauge practice.

Internal data acquisition and recording system specifications - An internal data acquisition system is used in order to prevent distortion of dummy motions which can be caused by external electrical cables. Past test experience indicates that such cables can influence test results by: applying forces to the dummy (due to cable inertia, or to catching on other objects) which may vary in amplitude and direction; impacting the dummy itself, during various phases of the crash test; wrapping around various dummy appendages; increasing the likelihood of data dropouts due to connector disruption; or obstructing photographic camera views and film data acquisition. Long cables (e.g., 30 m) typically require special impedance matching. Internal data acquisition systems are feasible and available for this type of application and a 32-channel unit has been used in motorcycle crash tests.

Data acquisition - Thirty-two channels were considered to be a minimum requirement in order to record up to 28 required variables and permissible variables which may be of interest.

A sampling rate of 10 kHz represents common practice for motorcycle crash testing; is compatible with the existing feasible internal data acquisition system; gives adequate frequency response on all signals including those which may have transients in the 0,001 s region (such as leg force or head acceleration); and is compatible with signal processing procedures defined in ISO 6487 (2987).

Sensor excitation - The excitation voltages of the sensors are specified in order to avoid problems associated with low signal-to-noise ratios and signal shifts due to self heating. The values cited are nominal values within the ranges of the devices, and are intended to standardize the performance of the sensors.

Anti alias filtering for digital systems - Sampled data can be distorted by high-frequency transients which are aliased (or "folded about") the Nyquist frequency (half of the sampling frequency). Anti-alias filtering is intended to reduce such distortion. This is especially important when peak measurements are being used for injury assessment.

ISO 6487 does not address the issue of anti-aliasing.

The specified attenuation by at least 40 dB is consistent with SAE J211 (1988), which requires less than 1% aliasing at the frequency of interest (F_h, typically 1 000 Hz).

The specification of "at and above a frequency of 7 kHz" extends the SAE recommended anti-aliased frequency range from 1 kHz up to 3 kHz (i.e., "above 7 kHz" folds about the Nyquist frequency of 5 kHz, to correspond to "less than 3 kHz"). This is desirable since SAE J211 (1988) allows aliasing to occur at any frequency above F_h, and this can significantly distort the data analysis (i.e., selection of maximums). In the specified requirement, aliasing may occur above 3 kHz, however, this will be greatly attenuated by subsequent band pass filtering per ISO 6487 (1987), which is defined under data reduction requirements and which is for a different purpose. Therefore, the requirement here is for a certain minimum level of anti-alias filtering before digitizing, in addition to band pass filtering after digitizing.

Analog to digital conversion specifications for digital systems - The specified maximum inter-channel skew is compatible with the characteristics of the existing feasible 32-channel internal data acquisition system, and lies well within the ISO 6487 (1987) requirement. The minimum resolution of eight bits corresponds to 0 to 256 counts, or in other words, a

resolution of better than 0,4% of range through the analog to digital conversion system. The physical resolution is also related to the scaling of variables specified in the Standard. The resolution was found to be within the U.S. DOT NHTSA Evaluation Test System requirements based upon testing with the existing 8-bit system (per the test system used by Radwan and Nickles, 1991). The latter test system incorporates the requirements of SAE J211 (1988) and ISO 6487 (1987) and also, in effect, requires a minimum 6,5-bit resolution. The specified gain sensitivity to temperature is consistent with the existing feasible data acquisition system.

Storage capacity - The minimum required storage capacity of 3,1 s is consistent with the measurement period specified. This allows for 0,100 s prior to impact in order to synchronize the electronic data with the film data, and to establish zero reference levels; and 3 s after impact, which is a time period within which all dummy motions and signals generally become quiescent.

Mechanical specifications for the internal data acquisition system - The interior volumes of the thoracic spine box and the modified sit/stand pelvis are two regions of the dummy which do not house other required equipment or directly influence the force/deflection (biofidelity) characteristics of the dummy. As such, they provide available space for the data acquisition system. The upper torso and lower torso component masses and centers of gravity are to remain the same as those of the standard Hybrid III in order to ensure minimum change from the properties of the known dummy and in order to standardize the motorcyclist dummy masses. The mass and center of gravity of the thoracic spine box per se, and all of the moments and products of inertia of the thoracic spine box, upper torso, and lower torso components are unspecified in the Hybrid III specification itself, and may vary. However, the moments of inertia of the motorcyclist dummy upper torso which incorporates the existing feasible data acquisition system are very close to those of one example, measured, standard Hybrid III upper torso.

The mechanical shock specification is included in order to help ensure that the system accurately records data when subjected to an impact typical of those encountered in motorcycle crash testing. This is consistent with the specification for the existing feasible data acquisition system. The specific conditions are those which are met by one feasible device (White and Gustin, 1989).

Scaling of variables - The recording ranges are standardized so that all facilities use the same dynamic range and have a basis for having similar resolution for all recorded channels. The values specified involve a compromise between over-range, on the high end, and resolution, on the low end. The proposed values correspond to approximately 130% of the maximum assessed injury levels for each body region as specified in Part 5 of the Standard for the head and torso, and in Part 3 of the Standard for the leg forces and moments; or the maximum likely recorded signals, based on past test experience. To record larger ranges is considered unnecessary, from an injury assessment viewpoint, and degrades the minimum resolution on the low end.

This also provides a common basis for reporting (plotting) time history results in Part 8 of the Standard, so that the plotted ranges correspond to the recorded ranges. This facilitates interpretation of the data.

Electronic data reduction - "Data zero" can be defined by averaging the data at 0,001s increments beginning 0,050 s before "time zero" because any steady state forces, movements, or accelerations prior to first MC/OV contact can be considered to be negligible. Three significant figures are used because this is consistent with the accuracy of the electronic sensors and the overall required precision of the measurements. The division of the data into primary and secondary windows is intended to facilitate data plotting; and in general to differentiate between effects which tend to be related to opposing vehicle OV contact (primary) and effects which tend to be more related to ground contact (secondary). The definition of electronic file content is intended to enhance data exchange.

Computer code for calculation of head linear and angular accelerations - A standardized code for angular and linear acceleration computation, based on data from the nine accelerometer array, is specified so that all laboratories will use the same computational algorithms, because such transformation techniques can be subject to numerical conditioning issues. The particular algorithm used was provided by a Canadian government agency, DCIEM, and it is understood to be based upon an Association Renault-Peugeot algorithm. The algorithm has had several enhancements and modifications, and was calibrated by

Dynamic Research using a three dimensional ATB MC crash simulation. The latter indicated that the nine accelerometer algorithm reproduced the angular accelerations to within 0,1%, and the linear accelerations to within 2,5% of the exact values at the head center of gravity.

Other Equipment

Helmet - The specified standard helmet is a Bieffe B10, either small (56 cm) or medium (58 cm). The Bieffe B10 helmet represents a widely available full face motorcycle helmet. It is manufactured to relatively narrow performance specifications. When it is impacted at ambient conditions according to the procedures described in ECE Regulation 22-03, at a position 275 mm $\pm$ 50 mm above the brow, centered on the mid-sagittal plane, upon a flat steel surface, the test head form maximum resultant acceleration falls between 170 *g* and 190 *g*. It is injected molded with polycarbonate. The liner is produced from expanded polystyrene bead foam with a density of 53 g/dm^3 to 57 g/dm^3.

A full face motorcycle helmet is used for two reasons. Firstly, this style of helmet represents approximately 85% of those manufactured worldwide. Secondly, the provision of protective coverage to the mouth and chin region of the Hybrid III head form eliminates concern that this part of the head form is not particularly biofidelic. The distributed loading to the dummy face that is induced by the helmet minimizes inappropriate contact phenomena.

The stipulation of the helmet according to ECE Regulation 22-03 insures that it will be generally available in the future. At the time of the drafting of the Standard, ECE Regulation 22-03 was the most widely accepted international regulation for motorcycle helmets.

The helmet size is specified as that which fits an ISO size J head form in order to be compatible with the Hybrid III head form; and to ensure a proper fit, which affects the dynamic measurements made in a full-scale test.

The mass of the J helmet was measured to be 1,387 kg. The mass of the M helmet was measured to be 1,417 kg.

The helmet is specified as new because the helmet liner will tend to be damaged in an impact test, changing and degrading its dynamic properties.

The same make, model, and specification helmet is required for all tests to control the amount of variation in the dynamic measurements due to this variable.

Clothing - The Standard specifies clothing and boots to be fitted to the dummy. It is desirable to provide clothing which provides some degree of abrasion protection to the exterior dummy surfaces; which can enhance the high speed photographic imaging of the dummy body regions; and which is sufficiently form fitting to enable mounting of adhesive photographic targets. Long sleeved, close fitting thermal knit underwear provides these functions. Some holes need to be cut in the clothing to allow access to dummy joint adjustments and position measurements.

It is desirable to fit the dummy with boots which provide: some protection of the dummy outer surfaces in order to enhance dummy durability; realistic motorcycle foot apparel; foot apparel which will tend to stay on the dummy during violent impact motions; a boot heel which will tend to stabilize the foot and lower leg on a motorcycle foot peg; and a standardized, relatively light weight (racing type) mass insofar as the boot mass may affect lower leg motions and forces. The specification of a relatively light weight also tends to preclude use of boots which may mechanically reinforce the lower leg region, thereby distorting leg injury assessment. Within a paired comparison the same make, model, and size boot is required so as to eliminate differences which may result from boot geometry, stiffness, strength, or fit.

Usage

Calibration - Calibration tests of the type applicable to the Hybrid III dummy are needed in order to verify that the head, neck, thorax, and knee components have not been mechanically degraded due to test usage, in order to maximize repeatability, reproducibility, and biofidelic response between tests and test facilities. The head, neck, thorax, and knee impact calibration tests are the applicable ones.

The number of full-scale tests between calibrations was selected to be 10, which is a compromise between test quality control and test efficiency and cost. In particular, it is desirable to perform several full-scale tests during one test day, and this tends to preclude calibration tests with the same dummy. Based on

experience and in general, the amount of physical degradation to the helmeted head, neck, mid-sternum region, and knee tends to be limited, over a series of ten or so tests (although damage to other dummy regions may be severe). Reporting of the calibration information is considered to be desirable from a quality control standpoint.

Sensor, data acquisition, and post processing systems verification - Some means for verifying the proper functioning and scaling of the required dummy sensors and data acquisition system, prior to each test, is highly desirable. Past motorcycle impact tests have involved situations where apparently: sensors have been noisy or broken; improper filtering has occurred; and improper scaling of sensor signals has occurred, in some cases, by an order of magnitude. These errors, in some cases, have affected the published data and conclusions which are based upon those data.

Prior to each test, a standard impact to the dummy head is used to generate response "signatures" for the nine head sensors. These signatures are to be included in the test documentation and, by comparison with signatures from previous verification tests, provide a means for verifying, approximately and retrospectively, the proper functioning of the entire data acquisition system (including sensors, gains, filtering, dummy response, recording, playback, scaling, and plotting). Such a procedure may also be of use at the time of the test setup, in order to detect hardware or procedural defects, and to enable appropriate countermeasures to be taken.

Joint tensions and position on motorcycle - Dummy joint tensions, if not set to be within certain bounds, can tend to have an adverse effect on: the stability of the dummy on the free rolling motorcycle as it is subjected to shocks from the roadway and trolley release systems; and motions of the dummy limbs and body regions after impact. A standardized dummy position is also necessary as this may greatly affect the dummy motion and injury data after impact.

Detailed procedures for joint tensioning, positioning on the motorcycle, and helmet and head/neck alignment are specified in the Standard, along with rationale.

Ambient conditions - The dynamic response of the Hybrid III dummy is known to be temperature dependent, and as a result, very tight tolerances (21,4° C ± 0,8° C) have been placed on its use in car regulatory testing (U.S. DOT, 1991b). In general, it is also desirable to control temperature in motorcycle testing. However, for motorcycles, there are a number of factors which make very tight control less important and/or more difficult to achieve. These include:

- The research nature of the Standard;
- The prevalence of large scale, outdoor test facilities for motorcycle/car, moving/moving, angled impact tests;
- The desirability of all-season testing;
- The exposed position of the rider (in contrast to a car), which makes temperature control more difficult;
- The wide variations in climate and seasonal variations, internationally (e.g., motorcycle impact tests often occur in the range of 0° C to 45° C in various facilities in North America);
- The wide variety of facilities used for dummy storage and preparation before a test (heated or air conditioned tents, bags, sheds and buildings; blowers; and various areas for dummy assembly, calibration, joint adjustment, verification tests, etc.);
- The likelihood of test delays, where the dummy may be on the motorcycle, in an exposed area, waiting an unpredictable amount of time, for test readiness;
- The lower relative importance and magnitude of chest injuries and deflections (which is the most temperature sensitive factor in the Hybrid III dummy) in motorcycles as compared to cars;
- The limited time window generally available for testing at a given facility;
- The need for a simple procedure.

As a result, there are two main aspects of the temperature requirements for motorcycle testing:

- Definition of an allowable temperature range;
- Temperature soaking procedures, to keep the internal dummy temperature in the allowable range at the time of impact.

The tight temperature tolerance required in car testing with the Hybrid III is related to chest response properties; however, it is unknown at this time what the specific response error tolerance was which corresponds to the ± 0,8° C band selected by NHTSA

(e.g., it might have been ± ½% on chest acceleration, which is not so relevant for motorcycle testing). In view of all of the above factors, a somewhat wider error tolerance for temperature is acceptable for a motorcycle research standard.

While data on the thermal response sensitivity of the Hybrid III was not obtained, data for the Hybrid II (Part 572), presented by Volkswagen (Seiffert and Leyer, 1976) may be representative, since the two dummies share many of the same components. The tightest temperature bands (i.e., highest thermal sensitivity) for a ± 5% response error are for the head form drop test, the abdominal insert and the thorax. So, if a ± 5% error tolerance was accepted for these variables, relatively tight temperature tolerances would be needed. However, it is suggested that these variables should not be the determining factors for motorcycle tests, because:

- The motorcyclist headform is helmeted, and does not strike rigid surfaces;
- Thoracic and abdominal injuries are relatively infrequent in motorcycle accidents, and the typical deflections in motorcycle impact tests are very small (e.g., 10 mm, where 3% of 10 mm is only 0,3 mm, which is negligible).

Instead, the next tightest temperature band is for ± 5% HIC error, which corresponds to ± 8° C. This is for a whole dummy test, and for a response variable (HIC) which is included the Standard. This is the error criterion, expressed as:

$$\text{range} = 21{,}4°\,C \pm 8°\,C = 13{,}4°\,C \text{ to } 29{,}4°\,C$$

which has been rounded off in the text of the Standard, for convenience of use.

AVAILABILITY

A list describing one or more example products which may meet the Standard is maintained by the ISO Central Secretariat and the Secretariat of ISO/TC22/SC22. The list is maintained for the convenience of users of the Standard and does not constitute an endorsement by ISO of the products listed. Manufacturers of dummies or dummy components may request that their products be added to the list, after filing a proprietary rights statement with the Central Secretariat, and self-certifying that the requirements specified in the Standard are met. In general, alternative products may be used if they can be shown to lead to the same results.

Manufacturers of dummies or dummy components which are intended to meet the Standard, are required to provide with the supplied dummies or dummy components, certification that the dummies or dummy components meet the requirements.

CONCLUSIONS AND RECOMMENDATIONS

An International Standard for a motorcyclist impact dummy and other methodologies for rider protective device research have been developed and approved. The Standard is based on existing technology, and for the dummy involves special modifications and replacements of some components of a Hybrid III 50th percentile male sit/stand dummy. In general, devices which meet the Standard exist, are in use, and are available from component vendors.

Practical experience as well as application to various research topics may result in a need to consider possible refinements to the motorcyclist dummy and to the Standard. Possible examples envisaged include:

- A new, specialized, motorcyclist dummy neck, for improved biofidelity and range of position adjustment, and in order to provide a better means for neck injury prediction in motorcycle impact tests;
- Additional, optional, specified dummy equipment including gloves and special alloy shoulder (for improved durability); and vest (to prevent arm separation due to shoulder failure);
- A frangible bone fracture sensor, which indicates the time instant at which, and in which bone, a fracture occurs.

It is hoped that the ISO 13232 motorcyclist impact dummy will contribute to further understanding of, and feasibility research into, devices which are intended to protect riders in collisions.

REFERENCES

Anon., BPICM Status Report on Leg Guards, Bureau Permanent International des Constructeurs de Motorcycles (BPICM, name changed to IMMA, Geneva), submitted to Economic Commission for Europe, Inland Transport Committee, Working Party on Road Transport, Group of Experts on the Construction of Vehicles, Group of Rapporteurs on General Safety Provisions (GRSG), Forty-Ninth Session, Geneva, November 1986.

Anon., Road vehicles - Measurement techniques in impact tests - Instrumentation, ISO 6487, International Organization for Standardization, Geneva, 1987.

Anon., Society of Automotive Engineers, Instrumentation for Impact Test, SAE J211, Warrendale, 1988.

Anon., Biokinetics and Associates, Ltd., Injury Assessment Considerations in Design and Use of a Motorcyclist Anthropometric Test Device, Volume I: Literature Review, Ottawa 1990.

Anon., Biokinetics and Associates, Ltd., Injury Assessment Considerations in Design and Use of a Motorcyclist Anthropometric Test Device, Volume II: MATD-2: Interim Motorcyclist Crash Test Dummy, Report R90-14a/jm, Ottawa, 1991.

Anon., "Leg protectors: Do They Work", Proceedings of the International Seminar on Leg Protectors - Chantilly, France, International Motorcycle Manufacturers Association, Fresnes, France, November 1991.

Anon., Uniform Provisions Concerning the Approval of Protective Helmets and of their Visors for Drivers and Passengers of Motorcycles and Mopeds, U.N. Economic Commission for Europe, ECE/TRANS/505 Rev 1/Add2/Rev 3, Geneva, 1992.

Anon., Anthropometric Test Dummies, U.S. Department of Transportation, NHTSA, 49 CFR Part 572, Sub part E, Washington, D.C., 1993.

Anon., Motorcycles - Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles, ISO 13232, International Organization for Standardization, Geneva 1996 (forthcoming).

Bartol, J.A., Livers, G.D., and Miennert, R., Near Term Safety Improvements for Motorcycles - Phase II, DOT-HS-801-653, 1975.

Bothwell, P.W., Knight, R.E., and Peterson, H.C., Dynamics of Motorcycle Impact, Volume II, Motorcycle Crash Test Program, DOT-HS-5-01160, 1971.

Chinn, B.P., Hopes, P.D., and Macaulay, M.A., "Leg Protection for Riders of Motorcyclists", 10th International ESV Conference, Oxford, 1985.

Fuller, P.M., and Snider, J.N., Third Year Report Supplement Recent Progress/Developments Dynamic Response of the Human Leg to Impact Loading Submitted to JAMA: Volume II, University of Tennessee, Knoxville, 1989.

Gibson, T.J., Newman J.A., Zellner, J.W., and Wiley, K.D., "An Improved Anthropometric Test Device", Proceeding of the NATO Advisory Group for Aerospace Research and Development Conference, Cesme, Turkey, 1992.

Inoue, T., and Miura, K., et al, "Experimental Collision Test on Motorcycles with Passenger Cars", Paper 15 of Safety Research Tour in the USA from the Viewpoint of Vehicle Dynamics, Stability and Control Committee, Society of Automotive Engineers of Japan, October 1969.

McElhany, J.H., "Dynamic Response of Bone and Muscle Tissue", Journal of Applied Physiology, Volume 21, 1966.

Martens, M., Van Audekercke, R., De Meester, P., and Miller, J.C., "The Mechanical Characteristics of the Long Bones of the Lower Extremity in Torsional Loading", Journal of Biomechanics, Volume 13, 1980.

Mayer, C., and Hochgeschwender, J., "Development of a Lower Leg Model for the Investigation of Accident Consequences in the Case of Collisions Between Vehicles and Pedestrians",

ISO/TC22/SC10/WG2 N334, 1993.

Melvin, J.W. and Weber, K. (editors), "Review of Biomechanical Impact Response and Injury in the Automotive Environment", DOT-HS-807-042, 1985.

Miyazaki, K., Kubota, M. and Sakamoto, S., "Load Measuring Method of Motorcyclists' Leg during Motorcycle Collision", Proceedings of the Twelfth International Technical Conference on Experimental Safety Vehicles, Volume II, Goteborg, 1989.

Motoshima, T., Studies on the Strength for Bending of Human Long Extremity Bones, Kyoto Prefectural University of Medicine, Kyoto, 1960.

Myers, B.S., McElhaney, J.H., Doherty, B.J., Paver, J.G., Nightengale, R.W., Lass, T.O., and Gray, L., "Responses of the Human Cervical Spine to Torsion", Society of Automotive Engineers, Paper 892437, 1989.

Newman, J.A., Zellner, J.W. and Wiley, K.D., "A Motorcyclist Anthropometric Test Device MATD", International IRCOBI Conference on the Biomechanics of Impacts, Berlin, 1991.

Nyquist, G.W., Savage, C.M. and Fletcher, D.L., "Dynamics of Biomechanics of Motorcycle-to-Car Glancing Impact: Theory and Experiment", Twenty-Ninth Annual Proceedings of the Association for the Advancement of Automotive Medicine Conference, Washington, D.C., 1985.

Padgaonkar, A.J., Krieger, K.W. and King, A.F., "Measurement of Angular Acceleration of a Rigid Body using Linear Accelerometers", American Society of Mechanical Engineers Journal of Applied Mechanics, Volume 45, Issue 3, September 1975.

Progress Report, Motorcycle Industry Rider Leg Protection Research - 1988, International Motorcycle Manufacturers Association, Paris, December 1988.

Radwan, R. and Nickles, J., "Performance Evaluation of Crash Test Data Acquisition Systems", Proceedings of the Thirteenth International Technical Conference on Experimental Safety Vehicles, Paris, France 1991.

Rogers, N.M., "A Preliminary Study into the Feasibility of Motorcycle Airbags", Safety, Environment, Future, Proceedings of the 1992 International Motorcycle Conference, Bochum, Germany, 1991a.

Rogers, N.M., "Further Evaluation of Motorcycle Leg Protectors as Proposed in the UK Draft Specification", Proceedings of the Thirteenth International Technical Conference on Experimental Safety Vehicles, Paris, France 1991b.

Rouhana, S.W., Viano, D.C., Jedrzeczak, E.A. and McCleary, J.D., "Assessing Submarining and Abdominal Injury Risk in the Hybrid II Family of Dummies", Proceedings of the Thirty-third STAPP Car Crash Conference, Warrendale, Pennsylvania 1989.

St. Laurent, A., Shewchenko, N. and Szabo, T., "Development of Frangible Knee and Hip Elements for a Motorcycle ATD (Summary)", Biokinetics and Associates, Ltd., Ottawa, 1989a.

St. Laurent, A., Shewchenko, N. and Szabo, T., "Requirements for an ATD for Motorcycle Crash Testing", Biokinetics and Associates, Ltd., Ottawa 1989b.

St. Laurent, A., Szabo, T., Shewchenki, N. and Newman, J.A., "Design of a Motorcyclist Anthropometric Test Device", Proceedings of the Twelfth International Technical Conference on Experimental Safety Vehicles, Goteborg, 1989c.

Sakamoto, S., "Difficulties in Leg Protection Research", Proceedings of the Twelfth International Technical Conference on Experimental Safety Vehicles", Goteborg, 1989.

Sakamoto, S., "Research History of Motorcycle Leg Protection", Society of Automotive Engineers, Paper 900755, February 1990.

Seiffert, U.W. and Leyer, H.E., "Dynamic Dummy Behavior Under Different Temperature Influences", Proceedings of the Twentieth STAPP Car Crash Conference, Dearborn, Michigan 1976.

Surowiak, J.F. and Gibson, T.J., Modified Torsional Response of the MATD Neck, Biokinetics and Associates, Report R92-15, Ottawa 1992.

Tadokoro, H., Fukuda, S. and Miyazaki, K., "A Study of Motorcycle Leg Protection", 10th International ESV Conference, Oxford, 1985.

Tadokoro, H., "Load Measuring Method of Occupant's Leg on Motorcycle Collision", Proceedings of the Eleventh International Technical Conference on Experimental Safety Vehicles, Washington, D.C. 1987.

Uto, T., Side Collision Test of Motorcycles Equipped with Side Protection Devices, Japan Automobile Manufacturers Association, 1975.

Van Driessche, H., "Development of an ISO Standard for Motorcycle Research Impact Test Procedures", 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, May 1994.

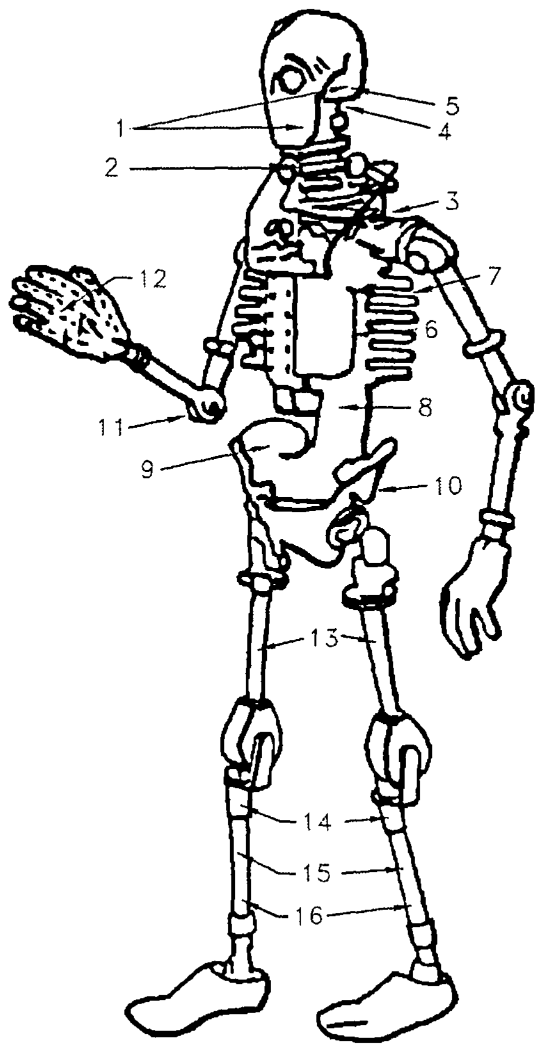
White, Jr, R.P. and Gustin, T.W., "The Application of a New Data Recovery System for Automotive/Motorcycle Dynamic Testing", Proceedings of the Twelfth International Technical Conference on Experimental Safety Vehicles, Goteborg, 1989.

Wismans, J. and Spenny, C.H., "Performance Requirements for Mechanical Necks in Lateral Flexion", Proceedings of the Twenty-seventh STAPP Car Crash Conference, San Diego, 1983.

Yamada, H., Strength of Biological Materials, Williams & Wilkins, Baltimore, 1970.

Zellner, J.W., Newman, J.A. and Rogers, N.M., "Preliminary Research into the Feasibility of Motorcycle Airbag Systems", Fourteenth International Technical Conference on the Enhanced Safety of Vehicles", Munich, 1994.

Zellner, J.W., Newman, J.A. and Rogers, N.M., "Further Research into the Feasibility of Motorcycle Airbags", Twenty-sixth International Symposium on Automotive Technology and Automation Conference, Paper 93SF099, Aachen, 1993.



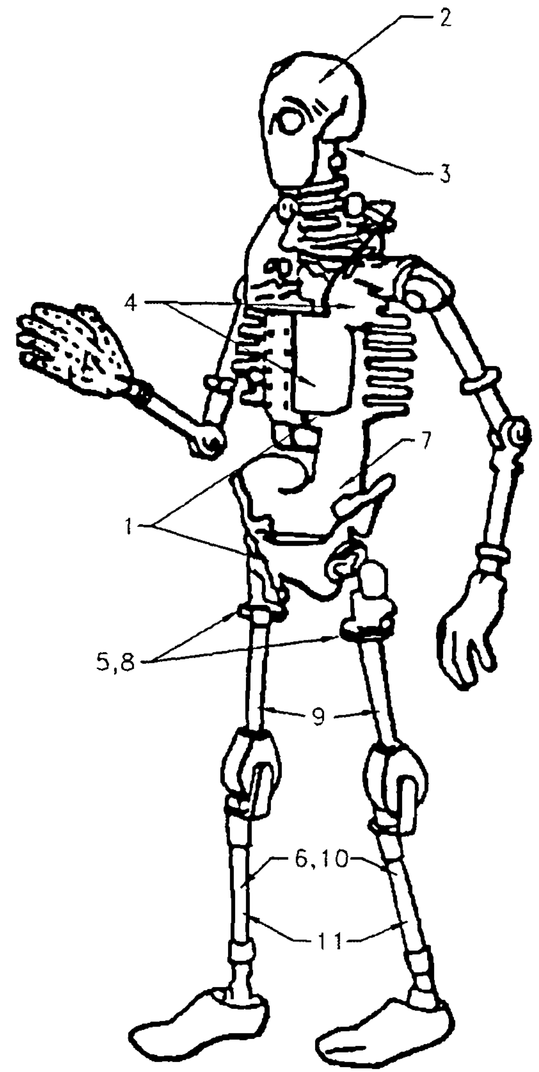
Basis dummy: Hybrid III

- 50th percentile male
- sit/stand construction
- compatible with 6 axis upper neck load cell

No external cables during test

Special components
1 Motorcyclist head skins
2 Neck shroud
3 Modified lower neck mount
4 Neck torsion element
5 Replacement nodding blocks (3 sizes)
6 Replacement thoracic spine containing data recorder
7 Modified chest skin
8 Modified straight lumbar spine (reduced stiffness)
9 Frangible abdominal insert
10 Modified pelvis containing data recorder (optional)
11 Indexed elbow bushing
12 Grippable hands
13 Frangible femur and mounts
14 Frangible knee (2 axis)
15 Frangible tibia and mounts
16 Leg retaining cables

Figure 1. Special mechanical components for ISO 13232 motorcyclist dummy



Electronics

Required Item	Channels
1 Data recorder	32 min
2 Accelerometers, head	9
3 Load cell, upper neck	6
4 String potentiometer, chest	4
5 Load cell, femur	6
6 Strain gauge, tibia	4
Optional	
7 Load cell, lumbar	6
8 Load cell, femur	2
9 Strain gauge, femur	8
10 Strain gauge, tibia	2
11 Strain gauge, tibia	6

Not recommended, due to metal/metal contacts

Chest accelerometers

Pelvis accelerometers

Figure 2. Electronic comfiguration of ISO 13232 motorcyclist dummy

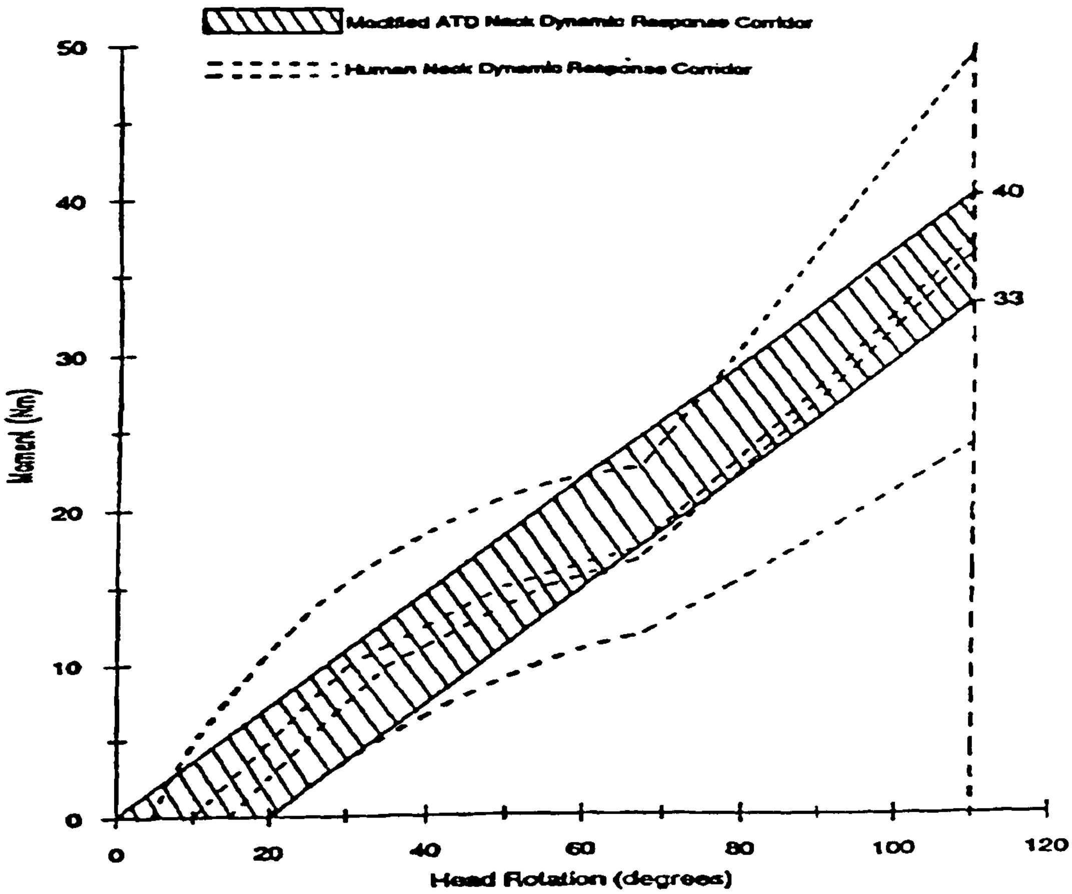


Figure 3. Motorcyclist neck torsional response corridor.

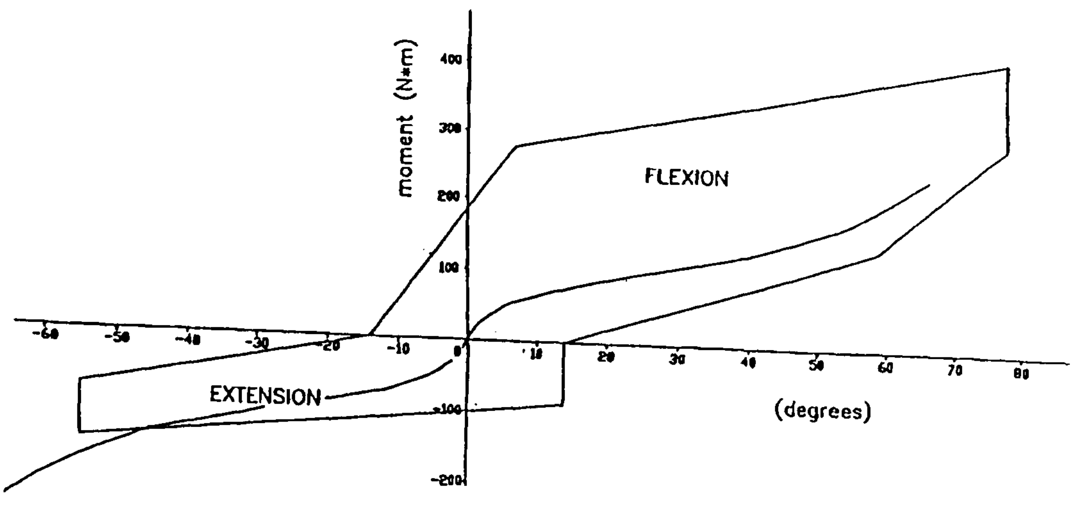


Figure 4. Human response corridor and modified lumbar spine response of static moment vs. thoracic angular displacement.

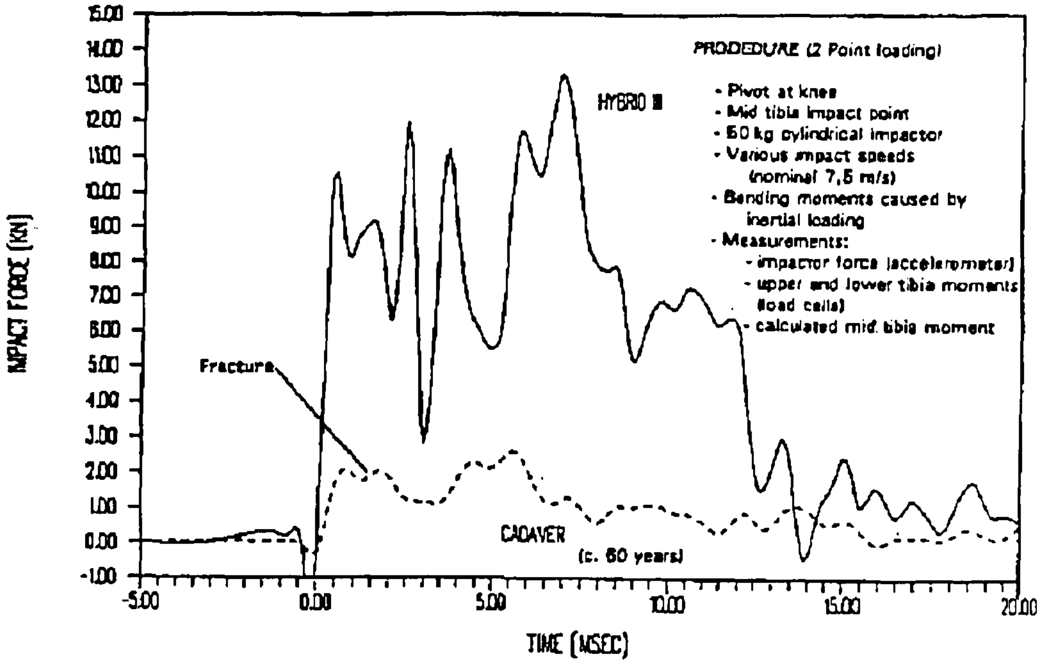


Figure 5. Lower leg dynamic impact force vs. time Hybrid III and cadaver legs.

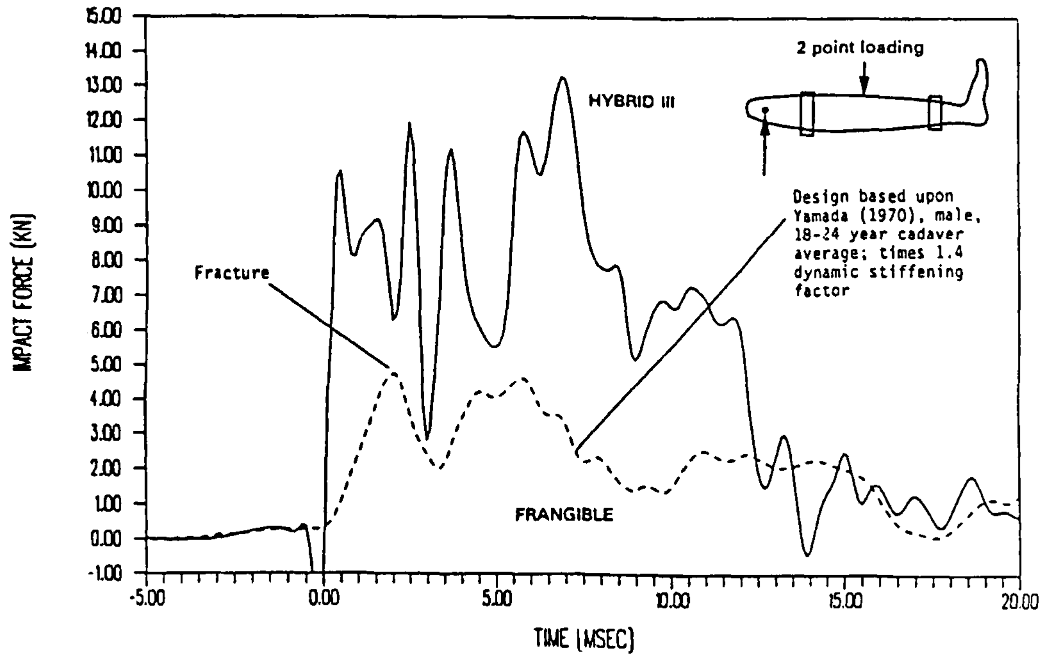


Figure 6. Lower leg dynamic impact tests force vs. time: Hybrid III legs and fragible leg.

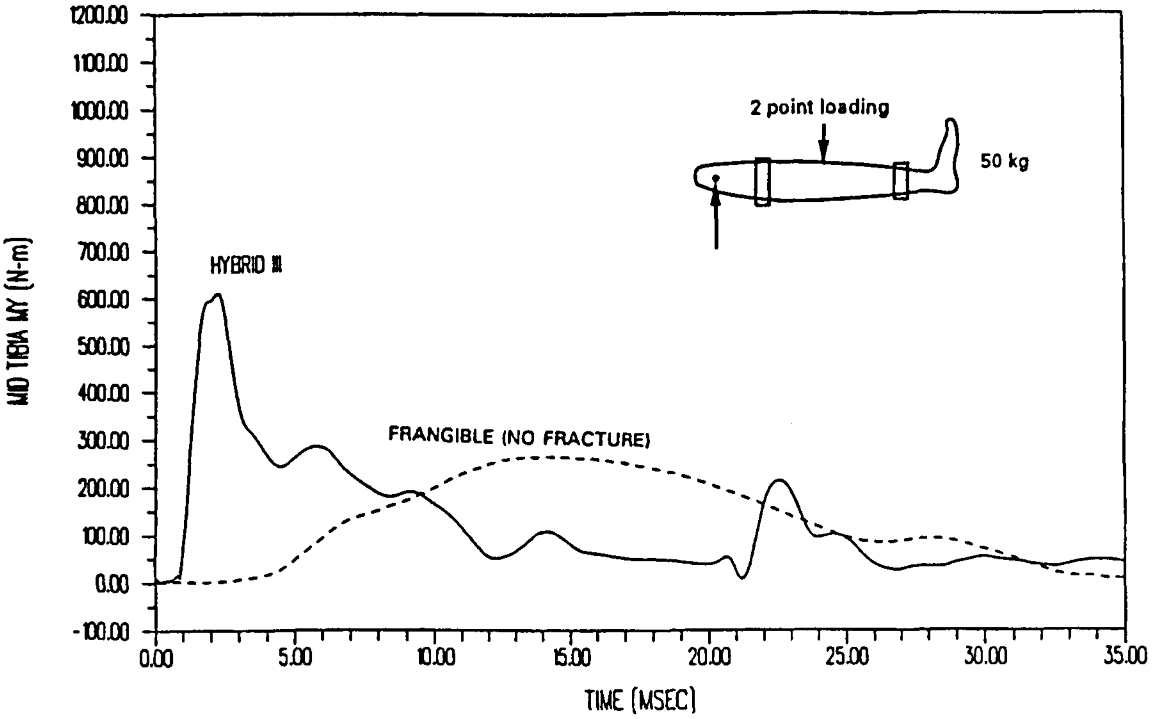


Figure 7. Instrumented lower leg impact tests mid tibia moment vs. time for drop height = 1,016 m: Hybrid III leg and frangible leg.

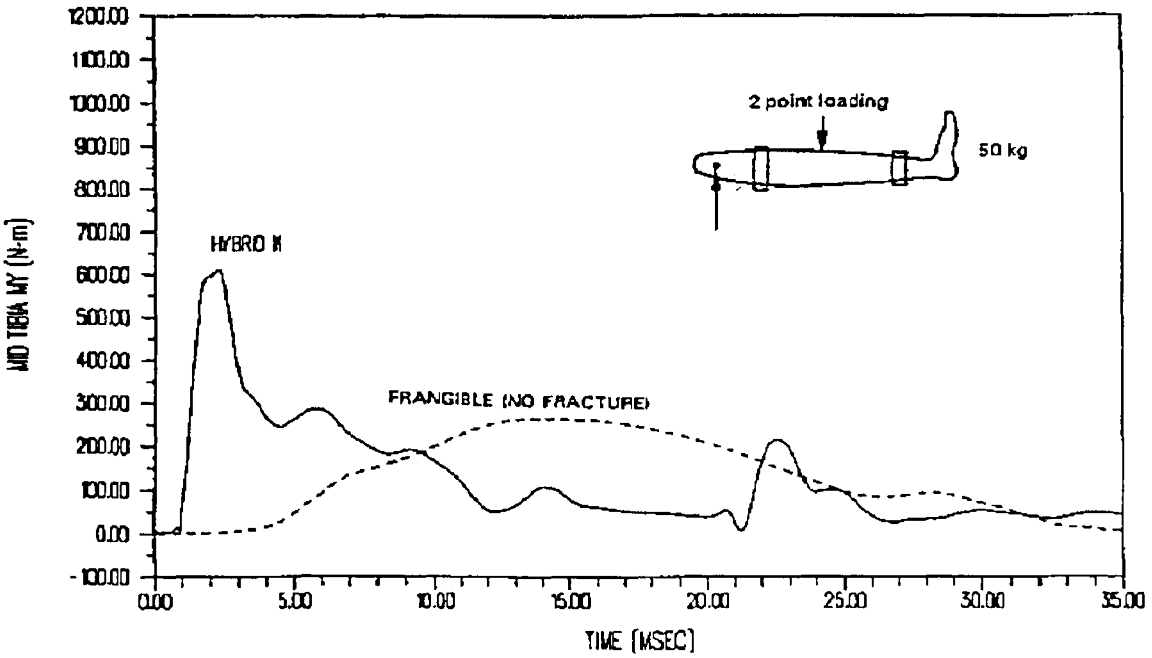


Figure 8. Instrumented lower leg impact tests mid tibia moment vs. time for drop height = 1,778 m: Hybrid III leg and frangible leg.

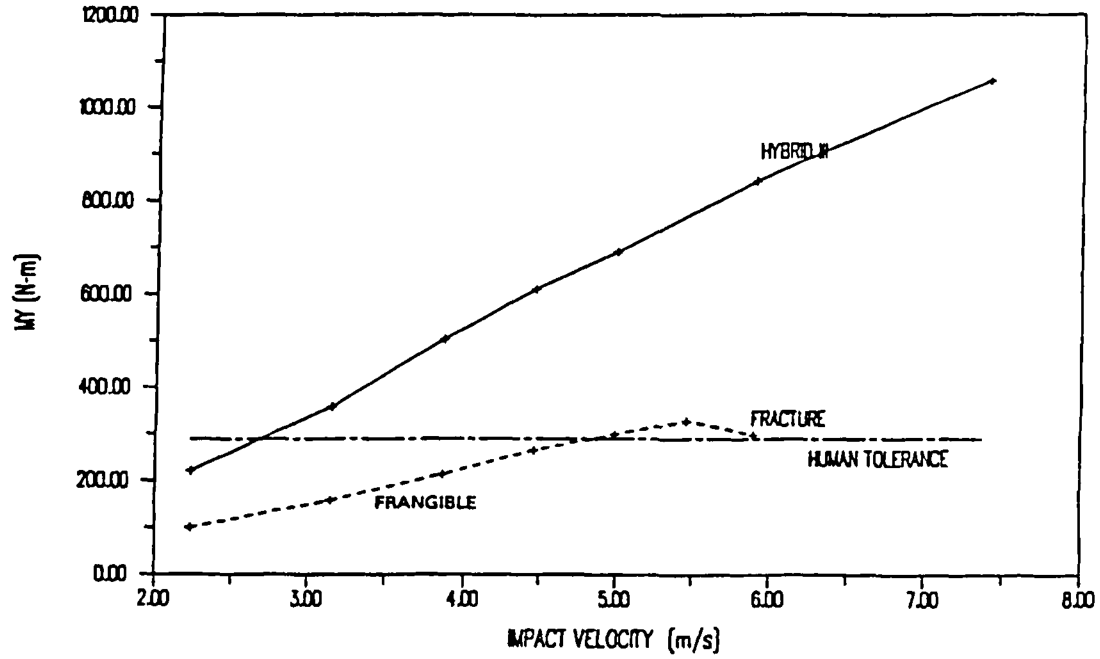


Figure 9. Lower leg impact tests mid tibia bending moment M_y vs. impact velocity: Hybrid III leg and frangible leg.

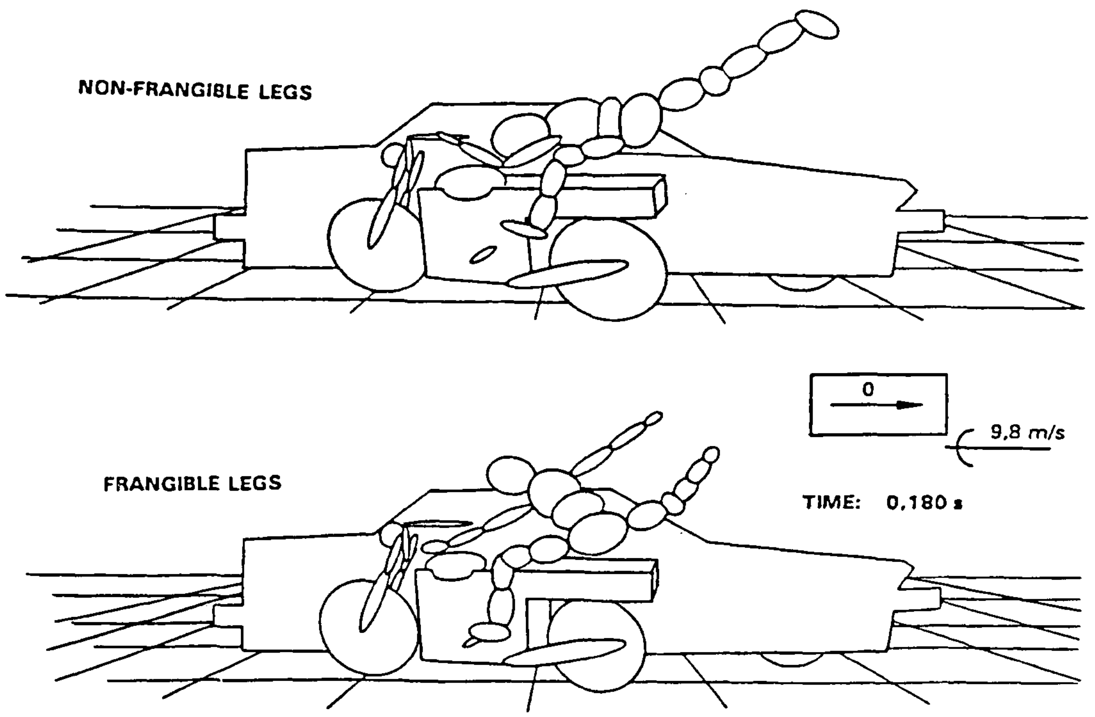


Figure 10. View of ATB simulated offset frontal impact, medium conventional motorcycle, with and without frangible leg bones.

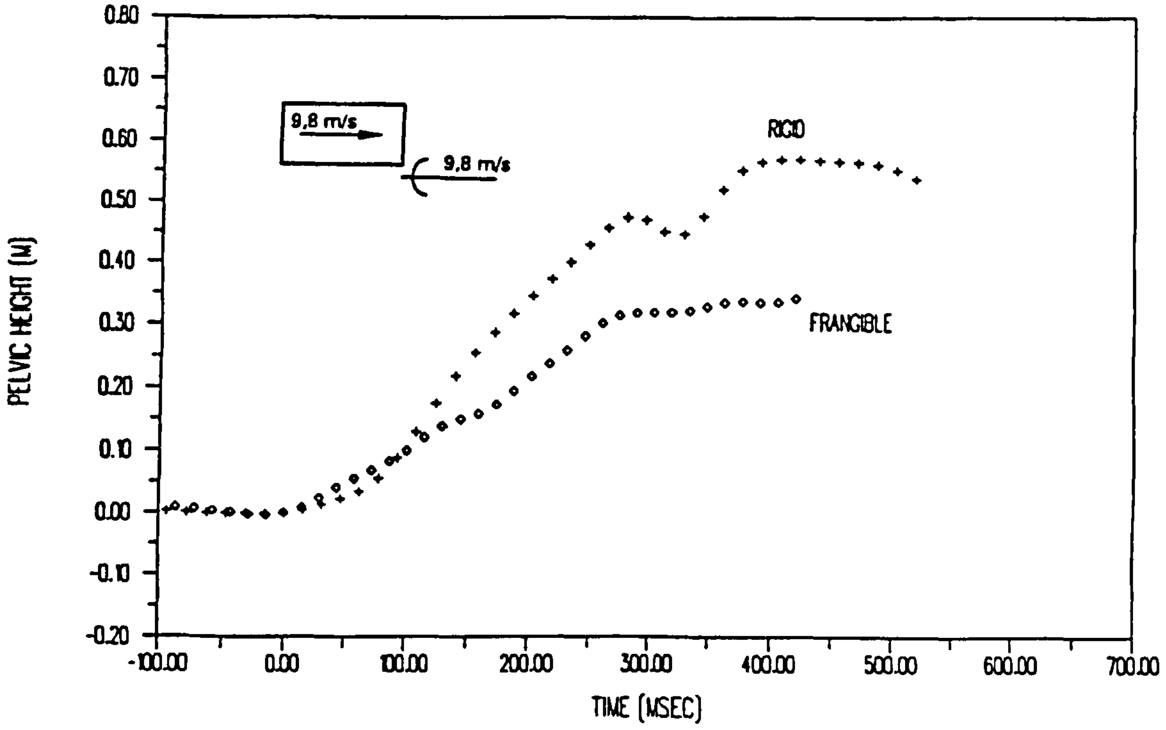


Figure 11. Pelvis trajectory comparison of frangible and non-frangible bones, full scale test, offset frontal impact, large motorcycle.

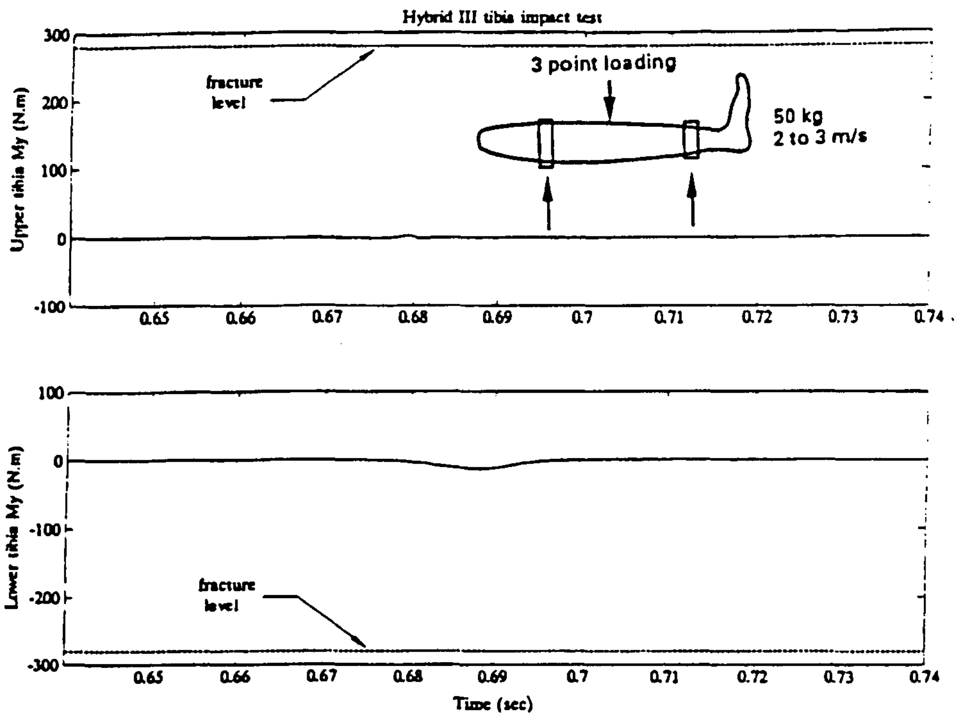


Figure 12. Sensed upper and lower tibia moments vs. time in Hybrid III tibia, for three point impact test sufficient to fracture human tibia.

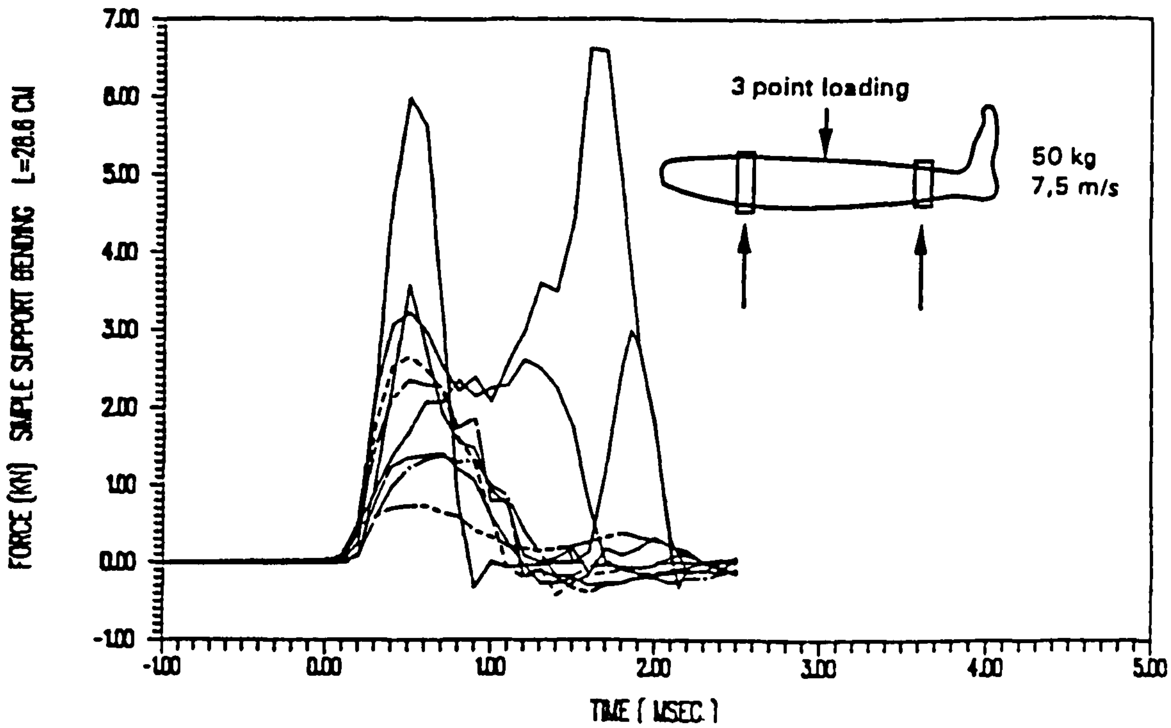


Figure 13. Impactor time histories for nine cadaver tibia specimens, from Fuller and Synder, 1989.

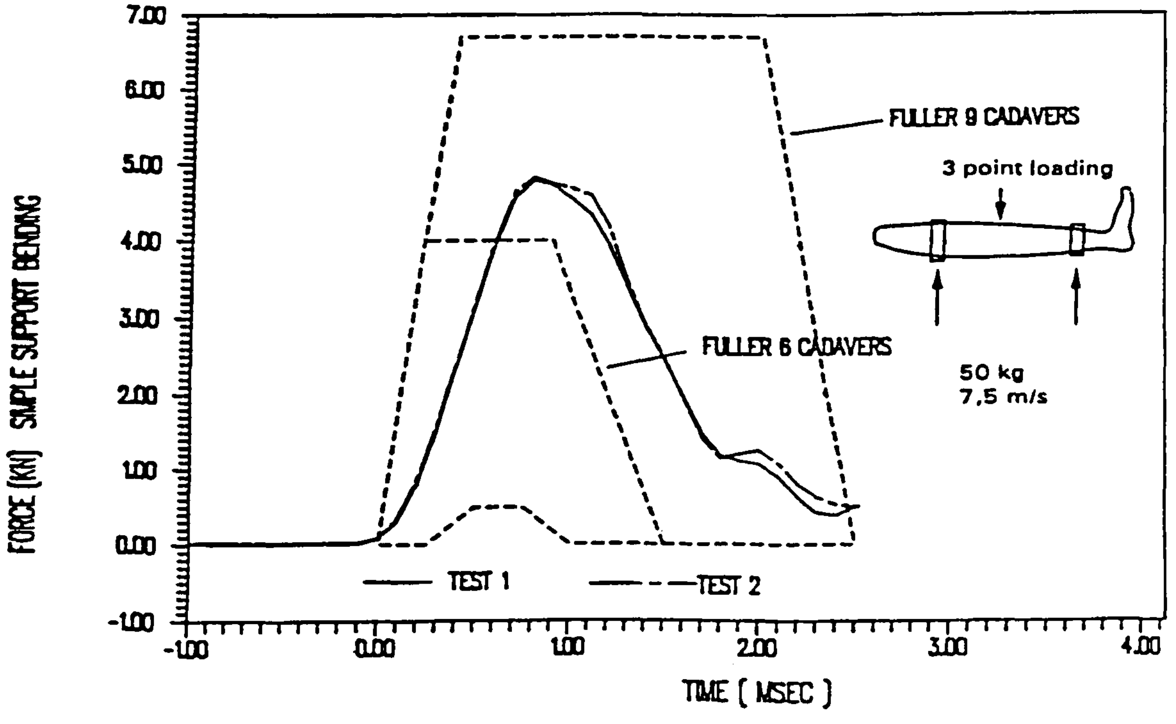


Figure 14. Comparison of composite tibia fracture force response with envelopes of cadaver tibia fracture response.

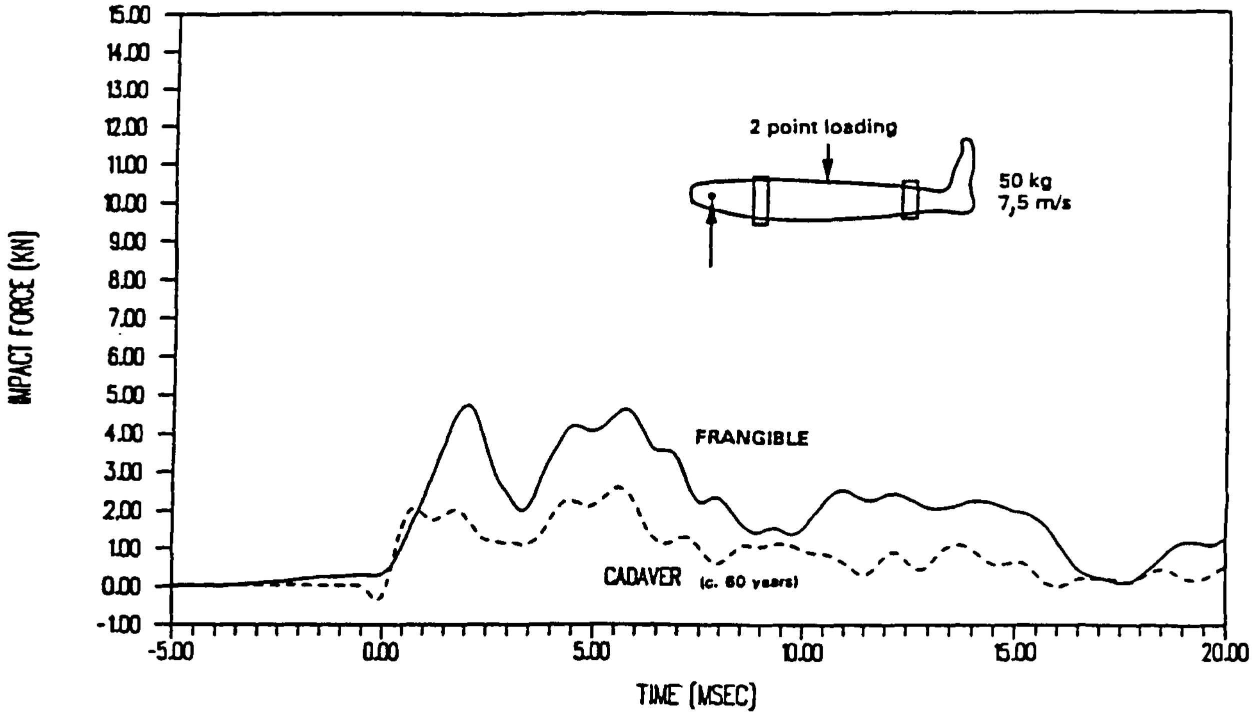


Figure 15. Lower leg dynamic impact tests impact force vs. time: composite and cadaver legs.

THE EFFECTS OF BULL BARS ON PEDESTRIAN INJURY MECHANISMS AND KINEMATICS

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Paper Number 96-S10-W-25

ABSTRACT

This paper describes a full scale crash testing program designed to assess the effects of bull bars on pedestrian injury mechanisms, severity and kinematics in pedestrian-vehicle frontal interactions.

Laboratory testing was conducted using an instrumented Hybrid-III dummy fitted with pedestrian pelvic conversion kit, and advanced lower leg assembly. The dummy was impacted by a late model production sedan, in control configuration and equipped with 2 popular aftermarket bull bars of varying aggressivity. Test speeds of 20 km/h and 30 km/h were used. Analysis of data and high speed film allowed comparison of the effect of the bull bars on pedestrian injury and kinematics.

The testing showed that kinematics were significantly changed by the addition of a bull bar. Biofidelity of the test dummy was a limitation of the testing. Further dummy development is necessary to provide a useful pedestrian test dummy.

INTRODUCTION

Bull bars are rigid metal structures attached to the fronts of vehicles. Originally they were intended to protect engines from disablement due to animal strike in remote Australian areas. Bull bars are now however, a common fixture on city-based vehicles, including four wheel drives and sedans. Bull bars are thought to be associated with increased levels of pedestrian injury in pedestrian-vehicle crashes. Pedestrian fatalities account for around one fifth of New South Wales road fatalities and serious injuries annually, with 128 people being killed, and 1070 seriously injured in pedestrian accidents in NSW in 1994.[1] This research aims to assess the potential of Hybrid-IIIP anthropometric test dummy to conduct full scale pedestrian testing.

METHOD

A full scale pedestrian crash testing program was designed to assess the potential of the Hybrid-IIIP anthropometric test dummy to measure pedestrian injury due to bull bars in real world crashes. The test set-up was designed to model a real crash.
The test matrix is shown in Table 1.

Dummy Selection

The groups most prominent in New South Wales pedestrian road accident statistics, were taken into account, both for fatalities and serious injuries. These were found to be 5-7 years old, 18 years old and over 60 year olds. The most suitable surrogate to represent the high risk 18 and 60 year old pedestrian populations was a 50th percentile Hybrid-IIIP dummy.

The 50th percentile Hybrid-IIIP dummy was reportedly sufficiently biofidelic for pedestrian testing, and had an unsupported standing capability. Instrumentation selected for use included head, thoracic, pelvic, upper and lower leg load cells and accelerometers.

H-IIIP Instrumentation Selected for use was as shown in Table 2

Lower leg instrumentation was not used for 30 km/h impacts, as some channels were significantly overloaded on some 20 km/h impacts.

Dummy instrumentation was connected to the off board data acquisition system via an umbilical cable from the

Table 1
Test Matrix

Test Subject	No Bull Bar	No Bull Bar	Bull Bar 1 Tubular Alloy Bar	Bull Bar 2 Tubular Alloy Bar with Bumper Replacement
H-IIIP 50% Male Dummy	20 km/h	20 km/h	20 km/h	20 km/h
H-IIIP 50% Male Dummy	30 km/h	–	–	30 km/h

dummy. The cable weight was supported during the impact by an overhead breakaway system.

Table 2
Dummy Instrumentation

Body Region	Channels
head	Gx, Gy, Gz
thorax	Gx, Gy, Gz
pelvis	Gx, Gy, Gz
lumbar spine	Fx, Fy, Fz, Mx, My, Mz
femur	Fx, Fy, Fz, Mx, My, Mz
upper femur	Fx, Fy, Fz, Mx, My, Mz
clevis	Fz
lower tibia	Mx, Fy, Fz
Upper tibia	Mx, My

Velocity Profile

Test impact speeds of 20 km/h and 30 km/h were selected. The vehicle was towed up to constant impact speed and held constant by a skate, which released prior to impact point. The vehicle's emergency hydraulic braking system was applied 1.0 m after impact for 20 km/h and 30 km/h tests using a programmable logic controller. Braking tests showed that braking by this method was controlled and repeatable, with consistent brake cuing, deceleration rate, vehicle tracking, and stopping distance.

Vehicle Selection

A 1993 VP Holden Commodore was selected as the test vehicle. The car is a high volume seller, well represented on Australian Roads, both rural and urban. Bull bars are often fitted on these vehicles in rural areas.

The car's current front profile has been used since 1988. It has similar frontal geometry to other popular large cars. Hence, it represents a significant percentage of vehicles on the road today. Figure 1 shows the frontal geometry of the test vehicle.

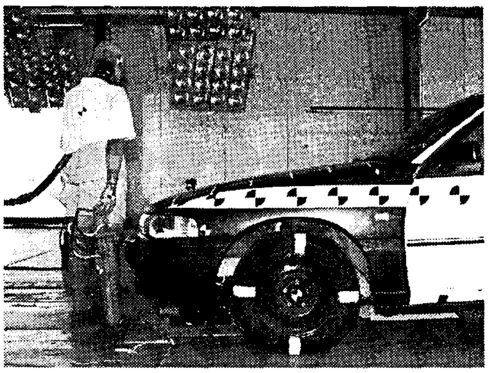

Figure 1: 1993 Holden Commodore

Bull Bar Selection

Two bull bar styles were selected for evaluation. These were:

Bull Bar 1: Aluminium alloy round tube looped horizontal member, I-beam vertical member

Bull Bar 2: Aluminium alloy round tube looped horizontal member, I-beam vertical member and C-channel bumper protection

The bull bars tested are shown below.

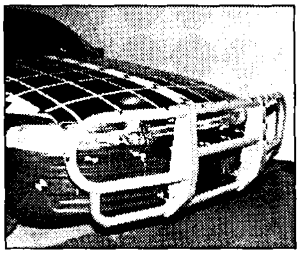

Figure 2a: Bull Bar 1

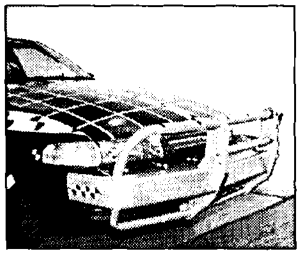

Figure 2b: Bull Bar 2

These bull bars were selected as they represent significant market segments in terms of sales volume and design style commonly seen on passenger cars. The bull bars tested were manufactured by Australia's largest bull bar manufacturer and distributor.

Dummy Orientation:

Research shows that lateral nearside impacts are most representative of real accident scenarios, the pedestrian generally travelling perpendicular to the vehicle.[2] In an Australian context, this relates to a pedestrian starting out from the left side of the road, and being impacted on the left front side of the vehicle.

Dummy impact position was selected in order to model a real pedestrian accident. Dummy position was as follows:

- dummy is in a walking attitude, left foot first, with arms by sides
- dummy standing in front of vehicle 300 mm to left of longitudinal axis of vehicle.
- impact point is on the right side of the dummy
- dummy is turned 15° towards the vehicle (in order to avoid arm interposition)

Photography

Nine high speed cameras operating at 500 frames/ second were used. They were located so at to provide left and right side close up and far shots, overhead and internal shots.

TEST RESULTS

Analysis of film and data showed that pedestrian dummy kinematics and injury parameters were changed by the addition of a bull bar to the impacting vehicle.

Dummy Kinematics

Different and very distinct dummy kinematics were observed in the two test configurations – vehicles with and without bull bars. Kinematic sequences at 20 km/h are shown in Figure 3 and at 30 km/h in Figure 4.

No Bull Bar tests, 20 km/h – The dummy was impacted first on the right leg (the trailing leg in the walking position) by the bumper. As the vehicle continued to travel forwards and struck the left (leading) leg, the dummy was rotated from its initial side-on position, to face the vehicle. This resulted in a predominantly frontal chest and head impact onto the vehicle bonnet. The dummy progressively wrapped around the vehicle front, upon impact. 'Wrap' was initiated at approximately knee height, corresponding to the initial striking point on the bumper. The body continued to wrap around the vehicle, resulting in the head and then the chest impacting the bonnet. There was minimal sliding up the bonnet during the wrap sequence. Upon the vehicle braking, the dummy slid off the bonnet, impacted and slid along the ground. The dummy came to rest face down, stretched out in line with the longitudinal axis of the vehicle, with the head closest to the vehicle. The arm cushioned the head impact with the ground, resulting in a lower head injury value.

Bull Bar 1 Test, 20 km/h – In the test with Bull Bar 1, the dummy was struck almost simultaneously at hip and knee height by the bull bar. Once again, the bull bar struck the right (trailing) leg before the left leg. This resulted in the dummy being rotated from its initial side-on position, to face the vehicle. This caused a predominantly frontal impact of the chest and head of the dummy with the vehicle bonnet. The legs did not progressively wrap around the vehicle. Instead, the dummy pivoted around the hip region, and the upper body was 'catapulted' onto the bonnet. The head impacted the bonnet before the chest. Upon the vehicle braking, as the body commenced to rebound, the left arm was caught in the bull bar horizontal members, resulting in a slight body yaw. The upper body started to slide somewhat off the bonnet, before the chest hit the bull bar, and the body was flicked to the ground. As the knees impacted the ground, the upper body continued to rotate backwards, resulting in the back of the trunk and the rear of head hitting the ground. The rear head impact with the ground was not protected by the dummy's arms. This resulted in greater head injury values due to interaction with the ground. The dummy came to rest face up, with the feet/knees closest to the vehicle.

Bull Bar 2 Test, 20 km/h – In the test with Bull Bar 2, the dummy was struck at right hip height by the bull bar. The bull bar struck the right side rotating the dummy from its initial side-on position, to face the vehicle. This resulted in a predominantly frontal impact of the head of the dummy with the vehicle bonnet. The legs did not progressively wrap around the vehicle. Instead, the dummy pivoted primarily around the hip region, with scarcely any upper body bending visible. The head hit the bonnet before the chest. Upon the vehicle braking, the upper body slid somewhat off the bonnet. The chest appeared to catch on the upper horizontal member of the bull bar before being

Figure 3a: No bull bar test, 20 km/h

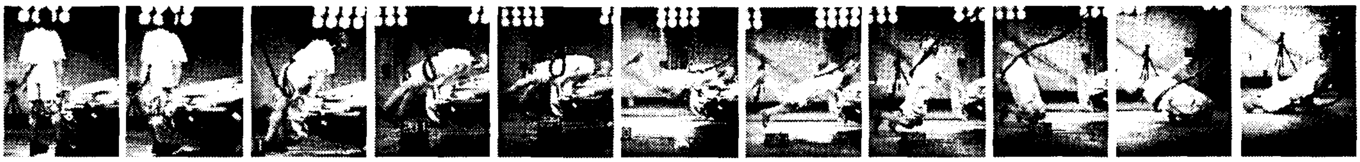

Figure 3b: Bull bar 1 test, 20 km/h

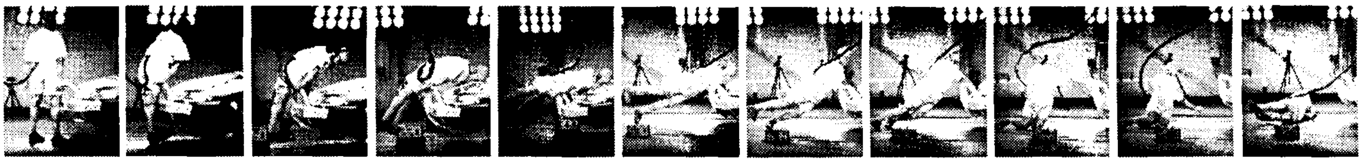

Figure 3c: Bull bar 2 test, 20 km/h

flicked to ground. The left arm caught in the upper horizontal member of the bull bar, causing significant body yaw. As the knees impacted the ground, the upper body continued to rotate backwards and sidewards, resulting in the back of the trunk hitting the ground. The head impacted the arm, softening the blow to the ground. The dummy came to rest on its side, laying parallel to the vehicle.

No Bull Bar test, 30 km/h – The dummy was struck at knee height by the bumper of the vehicle. Rather than a progressive wrap of the legs occurring, the dummy was swept off its feet, pivoting around the hip region, with the head striking the bonnet directly. When the chest struck the bonnet the head had rebounded, with the legs high in air. As the legs continued to rotate upwards, the chest also rose, and the head re-impacted the bonnet. On braking, the face slid down the bonnet, with the body vertically in the air above the head. As the dummy neared the ground, the orientation became horizontal, with knees, pelvis and chest striking the ground together. The dummy came to rest in line with the longitudinal axis of the vehicle, face down, with the head closest to the vheicle.

Bull Bar 2 Test, 30 km/h – In the test with Bull Bar 2, the dummy was struck at right hip height by the bull bar. The bull bar struck the right side rotating the dummy from its initial side-on position, to face the vehicle. This resulted in a predominantly frontal impact of the head of the dummy with the vehicle bonnet. Rather than a progressive wrap of the legs occurring, the dummy was swept off its feet, pivoting around the hip region, with the head striking the bonnet directly, with scarcely any upper body bending visible. The head hit the bonnet before the chest. When the chest struck the bonnet the head had rebounded, with the legs high in air. As the legs continued to rotate upwards, the chest also rose, and the head re-impacted the bonnet. On braking, the face slid down the bonnet, with the body vertically in the air above the head. The chest hit the upper horizontal member of the bull bar before sliding to the ground. As the dummy neared the ground, the orientation became horizontal, with limbs striking the ground before a simultaneous chest and head strike. The dummy came to rest in line with the longitudinal axis of the vehicle, face down, with the head closest to the vheicle.

Dummy Kinematic Biofidelity

Research indicates that for pedestrians, dummy kinematics differ from cadaver kinematics. With cadavers the thorax impacts the vehicle before the head. With dummies the head tends to impact the vehicle before the thorax due to arm interposition. To rectify this situation, the subject can be turned slightly towards the vehicle to eliminate arm interactions.[2]

A dummy test position of angle 15 degrees towards the vehicle was used to eliminate arm interactions. Evidence of arm interposition in vehicle impacts was not visible in either footage of the tests, or on the data traces. However, the phenomena that was linked to arm interposition, that of the head striking the bonnet before the chest struck the bonnet, was present in the majority of tests, suggesting that this is in fact a biofidelity issue.

A comparison of cadaver pedestrian test footage with the footage from this test series indicates that the Hybrid-IIIP dummy was considerably stiffer. The dummy wrapped around the vehicle far less than the cadavers. For a cadaver in this test configuration, when the leg/hip region is impacted by the vehicle, the legs progressively wrap around the vehicle, while the upper torso and head remain predominantly vertical. For cadavers, ground contact by the feet also appears to be maintained for longer, before being swept off the feet.[3] In this test series, this was verified, with the dummy being swept off the feet very early in the crash sequence.

Whilst the cadavers showed significant pelvic and thoracic bending around the vehicle structure, the dummy thorax moved as one 'solid' segment, with rotations only visible at the hip an neck. This resulted in the head

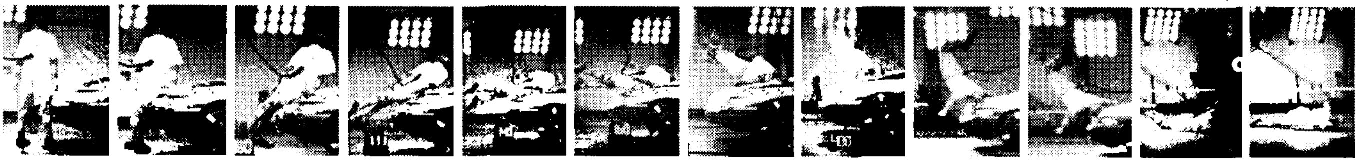

Figure 4a: No bull bar test 30 km/h

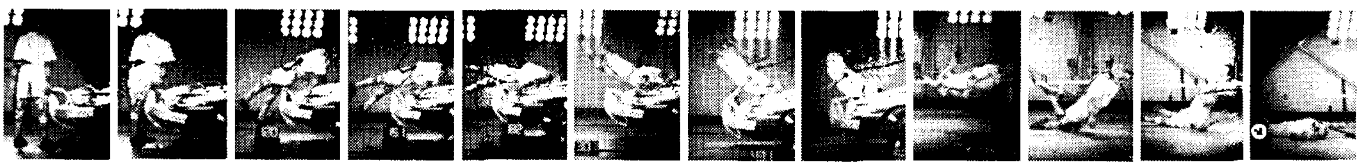

Figure 4b: Bull bar 2 test, 30 km/h

apparently being flicked onto the bonnet. It would seem that the dummy's rigid spine significantly limited the kinematic biofidelity of the dummy.

Additionally, the way the legs wrapped around the vehicle on impact appeared to be much more rigid for the dummy than for the cadaver. This is confirmed by Cesari & Cavallero[4] who state that rupture of knee ligaments gives complete rotational freedom of the lower leg compared to the thigh. The dummy knee junction is made from steel plate, which can bend during impact.

The combination of these factors means that the kinematics of the Hybrid-IIIP dummy are not closely comparable to cadavers for this kind of pedestrian test.

Table 3 summarises data from the 20 km/h tests.

Table 4
Injury Values for Vehicle Impact – 30 km/h Tests

	Test B6009 Bull Bar 2	Test B6010 No Bull Bar
HIC	292	753
head peak g, (3 ms clip)	61	92
chest peak g, (3 ms clip)	14	20
pelvis peak g, (3 ms clip)	58	32
lumbar peak force (kN)	1.9	4
lumbar moment peak (Nm)	199	148
left upper femur Fy (kN)	-2.3	-2.9
left upper femur Mx (Nm)	-338	-410
right upper femur Fy (kN)	-5.0	-3.5
right upper femur Mx (Nm)	-673	-443

Test Data

In the 20 km/h tests, the risk of sustaining life threatening brain or chest injury was low for all tests. However, injury severity patterns varied with the vehicle configuration. For the tests without a bull bar, the dummy impact onto the bonnet yielded higher data values than those tests with a bull bar.

The correlation in the data was poor for ground impacts in the 20 km/h test series. This was probably due to the arms breaking the fall in some tests. Therefore, conclusions cannot be drawn about ground fall severity in the various test configurations.

The results from the 30 km/h tests show that the configuration without the bull bar frequently recorded higher data values for the impact onto the bonnet.

Data Correlation to Humans

Many of the leg responses measured significantly exceeded documented human tolerances, without failure of the corresponding dummy components. This raises biofidelity issues of the suitability of the legs of the dummy to realistically evaluate pedestrian injury, even at such low test speeds.

Whilst results obtained for leg injury could not be directly compared to the criteria of Cesari et al,[5] due to the instrumentation limitations of existing dummy legs, some human tolerance parameters could be used as a guideline for evaluation of leg injury implications.

Upper tibia lateral bending moments on both legs in the 20 km/h tests significantly exceeded published human tolerances. Kajzer et al[6] quote a peak moment of 123 ± 35 Nm for an impact velocity of 20 km/h for medial collateral ligament rupture, which is ratified by Ramet et al[7] who quote an average bending moment of 134 Nm for first injuries of the knee.

Values obtained for the right upper tibia of the dummy tests range from 328 Nm to over 1000 Nm for the 20 km/h tests. Repeatability of the data was poor. However, bending moments of this magnitude would certainly imply ligament rupture and possible bone fracture. Resultant dummy damage did not reflect this. Indications are that dummy knee stiffness is excessive, and lacks the necessary degrees of freedom.

Upper femur lateral bending moments are limited to 220 Nm by proposed EEVC[5] guidelines. Bending moment

Table 3
Injury Values for Vehicle Impact – 20 km/h Tests

	Test B6005 No bull bar	Test B6006 Bull Bar 1	Test B6007 Bull Bar 2	Test B6008 No bull bar
HIC	198	40	26	272
head peak g, (3 ms clip)	80	30	23	70
chest peak g, (3ms clip)	12	9.6	8.2	11.5
pelvis peak g, (3ms clip)	19	28	24	18
lumbar force peak (kN)	2.0	2.2	2.0	2.1
lumbar moment peak (Nm)	122	156	147	204
Left upper femur Fy (kN)	-2.4	-1.9	-1.5	-1.5
Left upper femur Mx (Nm)	-370	-227	-220	-253
Left upper tibia Mx (Nm)	>-456 (clipped)	-451	-365	-582
Right upper femur Fy (kN)	-4.1	-3.2	-3.0	-3.3
Right upper femur Mx (Nm)	-507	-443	-447	-464
Right upper tibia Mx (Nm)	>-371 (clipped)	-556	-328	-1004

values obtained for the right leg in the 20 km/h tests ranged from 443 Nm to 507 Nm, clearly exceeding human injury tolerances. On the dummy these significant bending moments resulted in minor contacts to the femur ball shaft. Whilst these values were acceptably repeatable, there was no discernible difference due to the presence of a bull bar at 20 km/h.

However, at 30 km/h the right upper femur parameters are higher in the bull bar configuration.

Dummy Damage

No bull Bar Tests, 20 km/h – In both tests without the bull bar, there was lateral binding of the right ankle joint, probably due to the onset of primary impact forces. There was also light contact to femur ball shafts. However, no damage was evident.

Bull Bar 1 Test, 20 km/h – There was no ankle damage in this test. However, both knee stops were replaced due to bending set. The right knee stop was more bent than the left. There was light contact to the right femur ball shaft. However, no damage was evident.

Bull Bar 2 Test, 20 km/h – Rib no 1 was contacted by the clavicle on the left side. This contact caused rib mis-alignment. This was probably due to contact with the ground, with the clavicle digging into the ground. There was light contact to the right femur ball shaft. However, no damage was evident.

No Bull Bar Test, 30 km/h – The lower rib cage shifted to the left by 5mm. There were slight indents to the femur ball shafts. However, this damage was not considered of consequence. The right knee stop completely sheared off. The left knee stop was undamaged.

Bull Bar 2 Test, 30 km/h – Whilst rib symmetry was satisfactory, there was a slight shift of the lower rib cage to the left side. There was light contact to both femur ball shafts. However, no damage was evident. Both knee stops were replaced due to bending damage, the right stop being more severely damaged than the left. There was slight binding of the right ankle. However, ankles retained a full range of motion.

CONCLUSION

This paper describes some exploratory research into pedestrian kinematics, using Hybrid-III anthropometric test dummies with a standard pedestrian conversion kit in impacts with various car fronts.

In brief, what was found was that the biofidelity of the Hybrid-IIIP ATD, in substantially side on pedestrian impacts, was too poor to conduct such evaluations.

Whilst there were some indications of such a possibility prior to commencing the work, an overall impression had been gained from the existing literature that, if used with care, the Hybrid-III ATD had sufficient biofidelity to conduct pedestrian impact research.

The conclusions regarding the poor pedestrian biofidelity of the Hybrid-III ATD arose from subsequent comparisons with cadaver pedestrian impacts and cadaver tolerance testing.

REFERENCES

1. RTA Mass Crash Data

2. Brooks, D, Wiechel, J, Sens, M, Guenther, D, "A Comprehensive Review of Pedestrian Impact Reconstruction", Accident Reconstruction Technologies: Pedestrians & Motorcycles in Automotive Collisions SAE 870605

3. Brun-Cassan, F, Vallee, et al, "Reconstruction of Actual Car-Pedestrian Collisions with Dummy and Cadavers", Pedestrian Impact Injury & Assessment P-121, SAE 1983

4. Cesari, D, Cavallero, C, et al, "Effects of Crash Conditions on Pedestrian Leg Kinematics and Injuries Based on Cadaver and Dummy Tests", 29th Proceedings American Association for Automotive Medicine, 1985

5. European Experimental Vehicles Committee, "EEVC Working Group 10 Report – Proposals for Methods to Evaluate Pedestrian Protection for Passenger Cars", November 1994

6. Kajzer, J, Chalmers University of Technology, Cavallero, C, Bonnoit, J, Morjane, A, Ghanouchi, S, INRETS, "Response of the Knee Joint in Lateral Impact: Effect of Bending Moment", 1993 International Conference on the Biomechanics of Impacts

7. Ramet, M, Bouquet, R, Bermond, F, Caire, Y, "Shearing and Bending Human Knee Joint Tests in Quasi-Static Lateral Load", INRETS LBSU, 1995 International IRCOBI Conference on the Biomechanics of Impact

HEAD RESTRAINT MEASURING DEVICE

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ABSTRACT

Soft tissue neck injuries sustained in rear-end impacts (so called 'whiplash" injuries) are the most common type of injuries resulting from motor vehicle accidents. In fact, in Canada, these injuries exceed all other types of injuries combined.

In support of efforts to reduce the incidence and severity of these types of injuries, criteria for adequate head restraint position have been developed based on minimum height and set-back requirements. The North American fleet of 1996 model vehicles was measured against these criteria and 79% of 148 vehicles failed to meet the minimum criteria. In order to enable accurate and repeatable measurements of head restraint position, a Head Restraint Measuring Device was used.

This paper reviews the design and use of this device. The device is useful for measurement and rating of current motor vehicles, support of current or proposed motor vehicle regulations, and design of future vehicles.

INTRODUCTION

The estimated costs of soft tissue neck injuries to insurance companies across Canada is two billion dollars annually. These injuries are variously reported as neck pain, stiffness, reduced range of head motion, headaches and back pain. In British Columbia, soft tissue neck injuries account for about 70 per cent of all injury claims to the Insurance Corporation of British Columbia (ICBC). ICBC is Canada's largest automobile insurer with 1.7 million policy holders. As a Crown corporation ICBC's mandate is also to reduce the risk of road transportation for all British Columbians.

A number of studies have reported that the likelihood of soft tissue neck injuries sustained in low speed rear-end collisions can be reduced through improved head restraint and seat designs [Langwieder, Hummel and Sagerer, 1981; Lövsund, Nygren, Salen and Tingvall, 1988; Kahane, 1982; Nygren, Gustaffson and Tingvall, 1985]. Although the characteristics of the vehicle seat and seat belt usage influence the effectiveness of head restraints, to be effective head restraints must be correctly positioned. They need to be close behind the occupant's head and provide support or restraint for the head at the centre of gravity.

For the past four years, the Insurance Corporation of British Columbia has published an annual guide *How to Buy a Better Auto* which compares different model automobiles across basic safety features, one of which is the head restraint. For the first three years, the height and horizontal offset of the fully lowered head restraint of the driver's seat of each vehicle were measured using an "average" adult male subject and rated as good, fair or poor according to the following criteria:

Good: Adequate height for an average person and less than 10 cm from the back of their head.
Fair: Adequate height, but more than 10 cm from the back of the head.
Poor: Can be adjusted too low to be effective.

Many head restraint designs failed to meet these requirements for the adult occupant population. In 1995, the Head Restraint Measuring Device (HRMD) was developed for the Insurance Corporation of British Columbia (ICBC) to provide an accurate and repeatable means of measuring the position of head restraints in passenger vehicles.

DESIGN

The Head Restraint Measuring Device attaches to a standard SAE three-dimensional H-point machine. The HRMD comprises an anthropomorphic headform approximating the head of a 50^{th} percentile adult. The headform incorporates two probes, one to measure the vertical height of the head restraint relative to the top of the test headform and the other to measure the horizontal distance or "setback" from the back of the headform to the head restraint. The headform is secured to a bracket and the entire unit is mounted on the SAE H-point machine. The neck joint is then adjusted to level the headform.

The position of the headform relative to the H-point was determined using anthropometric data collected by the Transportation Research Institute at the University of Michigan [National Highway Safety Administration, 1983]. This data is based on the seating measurements of adult male subjects in a contoured hard-seat with a seat-back angle of approximately 25 degrees back from the vertical. Accordingly head restraint measurements

taken with the ICBC Head Restraint Measuring Device are made with the vehicle seat-back angle set at 25 degrees.

RESULTS

The Head Restraint Measuring Device (Figure 1) was used by ICBC to measure head restraints for the 1996 *How to Buy a Better Auto* [ICBC, 1996]. The ICBC *How to Buy a Better Auto* is written to provide consumers with guidelines to identify those vehicles in today's market which provide the best available head restraint position. All adjustable head restraints were measured in the fully down position to reflect local surveys which show the majority of drivers fail to adjust the head restraint correctly [Lubin and Sehmer, 1993; Viano and Gargan, 1995]. Both the vertical height and setback of the head restraints in the front seats were measured using the HRMD. Only 21% received a good overall rating in accordance with the criteria previously described.

Head Restraint Height

Of the 148 new passenger vehicles measured, 41% of the head restraints failed to meet the minimum criteria that the top of the head restraint should be at or above the position corresponding to the centre of gravity of the head or the top of the ears of a 50th percentile adult occupant. Again adjustable head restraints were measured in the fully down position. At an international meeting in Lyon, a group of experts agreed that the minimum head restraint height should correspond to the top of the head of a 50th percentile adult male seated in the vehicle seat [Tarrière, 1994].

Head Restraint Setback

There is general agreement that an effective head restraint should be close to the head. In the ICBC measurements, head restraint setback was rated good if the horizontal distance from the back of the HRMD headform to the front surface of the head restraint was

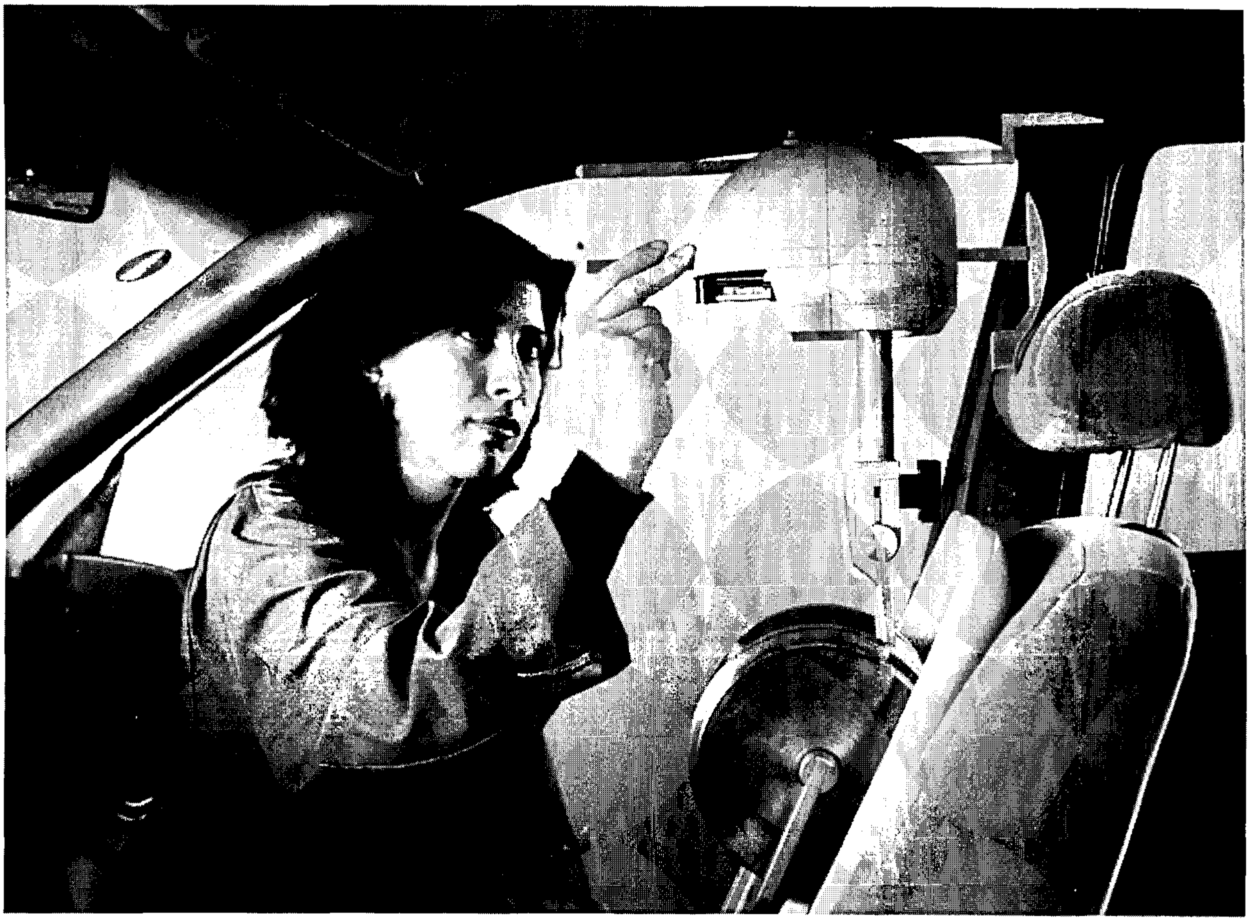

Figure 1. The ICBC Head Restraint Measuring Device.

less than 10 cm. Only 49% of the vehicles obtained a "good" head restraint setback rating. It is of note that it has been demonstrated that the rearward angular displacement of the head can be up to four times greater if the head restraint is 10 cm back from the head as opposed to 4 cm [Svensson, Lövsund, Håland and Larsson, 1993].

SUMMARY

The HRMD has proved an effective tool in measuring head restraint position to provide comparative ratings for consumer guidance in buying vehicles. It has been used by a number of other agencies around the world to assess head restraint position. Although the "best" head restraint position for reducing and preventing soft tissue neck injuries will also be influenced by the characteristics of the vehicle seat and seat belt use, the HRMD provides an immediate means of identifying head restraints most likely to be effective in reducing neck injuries. It has potential as a regulatory tool and ICBC is working to effect changes in current national regulations to encourage improved head restraint position in vehicles to accommodate a larger percentage of the adult population and so reduce soft tissue neck injuries.

REFERENCES

ICBC (1996) *How to Buy a Better Auto, 1996 Model Year,* Insurance Corporation of British Columbia Publication No. PI153(0196).

Kahane, C.J. (1982) *An Evaluation of Head Restraints:* Federal Motor Vehicle Safety Standard 202. U.S. National Highway Traffic Safety Administration, Washington, D.C.

Langwieder, K., Hummel, Th., and Sagerer, F. (1981) *Characteristics of Neck Injuries of Car Occupants.* Proceedings of the International IRCOBI Conference on the Biomechanics of Impact, Salon de Provence, France.

Lövsund, P., Nygren, Å., Salen, B., and Tingvall, C. (1988) *Neck Injuries in Rear End Collisions Among Front and Rear Seat Occupants.* International IRCOBI Conference on the Biomechanics of Impacts, Bergisch-Gladbach, Federal Republic of Germany.

Lubin, S., and Sehmer, J. (1993) "Are Automobile Head Restraints Used Effectively?" *Canadian Family Physician,* Volume 39, pp. 1584-1588

National Highway Traffic Safety Administration (1983) *Anthropometry of Motor Vehicle Occupants, Specifications and Drawings.* Drawing No. MM-104 Anthropometric Specifications for Mid-Sized Dummy, Transportation Research Institute, The University of Michigan.

Nygren, Å., Gustaffson, H., and Tingvall, C. (1985) *Effects of Different Types of Headrests in Rear-End Collisions.* 10th International Technical Conference on Experimental Safety Vehicles. U.S. Department of Transportation, National Highway Traffic Safety Administration.

Svensson, M.Y., Lövsund, P., Håland, Y. and Larsson, S. (1993) *The Influence of Seat-Back and Head Restraint Properties on the Head-Neck Motion During Rear Impact.* Proceedings of the International IRCOBI Conference on the Biomechanics of Impact, Eindhoven, The Netherlands.

Tarrière, C. (1994) Recommendations from Meeting in Lyon of International Group of Experts for the Improvement of Head Restraints. Automobile Biomedical Department of Renault, France.

Viano, D.C. and Gargan, M.F. (1995) *Headrest Position During Normal Driving: Implications to Neck Injury Risks in Rear Crashes.* 39th Annual Proceedings of the Association for the Advancement of Automotive Medicine, Chicago, Illinois.

BELT PRETENSIONING AND STANDARDIZED "SLACK" DUMMY

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ABSTRACT

Belt pretensioning systems are more and more prevalent in todays vehicles and their contribution will influence accident statistics positively.

Current developments are using test procedures and requirements not reflecting real life situations regarding slack. Field studies show that most occupants have a huge amount of slack in their belt system during normal operation.

Belt slack has a big influence on the performance of restraint systems and can therefore not be ignored in dynamic laboratory tests.

This paper proposes an improved test method with standardized slack, in order to make systems comparable and show customers the real advantages of pretensioning.

INTRODUCTION

Manufacturers of passenger cars has to test their vehicles according to legal requirements regarding occupant protection. Standards like FMVSS, ECE, ADR etc. must be meet before they can sell their products.

All these standards are defining minimum requirements for the performance of restraint system in certain vehicles. These standardized test conditions allow direct comparison of all test results, but should also reflect a high percentage of real world conditions. Therefore an average set up would most likely use the 50%tile male dummy sitting on the seat in mid position of the longitudinal adjustment.

But a test dummy dressed in underwear along with a tightly pulled seat belt around his body has nothing in common with the real world situation.

FIELD STUDY RESULTS

Autoliv has conducted two field studies regarding the amount of belt slack in real life conditions.

One has been conducted in Gothenburg, Sweden, together with Chalmers University, the other one in Munich, Germany. The Swedish study shows, that 80% of all drivers have a belt slack between 40 - 90 mm during summer months and 40 - 120 mm during the winter months, (Figure 1.). The average value measured was 58 mm slack (male) and 72 mm (female) during the summer, 62 mm (male) and 100 mm (female) during the winter.

The German study shows similar results for the summer season whereas the evaluation for winter has not been completed yet. The amount of belt slack was higher in the lap belt than in the shoulder belt.

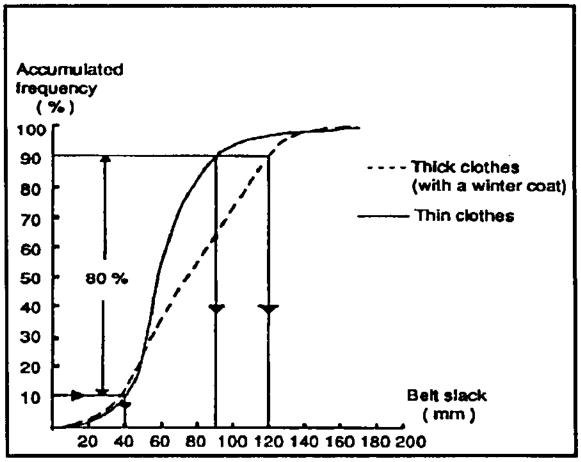

Figure 1. Frequency of belt slack dependent on clothes.

The results of these two field studies indicate that 80 mm belt slack should be used as a minimum requirement during all dynamic tests to represent real life situations. To cover 80% of belt slack in the field at least 100 mm should be used for testing. The distribution between lap and shoulder belt should be 60% : 40% as indicated in the studies.

OPTIMIZED BELT SYSTEM - CUSTOMER OPINION AND SAFETY

The user of a car has a completely different opinion of a optimized restraint system as that of the safety engineer (as long as there is no accident) (Figure 2.).

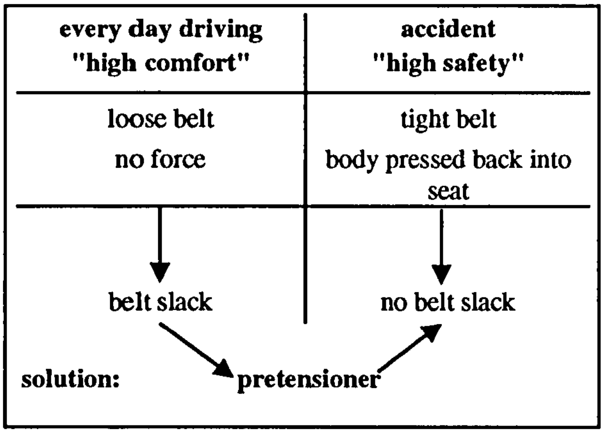

Figure 2. Requirements for a restraint system.

The occupant of a car wants to have a seat belt which is very comfortable to wear.

An easy to use and comfortable fitting seat belt system is one of the most important solutions to increase seat belt usage rates. Belt slack due to low belt retraction forces is a result of these demands.

But these demands are contradictory to the requirements for a seat belt system during an accident. In this case the occupant should be coupled to the decelerating car as soon as possible without any delay caused by belt slack.

One possibility to solve this problem is the use of a pretensioner in the seat belt system. The pretensioner eliminates the negative effect of belt slack in car crashes and therefore is the optimized solution for the users demands: "loose" belt during normal use and tight belt during an accident.

INFLUENCE OF BELT SLACK

Belt slack has a non negligible effect on the performance of restraint systems.

With belt slack the risk of submarining is increased as shown by a study of Autoliv Sweden and the Chalmers University, Sweden .

To investigate the influence of belt slack for different belt systems a series of sled tests were conducted. Test velocity was 56 km/h (35 mph) while crash pulse and dummy kinematics were correlated to a full scale crash. A reinforced body equipped with new interior for each test was used.

The baseline test configuration was a three point belt system along with a driver side airbag. The dummy was dressed and positioned according to FMVSS 208.

100 mm belt slack was then inserted in the belt system by using soft foam pads for the next test series. Some injury values such as HIC increased significantly due to belt slack whereas the chest acceleration showed only a minor increase (Figure 3.).

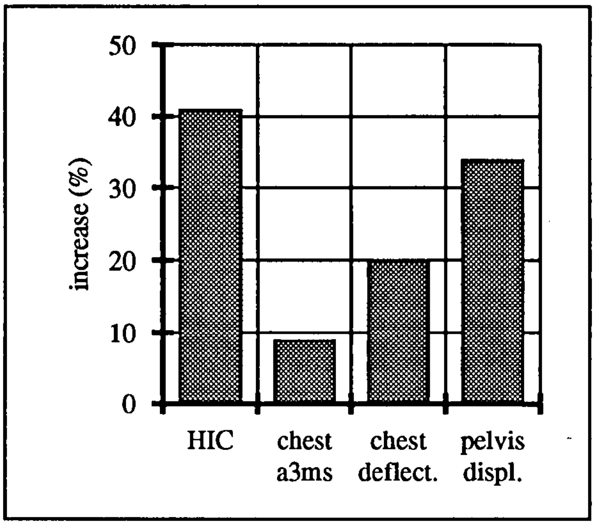

Figure 3. Increase of injury criteria caused by 100mm belt slack in comparison to standardized test method (no slack).

The head motion graph shows an 9% increased forward displacement with belt slack (Figure 4.).

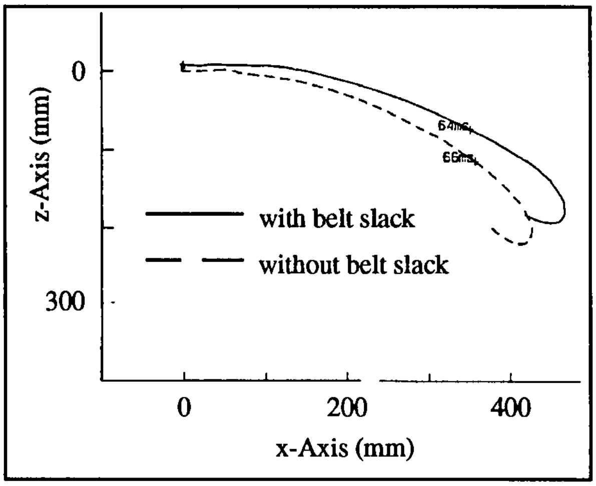

Figure 4. Head motion graph with and without belt slack

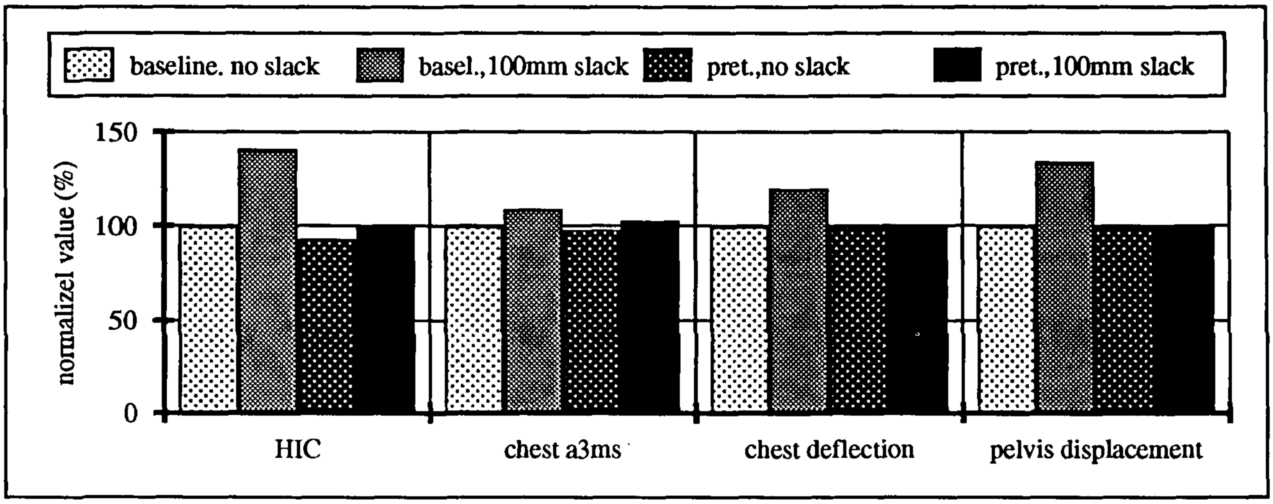

Figure 5. Change of injury values for different belt systems due to belt slack (100%=baseline system, no slack)

The downside of later coupling of the dummy to the vehicles deceleration, caused by belt slack, can also be observed in a later rise of belt forces.

Test results show that even the presence of an airbag cannot compensate for the negative effects of belt slack.

As a next step a buckle pretensioner was used in addition to the standard 3 point belt system. The values were similar to the baseline system if tested under standard conditions and also when 100mm of belt slack was used (Figure 5.).

This proves that pretensioners can eliminate the negative effect of belt slack that may be present during an accident.

A comparison study between pyrotechnical buckle pretensioner and pyrotechnical retractor pretensioner was conducted to check the effectiveness of both systems. Test parameters that varied were seat types, belt slack, pretensioner types and pretensioner performance.

Table 1.
Effects of Pretensioner Type

	Driver		Passenger	
	Buckle Pretensioner	Retractor Pretensioner	Buckle Pretensioner	Retractor Pretensioner
HIC 36	+	-	+	-
Head a3ms	+	-	+	-
Head displacement	o	o	o	o
Chest a3ms	o	o	+	o
Chest deflection	o	+	+	-
Chest displacement	+	-	+	o
Pelvis a3ms	o	o	+	o
Pelvis displacement	+	-	+	-

The design of experiments variance analysis showed that the buckle pretensioner is more effective (Table 1.). The results also show that the buckle pretensioner is particularly efficient if a high amount of lap belt slack is present which is often the case as found in the field studies.

TEST METHODS WITH STANDARDIZED SLACK

In order to simulate real world conditions, belt slack should be introduced into the test procedures. The question is what is the right amount of slack and how to simulate it in a standardized way. The field studies indicate that 100mm of belt slack represents approximately 80% of all cases and seems therefore to be a suitable value.

Belt slack is mostly caused by padded clothes or loose belts. For these reason an item introduced during a test to simulate belt slack should be also made from a soft material like foam.

The following methods are possible to obtain a certain amount of belt slack in the belt system:

- small foam pads
- use of a lined vest
- "chest size" foam pad

The use of a lined vest, - as used in the consumer

test of the "which ?" magazine in the UK - changes the seating position of the dummy. Reproducibility of the amount of slack for each test is also difficult.

The use of small foam pads placed underneath the lap and shoulder belt is another possible solution to create slack. But it is difficult to meet the some position of the pads for every test and to fix the pads underneath the belt. Even with a very soft foam used point loading of the dummy can not be avoided.

We propose therefore the use of a larger foam pad shaped like the dummies frontal body area on the inner side. The pad should be taped to the dummy to guarantee reproducibility. The dummy seating procedure should be the same as in FMVSS 208 except for placing and adjusting the seat belt.

Proposed procedure: Place the belt around the test dummy and fasten the latch. Pull the belt webbing out of the retractor and introduce slack into the lap and shoulder belt. Allow the retractor to retract. Apply a low force (to be defined) to the lap belt and then the same force to the shoulder belt. Allow the retractor to retract.

The thickness and stiffness of the foam pad has to be defined so that after this procedure 100 mm of slack remains in the seat belt system. With this test procedure the same reproducibility should be achieved as with the current procedure.

Together with the dummy manufacturers we are working on an hardware proposal.

SUMMARY

Field studies show that belt slack of a non negligible amount is a fact in real world situations. The results in the studies indicate that it is not realistic to perform dynamic crash tests with dummies wearing only a very thin shirt ("naked dummy").

Dynamic tests should also be performed with a realistic amount of belt slack. For example, 100 mm, distributed 60% : 40% between lap and shoulder belt.

As sled tests show, different types of belt systems are more or less influenced by belt slack. Pretensioners minimize the effects of belt slack and will therefore influence the accident statistics positively.

To create standardized belt slack the use of an foam pad attached to the test dummies chest seems to be a realistic and reproducible solution.

REFERENCES

Dermanovic, A., "Field Study of Slack in Car Seat Belts",Students graduate work. Dept. of Injury Prevention.Chalmers University of Technology, Göteborg, Sweden, Sept.1993.

Pilatus, K., "Internal Report", Autoliv Germany, 1995, paper to be published

Haland, Y., Nilson, G., "Seat Belt Pretensioners to Avoid the Risc of Submarining - A Study of Lap Belt Slippage Factors". 13.ESV Conference, Paris, Nov.1991

DEVELOPMENT OF MADYMO P6 CHILD DUMMY MODEL

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ABSTRACT

In this paper the development of a P6 child dummy model for the multi body system (MBS) program „MADYMO-3D" is demonstrated, thus making possible the evaluation of the results obtained during the simulations with the model. The P6 model was developped in cooperation with TNO on the basis of technical drawings, measurements on the dummy and the P3/4 model. The data base is constructed according to the P3/4 model for compatibility reasons of the child dummy data bases. The P3 model was developping during the genesis of the P6 model. The basis for the tuning of the P6 model are sled tests for frontal and side impact, three of each, which were carried out with the P6 child dummy on the pneumatic test device. These tests were subsequently simulated on the computer, the parameter were tuned and the P6 model validated.

INTRODUCTION

Computer simulation by aid of the MBS system is an acknowleged means for the passive safety design of motor vehicles. There are several models of anthropomorphic test devices in the form of data bases for the MADYMO-3D program. Apart from the different „Hybrid III" models for frontal impact and the different side impact dummies (SID) there now also exist child dummies for P3/4, P3 and P6. The MADYMO-3D program as well as the child dummies to the data bases are produced and sold by TNO Industrial Research, Netherlands.

TNO P-SERIES OF CHILD DUMMIES

During the mid 70s an United Nations group of experts began to elaborate prescriptions for Child Restraint Systems (CRS). Therefore a number of different child dummies that represented children of different age groups were needed. This series of child dummies was named and developped as „P-Series" (P for Pinocchio) by TNO. By now the P-Series consists of 6 dummies representing different age groups, each name indicating the age represented: P0 (new born), P3/4 (9 months), P1 ½ (18 months), P3 (3 years), P6 (6 years) and P10 (10 years). The dummies are constructed in the same type on the basis of anthropometric data of children of each age group (with exception of P0) and only differ in the sizes. Child dummies mainly consist of a metal skeleton surrounded by elastic foam material (Figure 1.).

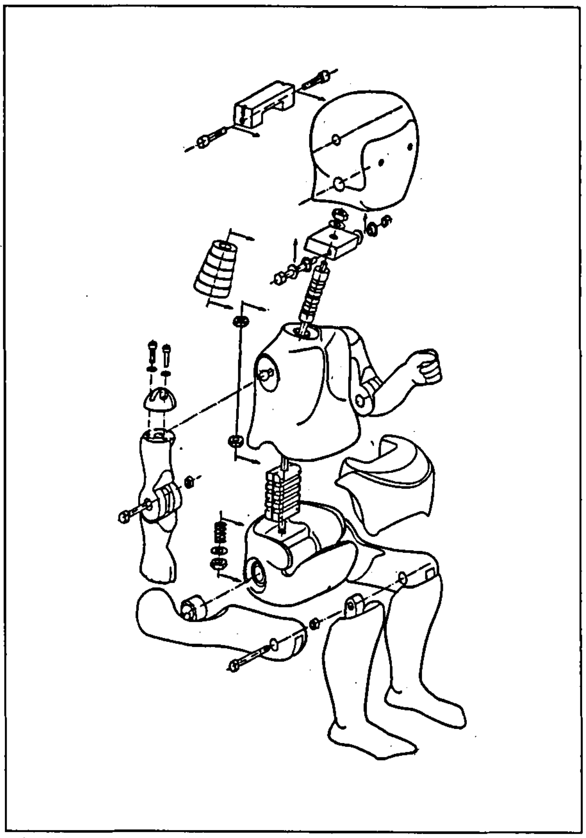

Figure 1. Exploded view of a TNO child dummy

P6 CHILD DUMMY MODEL DEVELOPMENT

The development of the P6 model mainly consits of the three following steps:

- creation of a P6 data base
- validation and calibration tests
- computer simulation of the tests and tuning of the P6 model

Generation Of The P6- Database

The first P6 data base was developped and scaled on the basis of the P3/4 data base (Vers. 2.1). The tree structures of the two models, P3/4 and P6, are identical. The numbering of the parts of the body was maintained in order to make possible the taking over of the interfaces between the dummy model and the other data structures when interchanging the different child dummy models. The scaling was made on the basis of the similarity mechanics.

Similarity Mechanics - A geometrical or dynamic similarity between the real carrying out and the model consists, if for the basic values as length l, measurements m, etc. the scaling factors are maintained for all points of the system. In order to scale the P6 model on the basis of the P3/4 model the components of the body are regarded one by one and thereof the scaling factors „R" are developped for the scaling of the moments of inertia and the force models. The length scaling factors *R(l)* for the three space dimensions are determined from the technical drawings, the mass scaling factors *R(m)* are determined by comparing the body masses of P6 and P3/4. Thus four scaling factors result for each body: $R(l_x)$, $R(l_y)$, $R(l_z)$ and *R(m)*. From these result the scaling factors $R(I_{xx})$, $R(I_{yy})$, $R(I_{zz})$ for the moments of inertia, $R(I_{xx})$ serving as example:

$$R(I_{xx}) = R(m)\left(1+\frac{I_z}{I_y}\right)\frac{R(I_z)^2\,R(I_y)^2}{\left(\frac{I_z}{I_y}\right)^2 R(I_y)^2 + R(I_z)^2} \qquad (1.)$$

The scaling factors for the determination of the elastic and damping moments correspond to the moments of mass inertia. The scale factors of the friction moments (M_f) are determined as:

$$R(m_f) = R(m)\cdot R(R) \qquad (2.)$$

R(R) being the scaling factor of the friction radius in the joints.

Geometry - The joint locations coordinates are taken from the technical drawings. The same joint types as with the P3/4 data base are used; the joint type determines the number of freedom degrees of a joint and the number is predetermined by construction. The positioning of the bodies to each other largely corresponds to the P3/4 data base, i.e. it is chosen that way. The dummy takes a sitting position, the arms bent. Neck and Atlas Block are bent foreward by 5° with respect to the upper part of the body, unlike the P3/4 which is bent by 10°.

The gravity centre coordinates of the head, the lower legs, the upper legs upper arms and the lower arms were determined in the test. The gravity centre coordinates of all other bodies were obtained by scaling the P3/4 data base. Each body of the dummy model is assigned a surface in the form of an ellipsoid. The geometrical data of the ellipsoids are taken from the technical drawings. By defining additional ellipsoids for the feet, the hands, the chin and the shoulders the dummy model is made as exact as possible.

Masses and Moments Of Inertia - The P6-dummy has a total weight of 22,0 ± 0,75 kg. The masses of the parts of the body were weighed and compared to the producer's statements. All values lie within the tolerances indicated by the producer. The moments of mass inertia of all bodies were scaled on the basis of the P3/4 values. The moments of mass inertia of the arms and legs were controlled by calculation with the formulation for the moment of inertia of a cylinder. The results of this calculation were nearly identical with the indications. The maximum deviations were of about 11%. In addition to this the moments of mass inertia of the arms, lower legs and the head were determined by means of a pendulum test. The deviation of the scaled values was of 13% maximum; that of the lower arms, however, was of 26%. The deviation is the bigger the smaller the moment of mass inertia is. Rounding the values on a certain number of decimal places causes a high percentage of inexactness in small values. Moreover, possible measuring faults have to be taken into account. The experimentally obtained values were used for the data base.

Force Models - Three different moments per degree of freedom can be defined for the dummy's joints: elastic load, damping load and friction load. The elastic load limits the movement of the joint, such the joint touches can be modeled. The data base takes into account that the head's movement possibilities are limited by construction on rotation angles between ·55° in the negative and 35° in the positive turning direction around the y-axis. The possible rotation angles for the P6's knee, ellbow and shoulder joints correspond to the P3/4's joints. The modeling of the elastic loads of the P6 data base is obtained by scaling the correspondent data of the P3/4 daba base. The damping moment depends on the speed change of the angle and is defined by a damping constant. The friction loads are defined by a ramp function in order to avoid numerical instabilities. They are dependend on the angle speed. If the angle speed is zero, no friction load is defined; a constant friction load only exists if a certain angle speed is reached. The damping and friction moments are scaled on the basis of the P3/4 data base.

Calibration and Validation Tests

P6-Dummy Calibration - It is necessary to calibrate the dummy before each slide test in oder to obtain reproduceable results. For this purpose the rotation joints are just fastened so far that friction force and mass force are equilibrated. The part of the spine cable that represents the lumbar vertebra is calibrated by tending the steel string until the spring on the lower torso is pressed to 2/3 of its unloaded length. The part of the spine clable which represents the cervical vertebra is calibrated by loading it with a defined mass and measuring the inclination of the neck. For that purpose the torso of the dummy is placed on an even surface with its backside; the bolt that normally is used to fasten the head to the atlas block is loaded with a vertical load of 50 N. The movement of the atlas block can be of 10 ± 1 mm in vertical direction; the bodies should not be rotated during this procedure.

Validation Tests - Three validation tests for frontal and side impact, three of each, were carried out on a pneumatic test device with the P6 child dummy. They are not carried out the dummy beeing slowed down from a certain initial speed but it is accelerated out of the immobile position. The acceleration puls of the slide corresponds to a half-sine-shaped deceleration with an impact speed of 30 - 35 km/h. The dummy is seated in an Atlas Royal CRS, the bench used corresponds to the ECE-R 44 specification and is positioned for the frontal and side impact. The belt system is of the simple 3-point type without belt pretensioner. The tests were filmed with a high speed camera (400 pictures/sec.) and of each of them 8 sequence fotos were made in order to seize the motion sequence of the dummy. Moreover, the head and torso acceleration (3 chanels each), the slide acceleration (1 chanel) and its speed (2 chanels) as well as the belt forces (4 chanels) were measured. The values of the frontal and the side imact were compared and the test that was closest to the mean in the decisive time zone up to 100ms was chosen as a reference. The results of the reference tests are shown in the comparison with the simulation.

P6- database Calibration and Validation

The calibration tests recommended for the child dummy represent a first possibility to adjust the models. The calibration tests are simulated with a scaled P6 data base and adjusted to it. Subsequently the CRS is adjusted by frontal impact tests in a first step. The data base obtained is the starting point for the next step, which is the adjustment of the P6 data base by frontal impact tests. Thus a P6 data base is obtained that is validated and modified by side impact tests. The masses, the moments of inertia and the whole geometry of the dummy remain the same. Adjustment and validation is made by changing the joint locations, i.e. the variation of the elastical moments of damping and friction. During the frontal impact the joints of the dummy are loaded to a negligeable extent in lateral direction by forces and moments; the same is to be said about the foreward movement during the side impact. When adjusting the joint locations the effects of changes on the interim results of the predecessing step have to be checked. To this purpose control calculations for calibration can be made after each adjustment by frontal or side impact tests.

Calibration Test Simulation - The computer simulation of the calibration of a dummy is only possible in part. The problem in simulating the rotation joints calibration is the dependance of the moment of friction on the angle speed during the simulation. As the bodies move very slowly against each other, i.e. the speed of the angles is very low, if the bodies are exposed to an acceleration field that corresponds to the gravitation field, the wished state of balance is reached in our opinion. The calibration of the lumber spine cannot be simulated whereas that of the neck spine is possible. For this purpose the dummy model - withouth head and legs - is placed on a surface just as described above. The Atlas joint is loaded by 50 N by increasing the load of the atlas block by 5 kg. The joint point which at the same time is the centre of the atlas block is moved by 10,25 mm in vertical direction by this force. This value lies within the prescribed tolerance. The location points of the joints of the neck spine thus correspond to the exigencies with respect to this degree of freedom (in the force area up to 50 N). The joint locations concerned were somewhat reduced in comparison with the scaled values in order the achieve this result.

Validation Test Simulation - For validatoin test simulation a basis data base has to be established where CRS, seat and 3-point belt are described by simple models according to the test construction. The 3-point belt is modeled in the same way as the MBS belt system. Moreover, the daba base contains the P6 data base and the acceleration field of the reference test. The parameters characteristic of retractors, belt pretension, belt slack, friction values, contact characteristics between dummy and CRS, between CRS and the seat as well as the position of the belt fastening points on the dummy are changed in such way that the movement of the dummy, the torso acceleration and the belt forces are largely the same in the test and in the simulation calculation. The validation of the P6 model is made on the basis of the basis data base modified in the described way. The location points of all joints except the hip joints can be

tuned and validated by simulation of the frontal impact test. The hip joints are too much limitated in their motion, i. e. the motion of the joints is not sufficient. After tuning and validating the model, the motion of the dummy corresponds quite well in test and simulation. The simulation of the sideward rotation of the upper body, the foreward bending of the torso and the head movement correspond well in test and simulation, too. The arm movement is different in simulation and reference test. However, the movement of the right arm can be adjusted in the simulation to the arm movement in the other two frontal impact tests by increasing the friction value between fist and seat cushion. The belt forces have a similar characteristics in simulation and test. The deviation is about 10% for the maximum values and the curve characteristics are largely the same. Larger deviations occur in the area of 50-60ms and are due to the more elastic reaction of the belt during the simulation.

Comparing the torso acceleration, the correspondance in the characteristic of simulation and test and that of the maximum accelerations are evident. The maximum values of the test and the simulation are very close in any of the three components. The x-components of the acceleration characteristic are partly the same and the deviation of the maximum values is of about 7%. The z-components of the characteristic suffer a time deviation; during the test the torso is accelerated 10 ms later, the acceleration is delayed. There is a good conformity of the maximum acceleration values, the deviations beeing of about 10%. It was possible to simulate the acceleration characteristics in direction of the y-axis. The maximum values correspond with each other in the decisive time area up to about 80ms. The conformity of the resultants is due to the conformity of the characteristics in the individual components (Figure 2.). Despite the conformity of kinematics and torso acceleration, the characteristics of head acceleration differ from each other to a greater extent. The curve characteristics in test and simulation are largely the same but the maximum accelerations of the test are not reached in the simulation.This mainly occurs with the x-component of the head acceleration (Figure 3.).

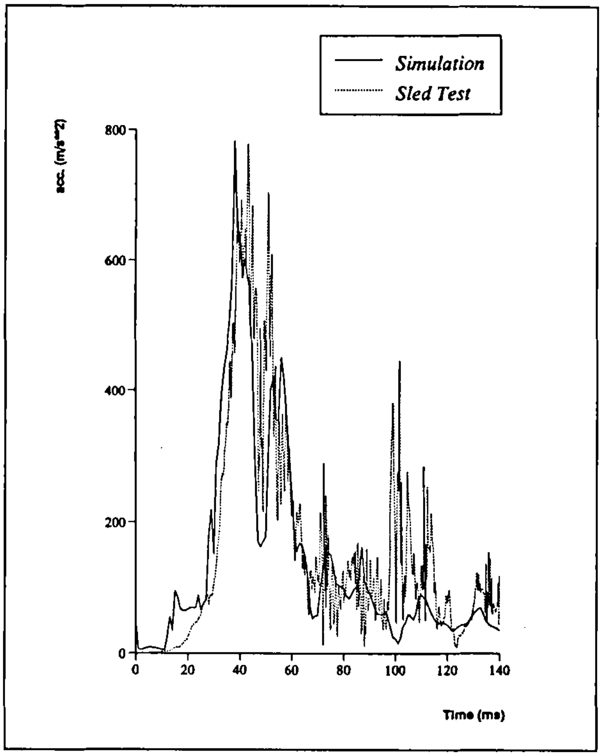

Figure 2. Frontal Impact Simulation: Resultant Upper Torso Acceleration

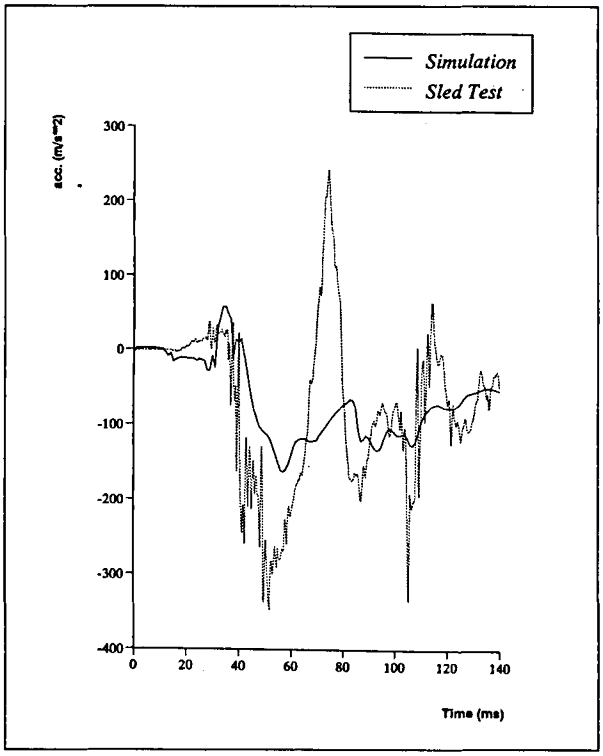

Figure 3. Frontal Impact Simulation: X- Component Head Acceleration

A greater conformity is reached in the characteristics and maxiumum values of the y- and z-components. However, the head acceleration in the simulation starts about 10ms earlier than during the test. The P6 data base validated by the frontal impact tests already constitutes a good immitation of the P6 child dummy. This is proved when comparing the P6 movement characteristics in side impact tests and in simulation. The side impact test was simulated with both, a MBS and a FEM belt. The cervical vertebra joint locations obtained by scaling the P3/4 data base and subsequent calibration condition a good conformity of the head movement with its simulation in side and frontal impact tests with a MBS belt. This is not valid for side impact test simulation with a FEM belt. This is due to the cervical vertebra beeing modeled with two rotation joints. In this case the two joints cannot immitate in a sufficient way the flexible steel string surrounded by the poliurethan discs. The belt force is introduced between the two joints, thus the neck can only be rotated in the upper neck joint. The lower neck joint is even twisted in opposite direction by the belt force. Moreover, the upper neck joint is more resistent against flexion than the lower one. This does not correspond to the geometrical situation. In reality the lower poliurethan discs have a bigger diameter than the upper ones which means that the upper neck joint should be more resistent against flexion. Taking this into account the flexion locations of the P6 neck joints were changed. The stiffness against flexion of the neck, however, had to remain approximately the same. This is why control calculations of the calibration test as well as of the frontal and side impact tests were carried out with the new joint locations. No considerable changes in the acceleration characteristics were obtained in frontal and side impact tests with MBS belt. The acceleration characteristics decribed in Figure 4. and Figure 5. have been obtained in side impact tests with FEM belt. The torso accelerations still correspond well in characteristics and maximum values. Concerning the head acceleration an improvement was obtained in comparison to the characteristics with the old joint locations. It was possible to approximate the x- and z-components of the head acceleration to the test values. However, this did not entail an improvment of the y-component.

The resulting head acceleration corresponds in test and simulation but conditioned by the changed movement the y-component share is too high and thus the z-component share too small. Despite small improvements the belt force characteristics do not correspond well only the maximum pelvis belt forces and the shoulder belt forces are similar. The correspondance of the kinematics is good except for the head motion. It was possible to obtain a good immitation of the rotation of the dummy around its z-axis.

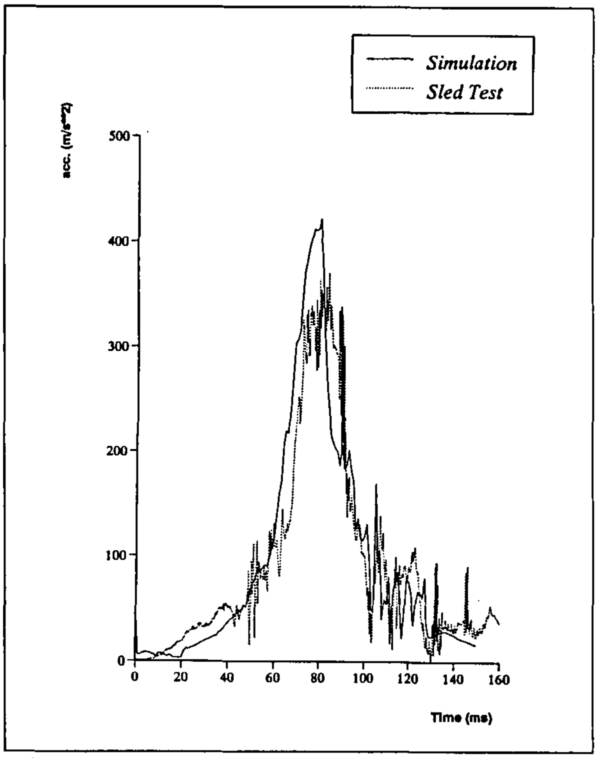

Figure 4. Lateral Impact Simulation: Resultant Upper Torso Acceleration

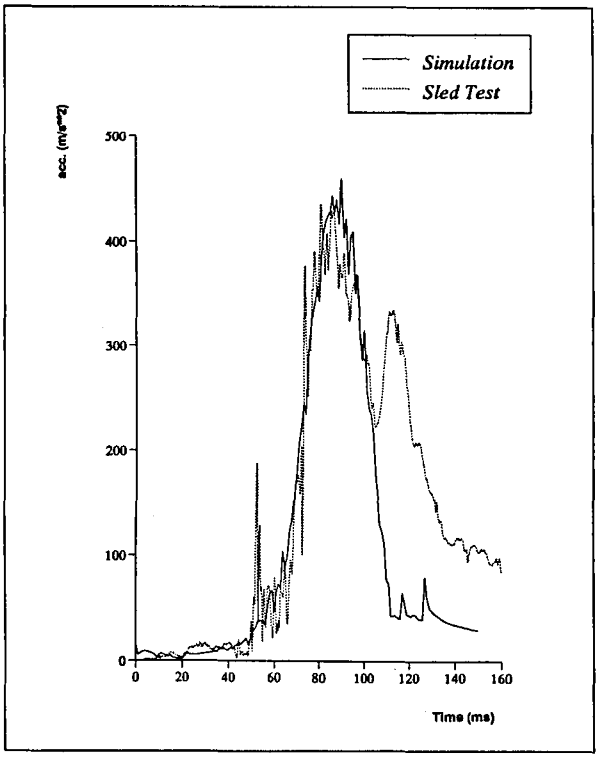

Figure 5. Lateral Impact Simulation: Resultant Head Acceleration

CONCLUSION

The P6 child dummy model developped is suitalbe for frontal impact test simulations with an impact speed of 30-35 km/h. The accelerations and belt force characteristics measured during the test as well as the kinetics correspond to the simulation results in all major points. The slide test for frontal impact carried out is comparable to a real crash test if the dummy has enough freedom of motion in the crash test. Apart of that the results should rather be evaluated in the qualitative sense. The use of MBS belts turned out to be unsuitable for side impact test simulations as the sideward sliding of the dummy from under the belt could not be simulated. However, it was possible to immitate well the head motion with this type of belt. It was possible to simulate the sideward sliding of the dummy from unter the belt by using the FEM belt. A good immitation of the dummy kinematics was achieved as well as a good correspondance of the rotation around the z-axis and the torso acceleration. Like in the test the dummy hangs with its neck in the shoulder belt but now the head motion and head acceleration do not correspond any more for the above mentioned reasons. The slide test carried out for the side impact cannot be compared to a real crash test as the normal environment, i.e. at least a limitation at the sides (e.g.: a door) does not exist. For the validation of the model, however, it is useful to do without the limitations in order to have as few parameters as possible in the data base and enough freedom of motion for the dummy. The use of the P6 model in side impact simulations is possible in principle. However, due to the above mentioned problems the results have to be analysed and evaluated critically.

ACKNOWLEDGEMENTS

We would like to thank TNO and especially M. Riender Happee for their kind support and the generous provision with the child dummy.

The views expressed in this paper are those of the authors alone and should not be interpreted otherwise.

REFERENCES

Beusenberg, M.C. et al., "Development and Design of a New 18-Month-Old Child Dummy". TNO Crash-Safety Research Centre, Delft, NL. Paper no. 94 S1 O 18 on "14th International Technical Conference on Enhanced Safety of Vehicles" in Munich. May 1994.

TNO Crash-Safety Research Centre, "TNO Child Dummies P3/4, P3, P6, P10, User Documentation". Delft, NL. April 1991

TNO Crash-Safety Research Centre, "MADYMO-3D Users' Manual". Version 5.1. Delft, NL. Mai 1994

Håland, I., "Feldstudie", Chalmers University Göteborg / Autoliv Research Sweden

Schüler, F., "Biomechanische Anforderungen an Kinderrückhaltesysteme". Vortrag anläßlich der Tagung "Kollisionsschutz" im Haus der Technik, Essen. Februar 1993

THE INFLUENCE OF SOME CRITICAL PARAMETERS ON THE SIMULATION OF THE DYNAMIC HUMAN ANKLE DORSIFLEXION RESPONSE

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ABSTRACT

In the automobile occupant safety, lower extremity protection is of growing concern. Indeed, the number of lethal injuries like head and thorax injury are decreased because of the protection mechanisms like the belt and the airbag. In addition, numerous lower extremity injuries have considerable public health implications.

At present, biomechanical tests were performed on the cadaver ankle/foot complex in the static and dynamic range in order to understand the injury mechanisms of the ankle/foot complex found in car crash.

However only a few numerical models of the human ankle/foot complex, in particular models with the diverse joints of the ankle/foot complex have been developed so far.

In a previous paper ([1]), the simulation of Begeman's tests permitted a preliminary calibration of a human ankle numerical model under impact loading. The objective was to simulate and understand the gross kinematics of the human ankle/foot complex during the dorsiflexion under impact loading. In this paper, after a brief description of the human ankle/foot model by the authors, the influence of the modeling of the soft tissues using a non-linear material model and of elastic bones is described. While the non-linear behavior of the soft tissues has not much influence on the global kinematics of the ankle/foot complex, the fact that the main bones are modeled by elastic shell elements instead of rigid bodies has a more pronounced effect on the dorsiflexion ankle under impact loading.

Therefore, in future work, more effort will go into modeling most of the bones as deformable. In addition, fractures criteria could be taken in account.

INTRODUCTION

Throughout this paper, the term ankle designates the region defined by the following bones (Figure 1):

- the distal part of the tibia (including the medial malleolus and the tibial pylon)
- the distal part of the fibula (including the lateral malleolus)
- the upper part of the talus,

and the region defined by the remaining foot bones (Figure 2).

It should be first noted that, although ankle/foot injuries are not lethal, they can result in serious impairment and disability. Permanent impairment can occur mainly when joint surfaces and ligaments are damaged or when fractures extend into the joint. Depending on injury and treatment, foot fractures can result in permanent partial impairment. In other respects, the ankle/foot injury mechanisms resulting from the specific case of road accident, where high impact energies are involved, are less known than the ones due to sport with low impact energy [3].

As was seen in the literature review of the previous paper [1], the ankle/foot injuries resulting from vehicle crash are skelatal like fractures, or internal like tendon tears, or ligament sprains ([2], [3], [4], [5], [6], [7] and [8]). Six mechanisms - contact with foot controls and contact with floor - which they consider the most frequent in vehicle crash were described by Morgan R. et al. [5]. These mechanisms correspond to a combination of ankle/foot simple movements like dorsiflexion, plantarflexion, pronation and supination These movements can be associated with direct or indirect loading conditions. Some ankle/foot injuries were identified as resulting from these movements. Dorsiflexion is a movement involved in several ankle/foot injury mechanisms in vehicle crash. This fact guided the

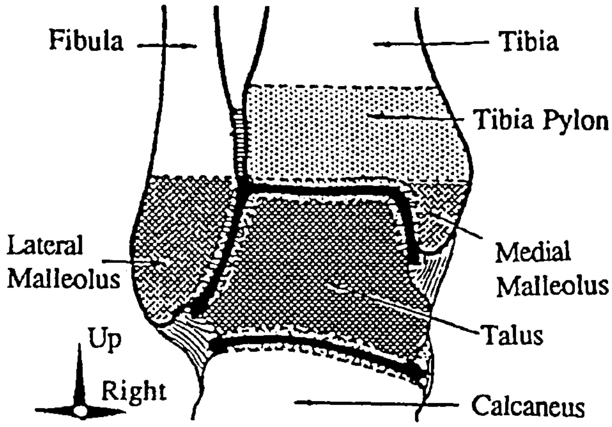

Figure 1: Frontal View of a Right Ankle Cut

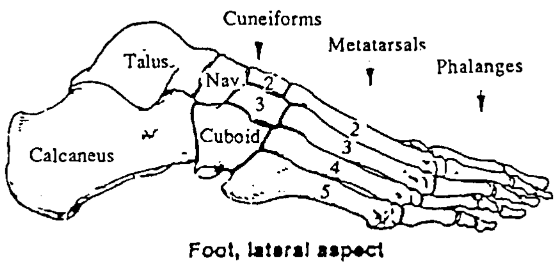

Figure 2: Lateral View of a Right Foot

research in selecting a dorsiflexion movement for the first simulation ([8], [9]), [7]).

DESCRIPTION OF THE MODELS

GEOMETRY - The finite element models correspond to an "average" right foot (Figure 3). It includes a geometrical description for all foot bones and the distal part of the tibia and the fibula, for the ankle ligaments and retinacula, for most of the foot ligaments and the Achilles tendon. A complete description can be found in [1].

FINITE ELEMENT MODELS - The diverse models have the same following representation of the biological components.

The bones are modeled as individual body shell surfaces. Ankle ligaments, retinacula and Achilles tendon are modeled by membrane elements, while foot ligaments are modeled with bars. The choice of membrane element for the presentation of the soft tissues (ligaments, retinacula and Achilles tendon) is due to their very structure. Like can be seen in the Figure 4, these soft tissues are composed of collagen and elastin fibers. The properties of the tissues depend on the properties and organization of these fibers. HAUT R. in [10] explains that the association and the network of these collagen and elastin fibers perform the specific function of the diverse soft tissues. For example, the ligament control function is due to the parallel arrangement of the collagen and elastin fibers. The membrane element material permits to model the fiber network. The properties of their microstructure are not taken into account, but the anisotropic elastic behavior of these soft tissues is thus represented. For the ligaments and the Achilles tendon the fibers are only in the longitudinal direction of the tissue. On the other hand, the retinacula are composed by longitudinal and transversal fibers.

Figure 4: Longitudinal Section through an Elastic Ligament (Elastin Fibers in Black) ([11])

The modeling of the joints remains the same than in the previous paper [1].

<u>Material Properties</u> - The significant difficulty for anatomical models resides in the choice of material properties. Linear or non-linear elastic properties found in the anatomical and biomechanical literature were taken for the bones, retinacula and Achilles tendon ([10], [11], [12], [13] and [14]).

For the ligaments, the tensile tests were used that were carried out by Professor Begeman at Wayne State University ([15]). The foot ligaments are modeled by the same nonlinear bar with a specified response curve for loading, unloading and reloading like in the previous work. For the ankle ligaments, a linear elastic and a nonlinear elastic with hysteresis membrane are calibrated.

For the surface contacts about the joints, the friction value was taken at 0.01 like articular hyaline cartilage friction which is between 0.01 and 0.02 ([11]).

The distinction between the different models presented here stands on the choice of material constitutive law used for the soft tissues and for the bones.

Model 1:

All bones are indivudual rigid bodies except for the phalanx which constitute a rigid body for each toe. The ankle ligaments, the retinacula and the Achilles tendon are linear elastic membrane elements (Table 1).

Table 1
Value Ranges of Soft Tissues and Bony Properties in the Model 1

Materials	Poisson's ratio	Young's modulus (N/mm^2)	Mass Density (10^{-9} t/mm^3)
bone	0.29	rigid body	2
Foot ligament		see [1]	1
Ankle ligament	0.22	88.2	1
retinaculum longitudinal direction	0.22	123.8	1
retinaculum transversal direction	0.22	111.2	1
Achilles tendon	0.22	574.5	1

Model 2:

All bones are modeled like in model 1. The ankle ligaments, the retinacula and the Achilles tendon are non-linear elastic with hysteresis membrane elements (see Table 2). In fact, in tensile tests the response of a soft tissue can be decomposed in four regions (Figure 5):

- in the first region, the elastin fibers are loaded, but the collagen fibers are uncrimping,

- in the second region, the elastin and some collagen fibers are loaded,

- all elastin and collagen fibers are loaded

- if the tension increases still, the failure of some collagen occurs.

Table 2
Value Ranges of Soft Tissues and Bony Properties in the Model 2

Materials	Poisson's ratio	Young's modulus (N/mm^2)	Mass Density (10^{-9} t/mm^3)
bone	0.29	rigid body	2
Foot ligament		see [1]	1
Ankle ligament	0.22	see Figure 6	1
retinaculum longitudinal direction	0.22	see Figure 7	1
retinaculum transversal direction	0.22	see Figure 7	1
Achilles tendon	0.22	see Figure 8	1

Model 3:

Over dorsiflexion can result in internal and external malleoli, talus and calcaneus fractures ([8]. [9]). At first, these bones are made in deformable material. They are modelled by elastic shell elements. The other bones remain rigid bodies. The ankle ligaments, the retinacula and the Achilles tendon are in linear elastic membrane elements like in the model 1.

Table 3
Value Ranges of Soft Tissues and Bony Properties in the Model 3

Materials	Poisson's ratio	Young's modulus (N/mm^2)	Mass Density (10^{-9} t/mm^3)
fibula	0.29	18900	2
tibia	0.29	18400	2
talus calcaneus	0.29	15000	2
other bone (rigid)	0.29	rigid body	2
Foot ligament		see [1]	1
Ankle ligament	0.22	88.2	1
retinaculum longitudinal direction	0.22	123.8	1
retinaculum transversal direction	0.22	111.2	1
Achilles tendon	0.22	574.5	1

THE INFLUENCE OF A FEW PARAMETERS ON DORSIFLEXION

OBJECTIVE - The objective is to present the influence of the diverse material consitutive laws used for the bone and the main soft tissues on the gross kinematics in the dynamic loadingof the ankle.

EXPERIMENTAL SETUP - The first step is a simulation of dynamic tests described in the paper by Begeman and Kopacz [9]. The five tests (numbers 10, 12, 13, 15 and 20) without injury are taken in account.

SIMULATION - For the three models, the same simulation is used like in the previous paper (see Figure 9 and Figure 10).

The initial positions of the ankle and the foot correspond to those of Begeman's tests. The tibia and the fibula are fixed for the simulation with rigid bones (models 1 and 2). For the model with a few deformable bones, the top of the fibula, the tibia and the Achilles tendon is fixed.

The non-linear explicit dynamic code PAM-SAFE™ was used for these simulations.

RESULTS - On the first hand, the results of the simulation with the model 1 and model 2 were compared with the measurements made in Begeman's tests with no injury (numbers 10, 12, 13, 15 and 20). On the other hand, the influence of deformable bones (model 3) on the kinematics of the ankle dorsiflexion is shown and these results are compared with those of the simulation with rigid bones (model 1) and of Begeman's tests.

For the test curves, a corridor with the maximum, minimum and average data value was established.

Influence of the material constitutive law used for the soft tissues - Figure 11 shows the impactor force magnitude for the simulation with model 1 and model 2 compared between the tests and the simulation. The peak force is roughly 9000 N for both simulations.

The reaction forces in the x-direction (the impact direction) on the heel are presented in Figure 12 with a peak at 4000 N for both simulations. But a difference appears when the talus rotates. The heel force with model 2 is smaller than the one with model 1 and is about zero at the dorsiflexion maximum. In relation to the Begeman test results this heel force value is too small.

The ball forces with model 1 and with model 2 are shown in Figure 13 with a peak at 2100 N and a peak at 1200 N, respectively. In average, we note that the ball force with model 1 is roughly twice as the one with the model 2. Both forces are about in the test corridor.

Figure 14 gives the dorsiflexion history as a function of time. The dorsiflexion is considered as the talus rotation about the transversal axis. Maximum dorsiflexions with model 1 and model 2 are roughly 31 and 33 degrees, respectively. Both values are in good agreement with Begeman's tests when no injury appears. It should be noted that the ankle joint movement is exactly a uni-axial rotation as that of a mortise. As described previously [1], for this articulation, no spring was used. It is the combination of the contact interface and the retaining ligaments, in particular the posterior fascicle of the internal lateral ligament, which controls the kinematics.

For both simulations, the four main steps describing the global kinematics of this dynamic test appear:

- the impact,
- the collapse of the longitudinal arch,
- the ankle rotation,
- the stop.

Both simulations could properly represent the global kinematics of the human foot under impact loading.

Influence of the material constitutive law used for the bones - The impactor force magnitudes for the simulation with model 1 and model 3 compared between the tests and the simulation are plotted in Figure 15. The peak force is roughly 9000 N for the both simulations.

Figure 16 gives the heel reaction forces with a peak at 4000 N for both simulations. The elastic property of the deformable bones acts on this contact roughly in the same manner as the non-linear elastic behavior of the soft tissues.

On the other hand, the influence of deformable bones on the ball force is inverted (Figure 17). The ball force peaks with model 1 and model 3 are at 2100 N and a peak at 3700 N, respectively. Indeed, this last reaction force differs between both simulations. For the simulation with model 3 the inital peak does not exist and during the rotation of the foot the force increases. This is not correlated with the results of the simulation with model 1 and of the test results. Perhaps this difference is due to the rigidity of the front versus the rear of the foot.

Figure 18 gives the dorsiflexion ankle for the simulations with model 1 and model 3. Maximum dorsiflexions are about 31 and 19 degrees, respectively. Both values are roughly in good agreement with Begeman's tests when no injury appears. But the kinematics of the talus are not the same in both simulations. Indeed, the model with deformable bones rotates more smoothly and less than the one with the rigid bones. This behavior can be explained by the fact that a part of the internal energy is absorbed by the deformable bones (roughly half of the total internal energy). If the plate rotations are considered, their peaks are 43 degrees with model 1 and 40 degrees with model 3 (they are plotted with "x" and "o" marks respectively in Figure 18). These values correspond to the rotation in the tests.

For both simulations, the four main steps describing the global kinematics of this dynamic test appear always in the same fashion.

The section through the Achilles tendon and the posterior fascile of the internal lateral ligament are plotted for both simulations. These results show that in the case of the simulation with deformable bones the tendon and this ligament are three times less solicited than in the case of the simulation with the rigid bones. This is correlated with the difference of the talus rotation between model 1 and 3.

CONCLUSION

The influence of the material constitutive laws used for the biological components has been studied.

It can be noted that the non-linear behavior of the soft tissues does not seem to have a real effect in the gross kinematics in this dynamic movement.

On the other hand, if the main bones are modeled by deformable bodies, this influences the rotation of the talus during dorsiflexion.

Other numerical simulations are being conducted currently on the same model for other loading situations such as the inversion-eversion dynamic response of the human ankle, static collapse of the foot longitudinal arch. It is expected that this incremental approach combined with access to more detailed material property information will yield a numerical model of the ankle/foot permitting to predict static and dynamic responses for a range of these situations.

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REFERENCES

[1] Beaugonin, M.; Haug, E.; Munck, G.; Ceasri, D.; " A Preliminary Numerical Model of the Human Ankle under Impact Loading"; PLEI Conference,Washington, D. C., USA, 1995.

[2] States, J. D.; " Adult Occupant Injuries of the Lower Limb "; Biomechanics and Medical Aspects of Lower Limb Injuries, 1986, SAE 861927.

[3] Begeman, P.; Balakrishnan, P.; Levine, R.; King, A.; " Dynamic Human Ankle Response to Inversion and Eversion "; 37th Stapp Car Crash Conference Proceedings 1993, SAE 933115.

[4] Nahum, A.M.; Siegel, A.W.; Hight, P.V.; Brooks,S.H.; " Lower Extremity Injuries of Front Seat Occupants"; 11th Stapp Car Crash Conference Proceedings 1968, SAE 680483.

[5] Morgan, R. M.; Eppinger, R; H.; Hennessey, B.;" Ankle Joint Injury Mechanism for Adults in Frontal Automotive Impact "; 35th Stapp Car Crash Conference Proceedings 1991, SAE 912902.

[6] Otte, D.; Von Rheinbaben, H.; Zwipp, H.; " Biomechanics of Injuries to the Foot and Ankle Joint of Car Drivers and Improvments for an Optimal Car Floor Development "; 36th Stapp Car Crash Conference Proceedings 1992, SAE 922514.

[7] Portier, L.; Troseille, X.; Le Coz, J.-Y.; Lavaste, F.; Coltat, J.-C.; " Lower Leg Injuries in Real-world Frontal Accidents "; Proceedings of the 28th International IRCOBI Conference on the Biomechanics of Trauma, September 1993, pp 57–78.

[8] Lestina, D. C.; Kuhlmann, T. P.; Keats, T. E.; Maxwell Alley, R.;" Mechanism of Fracture in Ankle and Foot Injuries to Drivers in Motor Vehicle "; 36th Stapp Car Crash Conference Proceedings 1992, SAE 922515.

[9] Begeman, P.; Kopacz, J. M.; " Biomechanics of Human Ankle Impact in Dorsiflexion "; Injury Prevention Through Biomechanics Symposium Proceedings, 1991, Wayne State University.

[10] Nahum & Melvin; "Accidental Injury,Biomechanics and Prevention"; Springer Verlag, 1993.

[11] Williams, P.; Warwick, R.; Dyson, M.; Bannister, L.; " GRAY's Anatomy Atlas"; 37th edition Churchill Livington, 1989.

[12] Yamada, H.; Editior Evans, F. G; " Strength of Biological Materials "; The Williams& Wilkins Company, Baltimore, 1970.

[13] Burton, A.; " Physiology and Biophysic of the Circulation "; Yearbook Medical, Chicago, 1968.

[14] Torp, S.; Arridge, R.; Armeniades, C.; Baer, E.; " Structure-Property Relationships in Tendon as Function of Age "; Structure of Fibrous Biopolymers, Butterworthjs, London, 1975.

[15] Begeman; P., Direct Communication, ; Wayne StateUniversity, Detroit, Michigan, June 1995.

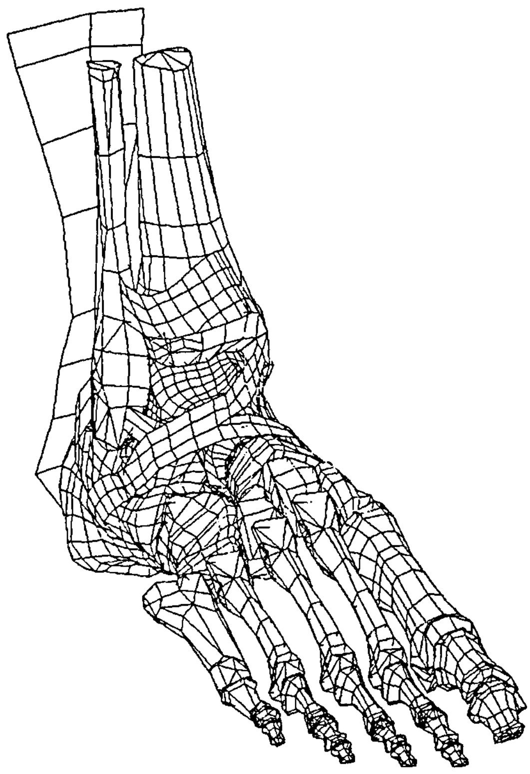

Figure 3: Human Ankle/Foot Model

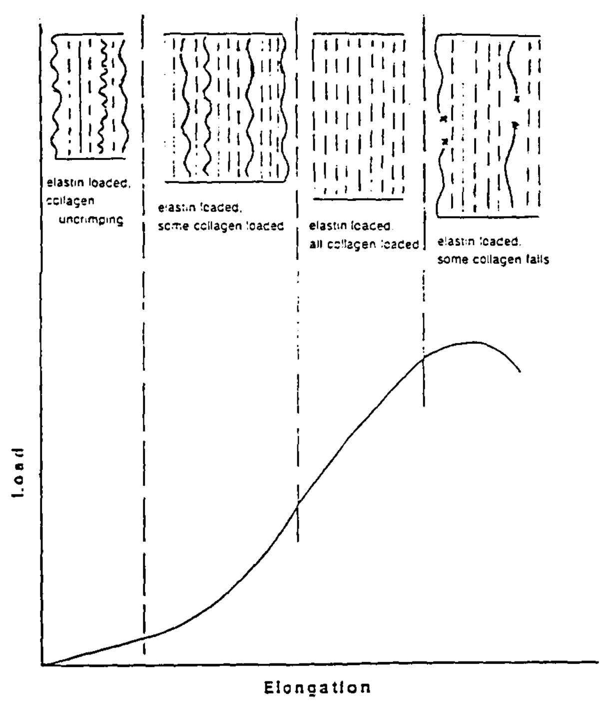

Figure 5: Schematic Drawing to Illustrate the Micromechanics of Ligament Deformation during Tensile Stretch ([10])

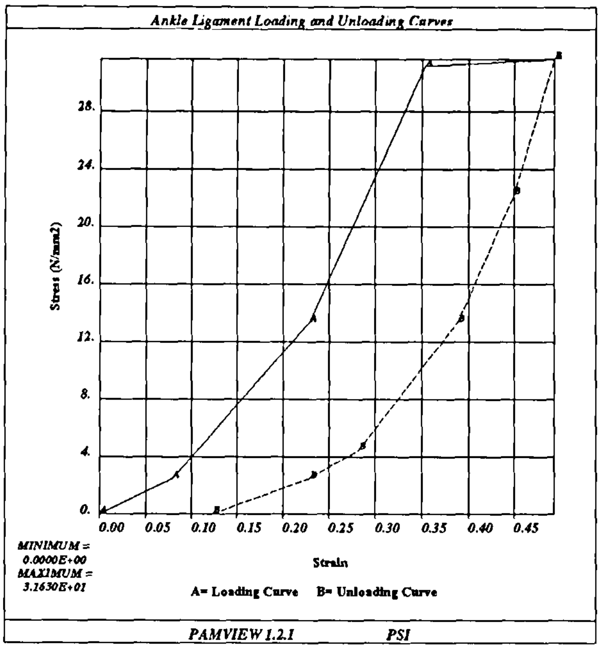

Figure 6: Ankle Ligament Loading and Unloading Curves

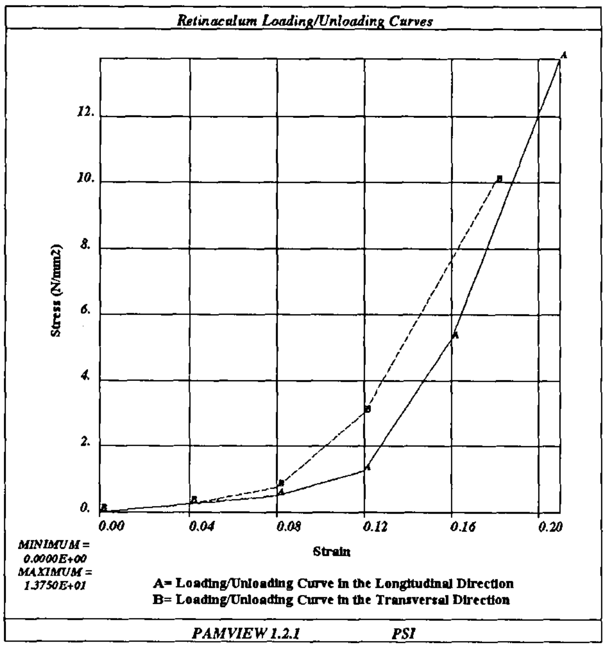

Figure 7: Retinaculum Loading/Unloading Curves

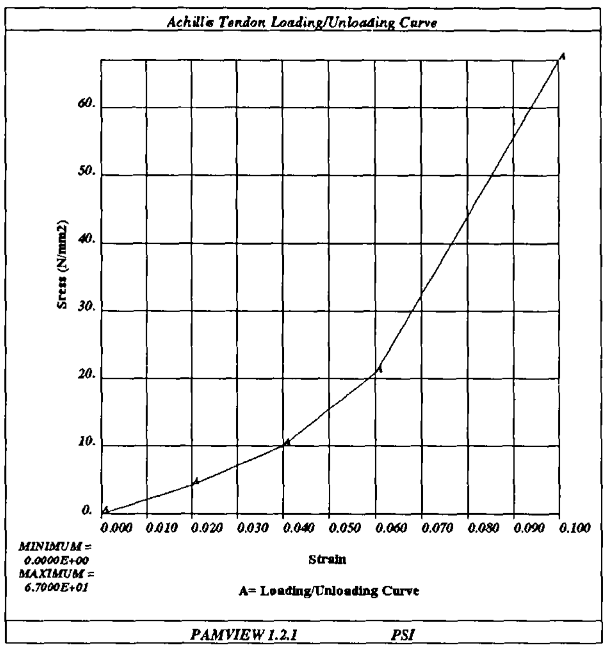

Figure 8: Achilles Tendon Loading/Unloading Curve

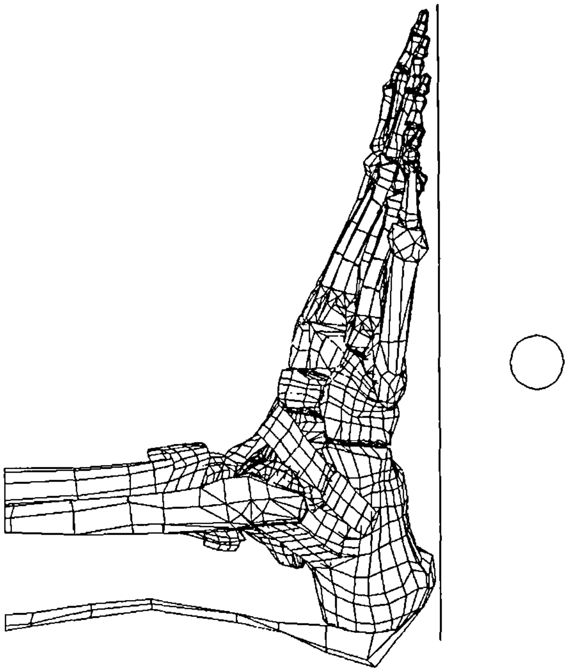

Figure 9: Initial State of the Simulation

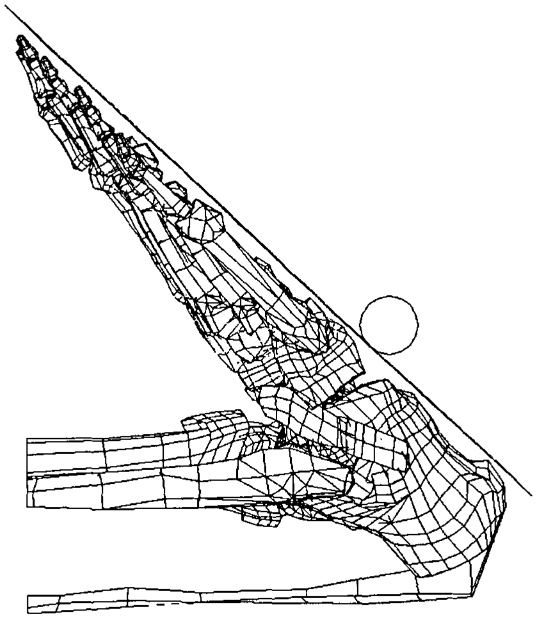

Figure 10: Maximum Dorsiflexion State of the Simulation

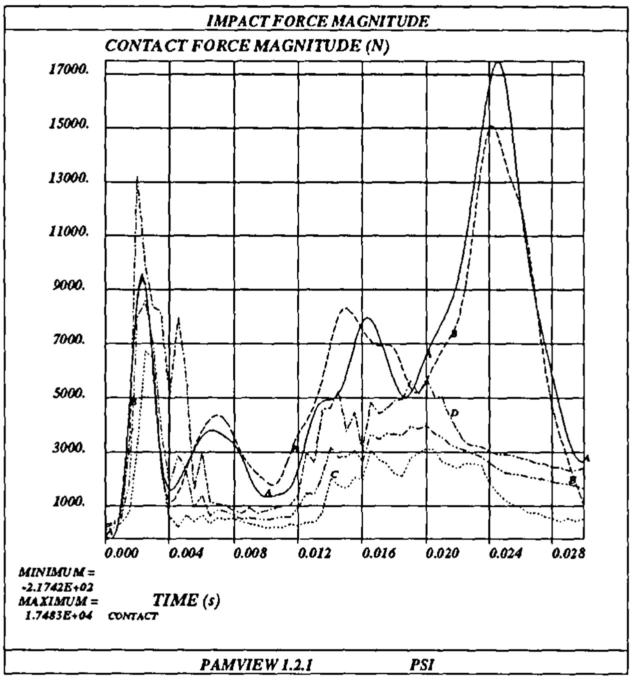

Figure 11: Impact Force Magnitude of the Tests and of the Simulations with Model 1 and 2

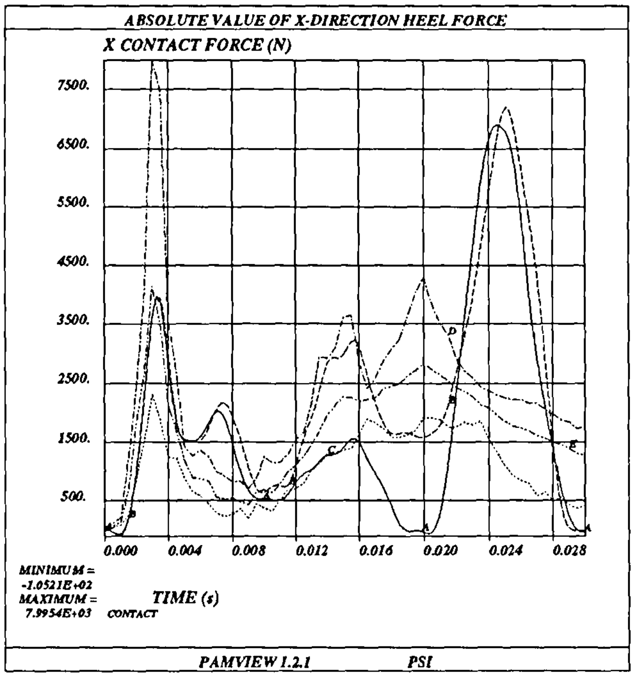

Figure12: Contact Force on the Heel in X-direction of the Tests and of the Simulations with Model 1 and 2

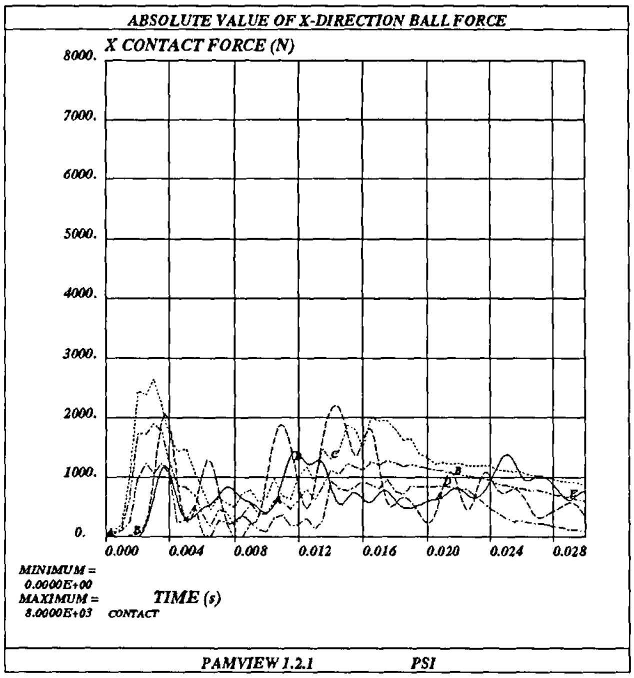

Figure 13: Contact Force on the Ball in X-direction of the Tests and of the Simulations with Model 1 and 2

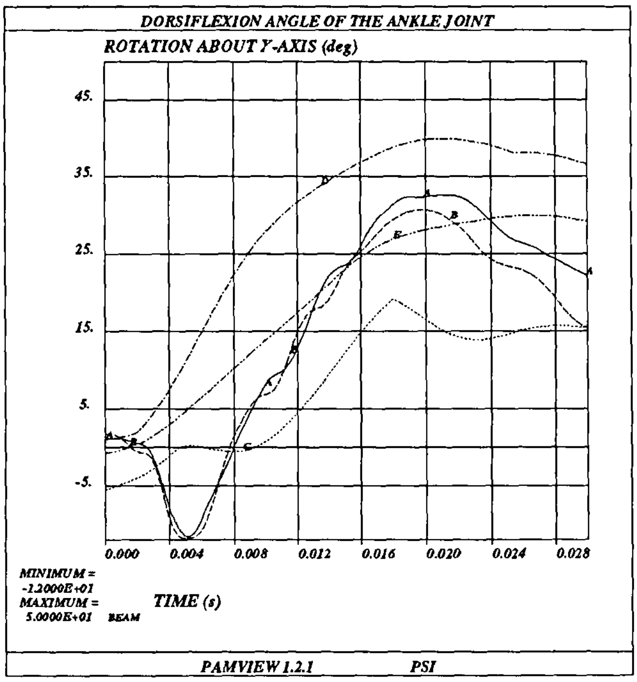

Figure 14: Dorsiflexion Angle of the Ankle joint of the Tests and of the Simulations with Model 1 and 2

A = Model 2
B = Model 1
C = Test Minimum
D = Test Maximum
E = Test Average

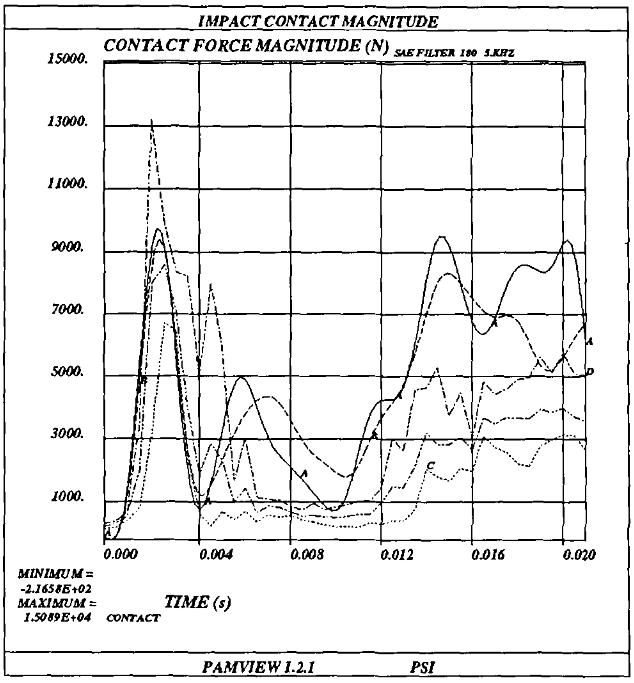

Figure 15: Impact Force Magnitude of the Tests and of the Simulations with Model 1 and 3

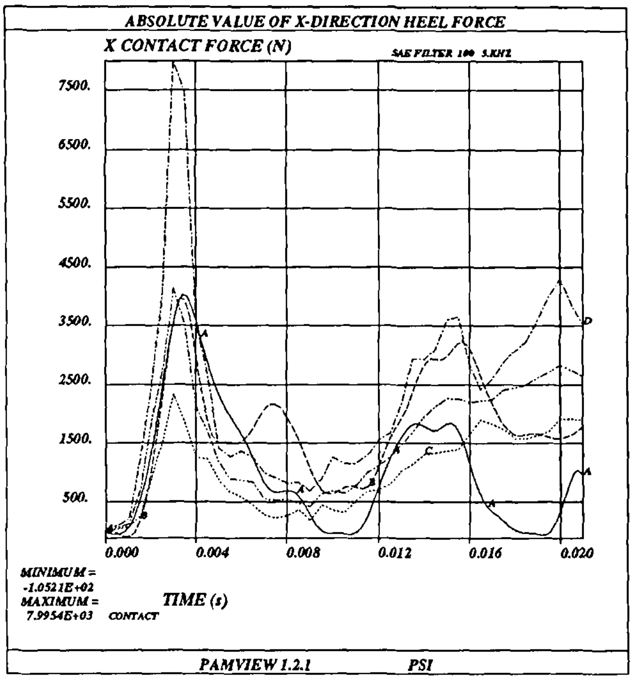

Figure 16: Contact Force on the Heel in X-direction of the Tests and of the Simulations with Model 1 and 3

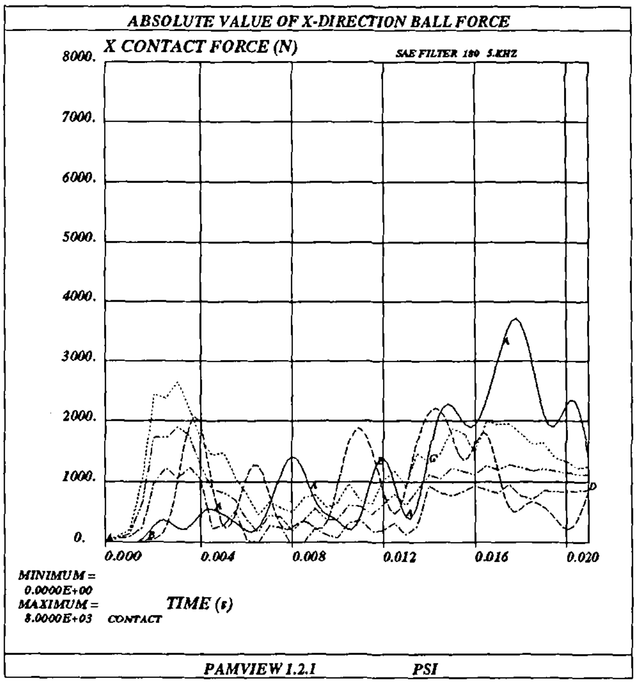

Figure 17: Contact Force on the Ball in X-direction of the Tests and of the Simulations with Model 1 and 3

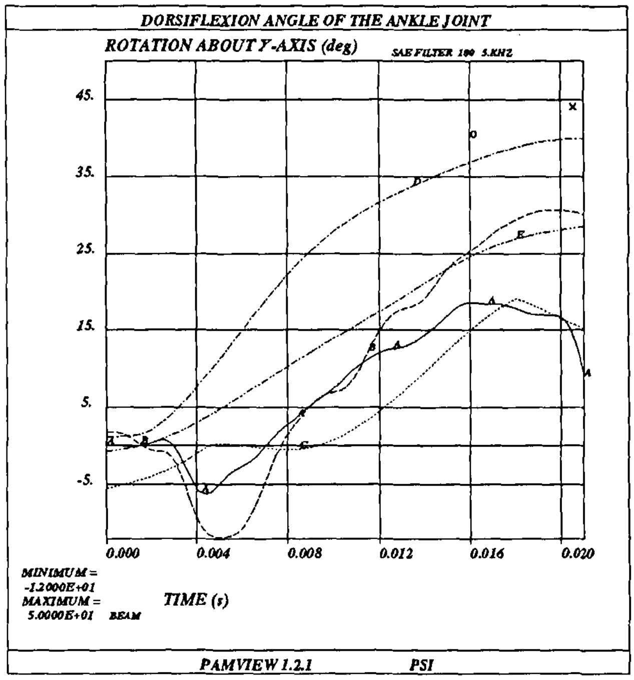

Figure 18: Dorsiflexion Angle of the Ankle joint of the Tests and of the Simulations with Model 1 and 3

A = Model 3
B = Model 1
C = Test Minimum
D = Test Maximum
E = Test Average

Technical Session 11

Heavy Vehicle Safety
Chairperson: Cezary Szczepaniak, Poland

EUROPEAN ACCIDENT STATISTICS RELATED TO CAR-TO-TRUCK FRONTAL COLLISIONS

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ABSTRACT

In 1993 the European Experimental Vehicles Committee has set up Working Group 14 to develop a test procedure for energy-absorbing front underrun protection systems (FUPS) for trucks. For this purpose the working group proposed a research programme, describing a stepwise approach to achieve this objective.

This paper reports on the first results of the project dealing with accident investigation and results from car-to-truck frontal crash tests with a front underrun protection device (FUPD) according to ECE Regulation No.93.

For the first time accident data of several European countries have been connected to give an overview about the accident scene in Europe with respect to car-to-truck frontal collisions. A representative accident type is defined as a basis for crash testing.

Car-to-Truck frontal crash tests with a FUPD according to the ECE Regulation are described and the results are discussed.

TRUCK ACCIDENTS IN EUROPE

In 1992 over 367 million people /1/ were living in the European Community, which was enlarged to 15 states to form the European Union on January 1st, 1995. The number of registered vehicles was more than 183 million. Thus, statistically, there is one vehicle for every two EU citizens (Table 1.).

A consequence of the high degree of mobility in the European Union are road traffic accidents. The number of accidents with personal injury amounted to nearly 1.3 million in 1992. Some 1.7 million people were injured in these accidents, of these 48,000 fatally. Even if the method of acquiring the data varies from country to country, for example in the case of accidents involving fatalities, these figures do show what enormous economic damage is caused by road traffic accidents, quite apart from the human suffering hidden behind each of these numbers.

Trucks over a gross vehicle weight of 3.5 tonnes are involved in 25 to 30% of the fatal accidents in the EU. About 13,000 people a year are killed and over 300,000 are seriously injured in these accidents /2/. Between 50 and 65% of the fatalities in truck accidents are car occupants. 4,200 of them die in car-to-truck frontal collisions. That represents around 18% of the car occupants killed in the European Union. A problem here is that the number of people killed in car-to-truck accidents fluctuates considerably for different countries. Thus in Germany in 1992 some 750 car occupants were killed in car-to-truck accidents (11.3%), (Table 2.). The number of car occupants killed in car-to-truck frontal collisions is, according to this, considerably lower than in countries with a large number of car-to-truck accidents.

On the other hand, it is precisely in countries with a high degree of traffic safety, such as Germany, that further success in traffic safety work can only be achieved if all possibilities to do so are exploited. This includes improving the protection of car occupants in car-to-truck frontal collisions.

PRESENT STATUS OF TRUCK ACCIDENT RESEARCH IN EUROPE

The analysis of real accidents is done by several institutions in different European countries, e.g.

- INRETS, France
- SWOV, The Netherlands
- TRL, United Kingdom
- VdS, Germany
- INSIA-UPM., Spain

Table 1.
Road Traffic Accidents in the European Community 1992

Country	accidents with personal injuries	fatalities	fatal injured car occupants	injuries	injured car occupants	inhabitants x 1000	registrated motor vehicles x 1000	registrated cars x 1000
Austria	44,730	1,403	853	57,473	33,862	7,861	3,937	3,100
Belgium	55,438	1,672	1,040	77,109	51,029	10,022	4,800	4,021
Denmark	8,965	577	261	10,514	4,431	5,162	2,084	1,594
Finland	7,882	601	320	9,899	5,562	5,029	2,280	1,923
France *	143,362	9,083	5,725	198,104	118,638	57,206	27,260	23,380
Germany *	395,462	10,631	6,431	516,797	320,058	80,570	44,481	37,947
Great Britain *	239,675	4,379	2,050	317,558	191,871	57,998	29,657	25,002
Greece (1991)	20,764	1,790	628	28,949	11,938	10,249	2,783	1,730
Ireland	6,677	415	169	10,188	6,026	3,548	1,126	858
*Italy (1991)**	170,702	7,498		240,688		56,757	34,100	28,519
Luxembourg	1,223	71		1,571		390	252	200
Netherlands *	41,054	1,285	626	48,328	17,914	15,129	6,534	6,134
Portugal	48,953	2,475	877	69,535	28,606	9,846	3,583	2,343
Spain *	87,293	6,014	3,404	129,949	69,676	39,114	16,528	12,537
Sweden *	15,599	759	466	20,727	13,543	8,643	4,347	3,589
total	1,287,779	48,653	22,850	1,737,389	873,154	367,524	183,752	152,877
total EEVC WG14	1,093,147	39,649	18,702	1,472,151	731,700	315,417	162,907	137,108
% in EEVC	84.9%	81.5%	81.8%	84.7%	83.8%	85.8%	88.7%	89.7%

* Countries involved in EEVC WG 14

Based on different studies depending on the national accident scene also a lot of frontal car-to-truck crash tests have been made in the past. The tests were based on different crash systems:

- car-to-truck test, both moving (Figures 1, 2.)
- car-to-truck, only car moving
- car-to-simulated truck (Figure 3.)

and also on varying configurations (relative speeds, overlap, size of car and truck).

The tests showed that:

- from existing truck designs without FUPD's the ground clearance of the truck and height of the bumper are too high for activating the energy absorbing structures of the car;
- a rigid front underrun device may result in survival of the car occupants at relative speeds up to about 60 kph;
- energy absorption by the truck is needed at higher relative speeds (> 60 kph) and overlaps for a survival of the car occupants.

Therefore, a first important step to more partner protection was made by establishing ECE Regulation No.93 /3/ (further referred to as R.93). The regulation describes a rigid front underrun protection device (Figure 4.) which is characterized by

- a ground clearance of 400 mm of the unladen truck;

Table 2.
Accident Opponents of Trucks (German national statistics 1992)

Accident opponent	truck				articulated trucks				total			
	casualties	%	fatalities	%	casualties	%	fatalities	%	casualties	%	fatalities	%
single trucks	2,769	8.1%	67	5.8%	436	10.1%	11	4.8%	3,205	8.3%	78	5.6%
trucks	1,628	4.8%	41	3.6%	266	6.2%	2	0.9%	1,894	4.9%	43	3.1%
articulated trucks	297	0.9%	13	1.1%	109	2.5%	0	0.0%	406	1.1%	13	0.9%
cars	20,924	61.2%	593	51.5%	2,770	64.1%	158	68.7%	23,694	61.5%	751	54.3%
busses	525	1.5%	2	0.2%	177	4.1%	1	0.4%	702	1.8%	3	0.2%
motorized two-wheel	2,131	6.2%	102	8.9%	163	3.8%	14	6.1%	2,294	6.0%	116	8.4%
bicycles	3,303	9.7%	167	14.5%	175	4.0%	18	7.8%	3,478	9.0%	185	13.4%
pedestrians	1,990	5.8%	156	13.5%	97	2.2%	22	9.6%	2,087	5.4%	178	12.9%
others	632	1.8%	11	1.0%	129	3.0%	4	1.7%	761	2.0%	15	1.1%
total	34,199	100.0%	1,152	100.0%	4,322	100.0%	230	100.0%	38,521	100.0%	1,382	100.0%

Accidents with personal injuries: 30,165

Source: Stat. Bundesamt

- resisting a maximum force of 80 kN in the testing points P1 and P3 (for location see Figure 4.) which is about three times higher than in ECE Regulation No.58 "Rear Underrun Protection Systems";
- resisting a maximum force of 160 kN in points P2 (1.6 times higher than in Regulation No.58);
- a moving distance of maximum 400 mm for the device during testing.

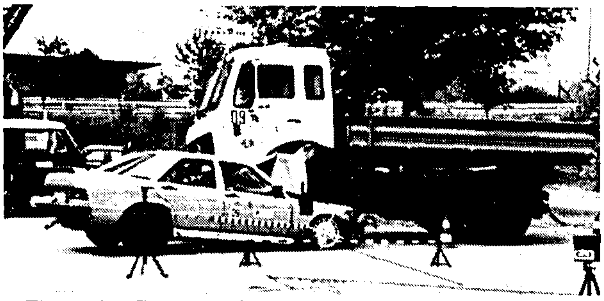


Figure 1. Car-to-truck crash test with an upper mid-size car, carried out by VdS /4/.

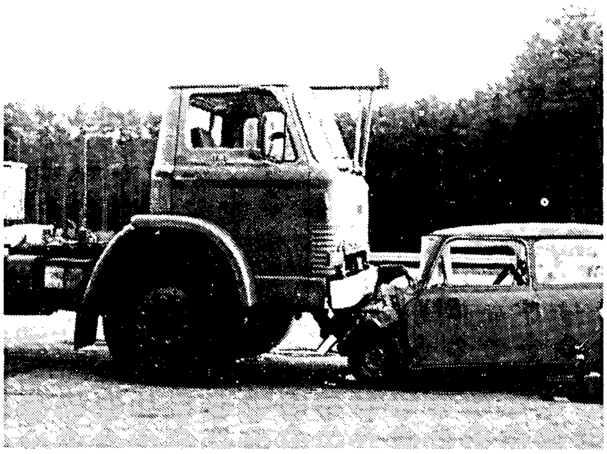


Figure 2. Car-to-truck crash test with a sub-compact car, carried out by TRL /5/. (Photograph courtesy of TRL)

The next step, that is "Energy-absorbing front underrun protection of trucks" was dealt with on a European level by the EEVC ad hoc group "Front Underrun Protection of Trucks", which presented its final report in June 1992 /2/. In this study first steps were taken to collate European accident material. On account of the relatively great differences in the individual data sources and methods of collecting the data this was, however, not completely successful.

The present paper is based on the work of EEVC Working Group 14 "Front Underrun Protection of Trucks" which was established as a successor of the ad-hoc group and which has to define the requirements for an energy absorbing front underrun protection system.

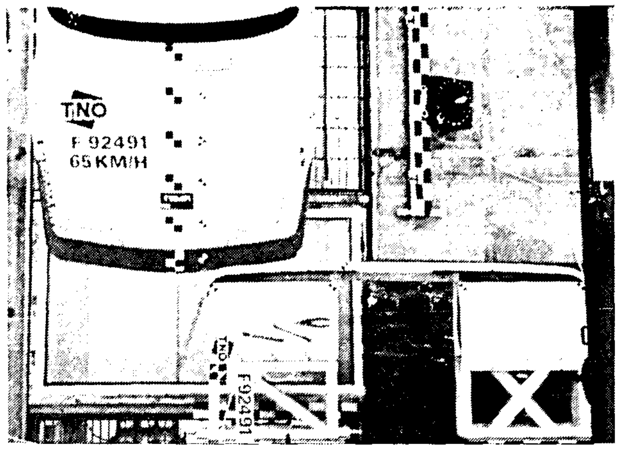


Figure 3. Crash test using a simulated truck front, carried out by TNO /6,7/.

The countries represented in the working group are
France
Germany
Great Britain
Italy
Spain
Sweden
The Netherlands

As a consistent continuation of the ad-hoc groups' investigations effort was put into combining the accident data established on a national basis to a European dataset. The aim was to define a typical crash configuration for frontal accidents on European accident material.

Therefore the present study is based on national research data (detailed statistical data by in-depth analysis) which is basically comparable. The parameters were harmonised in the sessions of the working group. It was possible to use datasets from the following countries to analyse frontal collisions between trucks and cars:

- France	Research Data
- Great Britain	Research Data
- Spain	Research Data
- Germany	Research Data
- The Netherlands	Statistical Data.

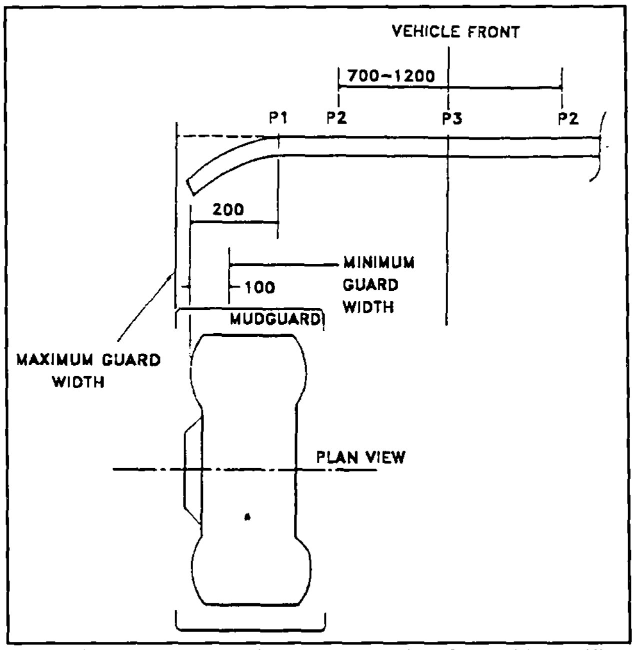


Figure 4. Geometric requirements for a rigid fupd with specification of points for force application according to /3/.

For some of the parameters, e.g. the overlap, further data from other nations were available. These are indicated in the graphs concerned. The British and Spanish data are based on accidents with fatalities, and the French and German figures on accidents with personal injury. It was possible to split up the German material by accidents with

- slightly injured persons
- severely injured persons
- fatalities.

This allowed the accident data of the different countries to be compared and to be combined in joint diagrams. In the course of the work it turned out that there was a high degree of correspondence between the British and the German data in particular. The Spanish data deviated from the other accident material mainly w.r.t. the relative speeds. They indicated considerably higher relative speeds in accidents with fatalities than the other material.

TYPICAL ACCIDENT PARAMETERS IN CAR-TO-TRUCK FRONTAL COLLISIONS

The Mass of Truck and Car

It turned out from the individual sets of accident material that car-to-truck frontal collisions are characterised by the fact that mainly trucks of over 12 tonnes gross weight and cars with a mass of between 800 and 1,100 kg are involved (Table 3.).

The French data could not be directly incorporated into this consideration, since the mass classes recorded were different but there is also a similar tendency in France to that in the other countries. Trucks of a gross vehicle weight of more than 7.5 t dominate. Furthermore, chiefly articulated trucks are involved in the accidents. It can therefore be assumed that in France, too, trucks of over 12 t represent the bulk of the trucks involved in accidents.

The mass classes of the cars deviate from those of the other countries in the medium range in that the French group comprises 800 to 1,000 kg, while in the other countries it is 800 to 1,100 kg. If this is considered in the light of Figure 5, there is here, too, a large measure of agreement with the other countries. It can thus be stated that in car-to-truck frontal collisions in the European Union the dominating vehicle categories are

- trucks > 12 t and
- cars between 800 and 1,100 kg.

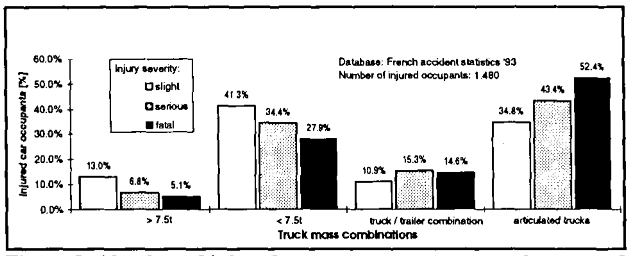


Figure 5. Number of injured car occupants versus truck mass and truck type, France.

Overlap and Relative Speed

The severity of a frontal car-to-truck accident is mainly characterized by overlap and relative speed between truck and car. Other parameters such as mass of the car are compared with these two parameters of minor influence /8/.

In former studies /4/ concerning front underrun horizontal overlap and relative speed had been looked at seperately. For this report an individual case analysis of the German accident material was made because in the

Table 3.
Number of Frontal Car-to-Truck Accidents Concerning All Weight Classes (trucks > 3.5 t)

Country	<= 800 kg			801 - 1100 kg			> 1100 kg			
	< 7.5 t	7.5-12 t	> 12 t	< 7.5 t	7.5-12 t	> 12 t	< 7.5 t	7.5-12 t	> 12 t	total
U.K.	6	0	34	13	3	108	4	1	21	190
%	3.2%	0.0%	17.9%	6.8%	1.6%	56.8%	2.1%	0.5%	11.1%	100.0%
Netherlan	32	10	31	86	23	140	28	8	26	384
%	8.3%	2.6%	8.1%	22.4%	6.0%	36.5%	7.3%	2.1%	6.8%	575.00
Spain	6	13	38	28	50	133	3	8	25	304
%	2.0%	4.3%	12.5%	9.2%	16.4%	43.8%	1.0%	2.6%	8.2%	100.0%
Germany	13	8	38	32	5	60	21	5	33	215
%	6.0%	3.7%	17.7%	14.9%	2.3%	27.9%	9.8%	2.3%	15.3%	100.0%

Spanish and German datasets there were some cases with very high relative speeds and only minor injuries of the car occupants. As the case analysis showed, this effect depends on a very low overlap. For example there were accidents with high relative speeds of 150 kph and more in which the car occupants sustained only minor injuries and there were overlaps of less than 10%. On the other hand, it was noticed that in the cases of fairly low relative speeds of about 45 kph at which the car driver was killed there were a 100% overlaps. Relative speed and overlap therefore have to be looked at in combination with each other.

Figures 6 and 7 show the dependence on overlap and relative speed in accidents with fatally injured car occupants for the German and Spanish material.

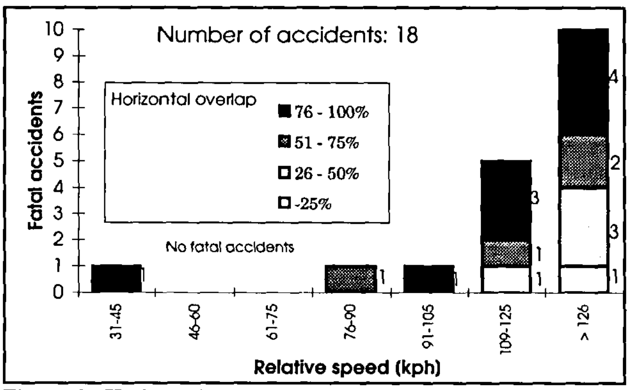


Figure 6. Horizontal overlap versus closing speed in fatal car-to-truck accidents, Germany.

Although the two bodies of accident material vary considerably with regard to the relative speed (Spanish figures are much higher), it can nevertheless be observed that for both bodies of accident material the same trend is evident. As relative speed increases so does the number of accidents with slight overlap. Conversely it can be seen that in the case of fairly low relative speeds accidents resulting in fatalities only occur when the overlap between truck and car is correspondingly large.

The available sets of accident material thus result in two crash configurations, which on the one hand are typical for the accident scene and on the other hand can technically still be coped with. These are the crash configurations with:

- a relative speed of 75 kph and an overlap of 75 to 100% or
- a relative speed of 105 kph and an overlap of between 50 and 66%.

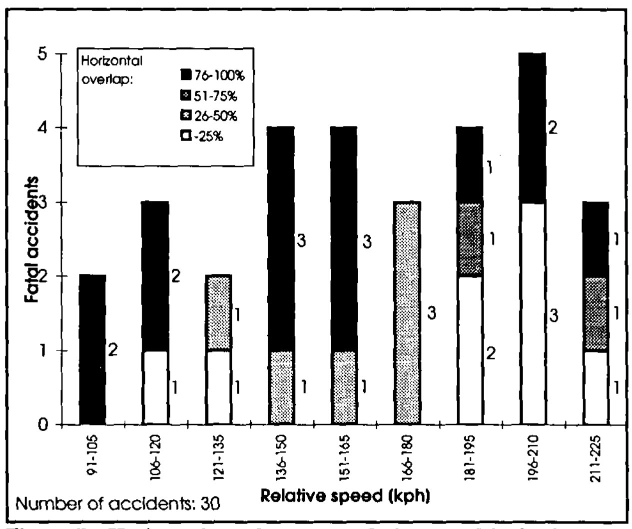


Figure 7. Horizontal overlap versus closing speed in fatal car-to-truck accidents, Spain.

If we restrict ourselves to the British and German data (Figure 8.), which show a high degree of agreement (the Spanish data with the very high relative speeds clearly deviates from the results of the British

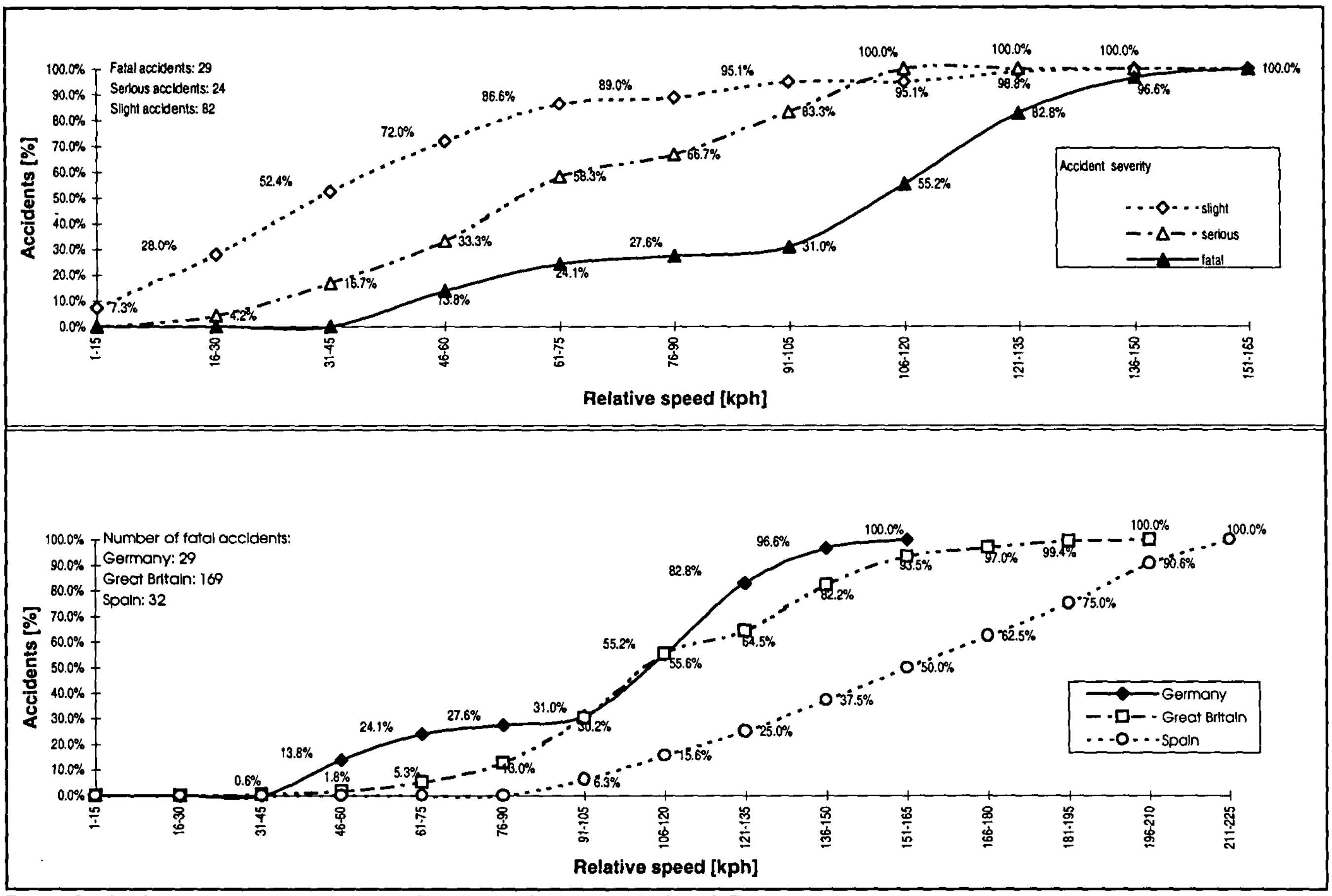
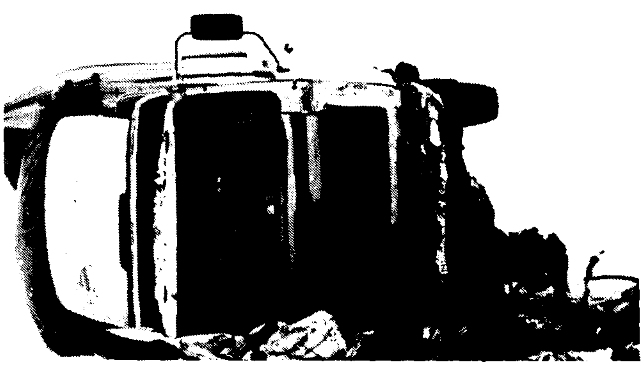


Figure 8. Closing speeds in car-to-truck accidents resulting from British and German data.

and German studies) it can be stated that the crash configurations with the above-mentioned relative speeds would cover between

- 13% and 31% of the accidents with fatalities (British and German data);
- 66% to 83% of the accidents with serious injuries to the car occupants (German data) and
- 89% to 95% of the accidents resulting in slightly injured car occupants.



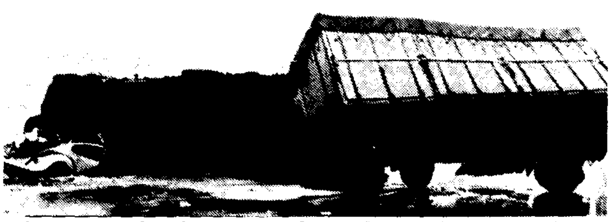


Figure 9. Fatal car-to-truck accident with a very high closing speed (v_{rel}=150 kph).

Higher relative speeds do not seem appropriate. Most of these cases are absolute "disaster cases", as Figure 9 shows. The car was run over by almost up to the rear axle of the truck. The truck itself then rolled over. The car was completely demolished.

Collision Angle and Typical Cars in Individual Mass Classes

Table 4 shows the large measure of agreement between the individual sets of accident material. A collision angle of 180° ± 15° appears to be typical.

Table 4.
Collision Angle Between Car and Truck

Country	Angle of Impact	Frequency
Great Britain	180°±15°	72.0%
Spain	180°±10°	80.0%
France	180°±10°	60.0%
Germany	180°±15°	73.5%

The available figures for The Netherlands, Great Britain and Germany indicate the following cars in the individual mass groups:

small cars ≤ 800 kg

medium cars > 800 kg, ≤ 1100 kg

large cars > 1100 kg.

Other Typical Parameters in Car-to-Truck Frontal Collisions

It was noticed from the case analysis of the German material that the typical occupancy frequency for a car is n = 1.5. It therefore seems appropriate to use two front seat dummies in the test car.

Resulting Crash Configuration

As typical crash configuration for a European car-to-truck frontal crash test regarding an energy-absorbing front underrun protection system the following configuration is suggested:

- relative speed 75 kph;
- horizontal overlap 75 %;
- collison angle 180°;
- car occupied with two dummies on the front seats;
- mass of the car between 800 and 1100 kg;
- mass of the truck >12000 kg.

CRASH TESTS

Trucks on the road in Europe generally have no FUPD up till now. So from the present accident data the effect of R.93 can not be evaluated. To investigate yet the effect of this regulation and to put a reference to compare with oncoming developments in the energy-absorbing front underrun protection systems, three tests have been carried out using a car out of each mass group. The curb weights of the cars were 840, 1150 and 1480 kg. The truck mass was 12200 kg. The truck was supplied with a 'rigid' front underrun protection device fulfilling Regulation No.93 (Figure 10.). The ground clearance was 350 mm (≤400 mm according to /3/).

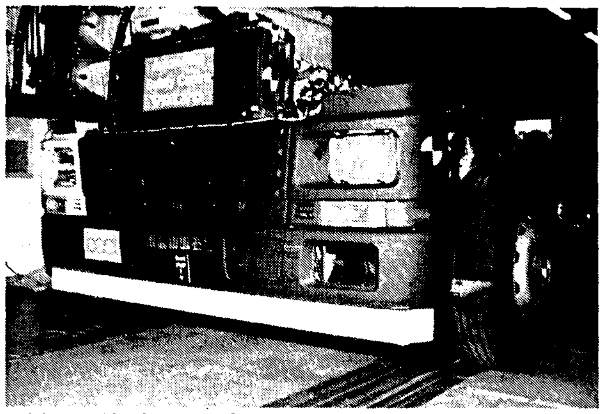


Figure 10. Picture of the 'add-on' front underrun protection device (TNO design).

The test set-up was according to the crash configuration as defined previously (Figure 11.), except that the impact speed of the car was reduced to 56 kph*** (in combination with a rigid fupd an impact speed of 75 kph would have been unrealistic). At the moment of impact the truck was stationary. The parking brake was not activated. The gear was set neutral.

***For comparison purposes: in EEVC Working Group 11 an offset frontal collision into a deformable barrier is evaluated as a future approval test set-up /9/. The impact velocity is 56 kph and the overlap is 40 %. This test results in a crash severity which is feasable with modern cars and survivable for the occupants.

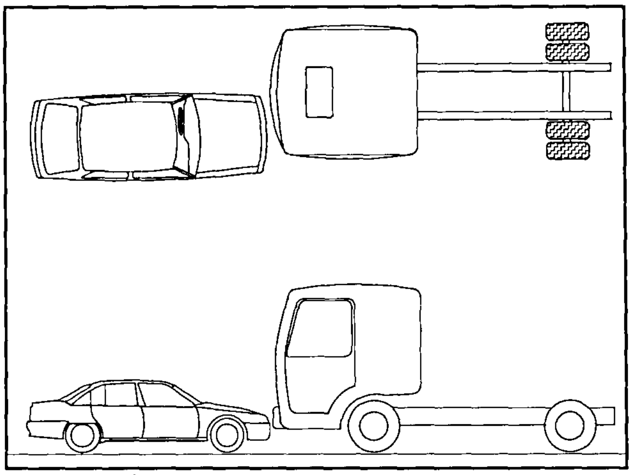


Figure 11. View of car-to-truck test set-up.

The test results showed that indeed this crash configuration is survivable for restrained occupants and that collisions with higher relative speeds (the typical relative speed is 75 kph, as discussed earlier) are only survivable if a substantial part of the impact energy is absorbed by a deformable truck structure.

FUTURE WORK

In the next phase, the sensitivity of the parameters which define the representative accident type w.r.t. variations will be studied. Further, the requirements for energy-absorbing FUPS which guarantee a predefined injury reduction to car occupants will be defined.

For this purpose, numerical models simulating the 'reference' tests will be developed. With these models the effect of energy-absorbing structures on the truck can be evaluated simulating collisions with relative speeds of 75 kph.

The mathematical simulations provide a prognosis for injury reduction and estimations for car and truck damage reduction (and thus cost reduction) due to application of energy-absorbing FUPSs. Based on these figures, earlier cost-benefit analyses /10,11/ can be improved and the benefit of energy-absorbing FUPSs for trucks compared with rigid devices can be determined more precisely. The outcome will be decisive for the continuation of EEVC Working Group 14.

Continuation includes the development of a test procedure for energy-absorbing front underrun protection systems for trucks in order to reduce the injuries in frontal collisions with passenger cars and to demonstrate the robustness of the proposal by means of tests with prototype energy-absorbing FUPSs.

CONCLUSIONS

The accident analysis carried out within the framework of EEVC Working Group 14 is for the first time based on combined accident material from European countries and has shown that combining different national accident material is possible and useful. The countries taking part in the working group represent about 80 to 90 % of the accident scene in the European Union.

It does not seem to be very useful to consider overlap or relative speed separately to determine a typical crash configuration, since only the combination of these two parameters characterises the accident loading on the car occupants that actually occurs.

Crash tests between cars and trucks show that relative speeds up to 56 kph are feasible for modern cars and survivable for the occupants. Higher relative speeds increase the need for energy-absorption by the truck structure.

Cost-benefit analists notice to be careful with the predictive value of calculated figures on the benefit/cost ratio. Also the social aspects need attention. For this reason one may conclude that, in case the calculated costs are higher than the benefits, the introduction of energy-absorbing front underrun protection systems for trucks may be beneficial based on social considerations.

The figures on the benefit/cost ratio from earlier studies (/10,11) indicate the advantage of energy-absorbing front underrun protection systems compared with rigid devices.

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Mr Klaus Langwieder, Mr Hans Bäumler - VdS
Mr Jean Bloch - INRETS
Mr Francisco Aparicio, Mr Carlos Vera - INSIA
Mr Ian Knowles - UK DoT

Mr Brian Riley - TRL
Mr Jan Wenäll - VTI
Mr Eugenio Pippione - IVECO S.p.A.
Mr Lars-Göran Löwenadler - Volvo Truck Corp.
Mr Horst Lambrecht - Mercedes Benz AG
Mr Hervé Desfontaines - Renault V.I.

Past members

Mr Hans Driever - TNO (Chairman)
Mr Andrew Cook - UK DoT
Mr Gerhard Hammer - Mercedes Benz AG

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Data on clearances for energy-absorbing FUPS installation on several truck makes were made available by ACEA.

REFERENCES

/1/ Statistisches Bundesamt Wiesbaden: "Straßenverkehrsunfälle 1992", Verlag Metzler-Poeschel, Stuttgart.

/2/ European Experimental Vehicle Committee: "Report EEVC Ad Hoc Group Front Underrun Protection of Trucks", June 1993.

/3/ ECE Regulation No.93: "Uniform Provisions concerning the Approval of: I. Front Underrun protection Devices (FUPDs), II. Vehicles with regard to the Installation of a FUPD of an Approved Type, III. Vehicles with regard to their Front Underrun Protection (FUP)". May 1994.

/4/ M. Danner, K. Langwieder, H. Appel, V. Middelhauve: "Passive Safety Measures for Trucks - Effectiveness and Priorities", XIIth ESV-Conference, Gothenborg, May 1989.

/5/ B.S. Riley, A.J. Farwell, T.M. Burgess: "Front Underrun Guards for Trucks". 11th ESV Conference, Washington, 1987.

/6/ P.J.A. de Coo, A.P. Goudswaard, J.J. Nieboer, V. Raue: "Numerical Analysis of an Energy-absorbing Truck Front Underrun Protection Device". 6th International Congress on Numerical Analysis in Automotive Engineering, Würzburg, Germany, September 1992.

/7/ P.J.A. de Coo, J.J. Nieboer: "Improved Safety of Car Occupants in Frontal Collisions with Trucks". SAE paper 945165. 25th FISITA Congress, Beijing, October 1994.

/8/ K. Langwieder, H. Bäumler: "Energy-absorbing Front Underrun Protection of Trucks - Final report on Phases A and B; Accident statistics and investigations, EEVC Working Group 14, March 1995.

/9/ EEVC Working Group 11: "Draft Final Report on the Front Impact Test Procedure". Revision 1, January 1996.

/10/ B.S. Riley, B.J. Robinson: "Protection Car Occupants in Frontal Collisions with heavy Good Vehicles". ISATA Conference, Aachen, Germany, November 1994.

/11/ H. Willms: "Frontunterfahrschutz an LKW". FAT Schriftenreihe Nr.107, Frankfurt am Main, April 1994.

IMPROVING THE SAFETY OF COMMERCIAL VEHICLES ON THE BASIS OF ENTIRETY OBSERVATIONS WITH ACCIDENT ANALYSES AND CRASH TESTS

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SUMMARY

The article commences with a summary of accidents involving commercial vehicles. A discription of the major points is followed by the results from the analyses of 400 accidents involving injury or deaths to the vehicle passenger. The injured or killed commercial vehicle passengers are of particular significance because the commercial vehicle is also the workplace at the same time. In conclusion, measures to lower the accident risk to commercial vehicle passengers are discussed while taking the results of crash tests into consideration. Further aspects are the hazards to other road-users. Safety measures are also discussed to this end. Entirety observations indicate possible additional applications for existing special safety installations through the general protective functions. The closing discussion considers the possible benefits and defines the needs for further research.

INTRODUCTION

If the year 1970 is defined as the beginning, then passenger vehicle passive safety can today look back over a history of development rigorously pursued over more than 25 years. At that time the American national highway traffic safety administration NHTSA announced details of a general research project in which the requirements for a safe vehicle (Experimental Safety Vehicle ESV) were set out. Pioneering manufacturers had already been pushing ahead with the development of passive safety for their own vehicles for some considerable time before this [1].

The situation with commercial vehicles is different. Basic series of trials with full-size crash tests have only recently begun in this field [2]. However, investigations into the actual events of accidents involving heavy commercial vehicles had already been carried out at the beginning of the 70's. Much attention was paid at the time to the Volvo accident reports which looked at unprotected road users and passenger vehicles as the other parties involved in accidents with commercial vehicles, as well as accidents in which the occupants of commercial vehicles suffered injury [3, 4, 5].

Since 1991, DEKRA Accident Research has on the one side been using its own Crash Centre in its investigations. Secondly, since the beginning of the 80's, it has been evaluating technical reports which DEKRA experts in the Federal Republic of Germany consistently produce in large numbers for the purpose of analysing actual road traffic accidents. The accident investigations are carried out in this respect on a manufacturer-independent basis, giving consideration to integrated approaches. Within this context DEKRA pursues a self-funded programme of research, commissioned research and cooperation arrangements with outside partners. Clients include government authorities (The Federal Institute for Roads BASt) [6] and vehicle manufacturers (Vehicle Engineering Research Association FAT) [7]. THESEUS (for road tankers with maximum achievable safety through experimental accident simulation) [8], was a project of national prominence on behalf of the Federal Ministry for Education, Science, Research and Technology (BMBF) and was completed in 1995.

Mercedes Benz has been investigating the course of events in accidents involving commercial vehicles of its own manufacture since 1972. The knowledge gained in the process is incorporated in the planning of crash tests which have been carried out since 1993 at the DEKRA Crash Centre and assisted by computer simulations at Mercedes Benz.

Today, it can be generally noted that relevant importance has since been attached to the passive safety of commercial vehicles by both the vehicle manu-

facturers as well as in the research activities carried out independently of the manufacturers. The key aspect in this context is that in most cases the commercial vehicle also represents its driver's workplace. His safety is therefore accorded particular importance. In the meantime, we have seen the development of seat belt systems which have been adapted to the specific requirements applicable in commercial vehicles. Furthermore, the airbag has been developed ready for fitting to be fitted in commercial vehicles as standard. Its widespread market launch is imminent.

However, there continues to be a major need for discussion and research regarding the potential benefits and necessity, as well as the targeted approach to the optimization of the passive safety elements in commercial vehicles. In this process knowledge gained from the actual course of the events of accidents provide an insight into the relevant problem focal points. Instrument-recorded crash tests and computer simulations supply results for the ongoing processes of technical development. Integrated approaches incorporate the other factors involved in accident with commercial vehicles. Benefit/cost analyses must in future deliver additional, well-researched information to enable those developments for which there appears to be a pressing need for realization or optimization, to be highlighted from amongst the developments which are in principle technically feasible or have already been initiated.

ACCIDENTS INVOLVING COMMERCIAL VEHICLES IN GERMANY

Official Road Traffic Accident Statistics

The official road traffic accident statistics [9] provide an overall picture of accidents involving commercial vehicles. Immediately after the reunification of Germany the number of accidents in the new German countries rapidly increased. The picture was also reflected in the overall statistics for the Federal Republic of Germany. The reasons given for this were extremely diverse and primarily at short notice. When taking a look at longer term developments in accidents on German roads it is therefore currently advisable to limit this examination to the former German countries. In this respect the statistical long term overview for the years 1962 to 1994 show an overall favourable movement in the numbers of drivers and passengers in commercial vehicles killed and seriously injured each year in traffic accidents (Figure 1).

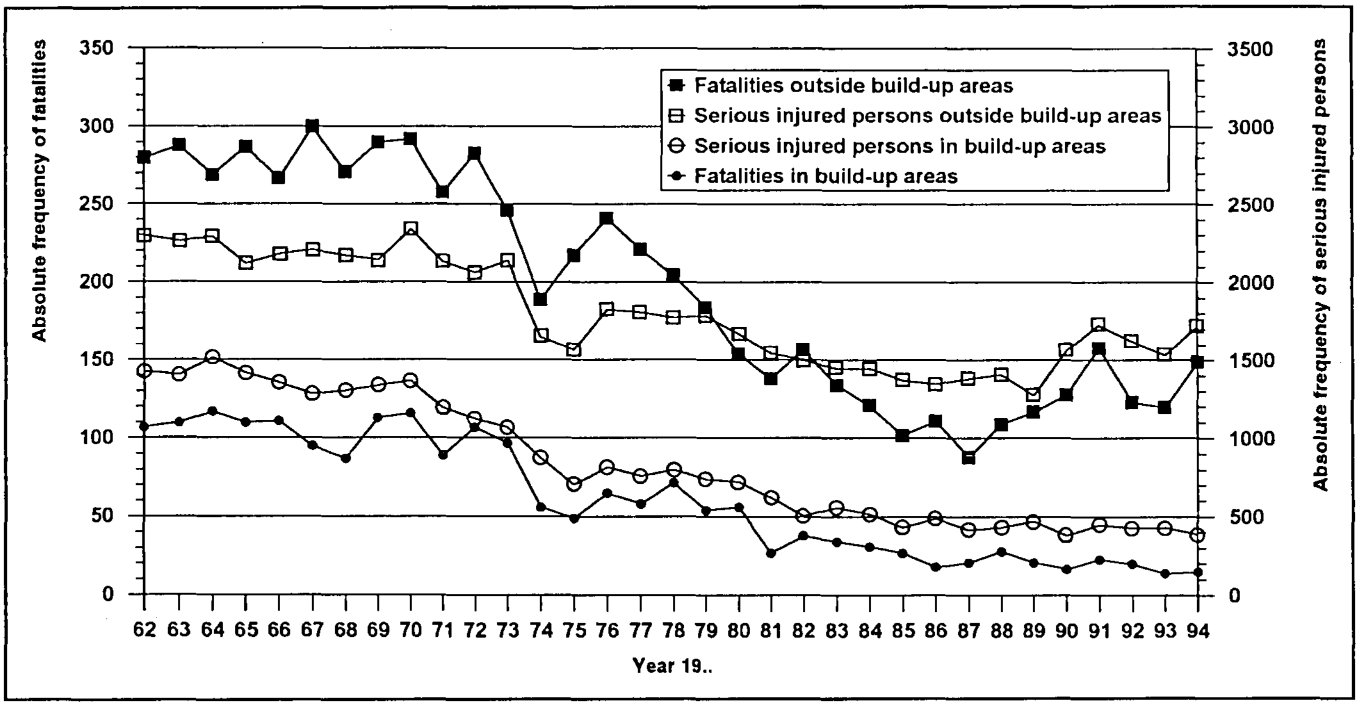


Figure 1. The number of fatally and seriously injured occupants of commercial vehicles in road traffic accidents in and outside built-up areas in the former countries of the Federal Republic of Germany (Source: German Federal Ministry of Statistics, 1996)

From 1962 to 1972 the number of occupants of commercial vehicles fatally injured in accidents outside built-up areas fluctuated between 258 and 300. During that period between 2 063 and 2 341 occupants of commercial vehicles were seriously injured each year in accidents outside built-up areas. The numbers of drivers and passengers of commercial vehicles killed and seriously injured in accidents outside built-up areas then showed a marked decrease up to about 1987 (88 fatalities and 1 380 seriously injured). This trend subsequently failed to continue. In 1994 the official figures show that there were 149 fatalities and 1 721 seriously injured amongst the occupants of commercial vehicles in accidents outside built-up areas.

In accidents within built-up areas the positive trend has continued. 107 occupants of commercial vehicles were killed and 1 428 seriously injured in 1962. The corresponding figures for 1994 are: 15 killed and 390 seriously injured.

The definitions which form the bases for the official statistics on road traffic accidents in Germany must be incorporated when evaluating these figures. According to these definitions a person is recorded as a fatality if he/she dies as a result of the accident either immediately after the accident or within 30 days of it. Those categorised as seriously injured are people who are sent to a hospital for in-patient treatment after the accident.

Commercial vehicles are vehicles which are licensed as such by the Ministry of Transport. These include not only heavy commercial vehicles but also transporters, a number of vans and station wagons. In the past the statistics showed an almost continuous increase in the number of commercial vehicles (Figure 2).

Whereas in 1962 there was a total of 828 000 licensed commercial vehicles (of which 261 000 were above the 7.5 t max. permitted total weight), in 1993 their total number had already risen to 2 092 000 (of which 800 000 were above the 7.5 t max. permitted total weight). As such, in the 31 year period under investigation the number of commercial vehicles rose by 1 264 000, representing a 153 % increase over the 828 000 vehicles licensed in 1962.

Against this background the trend in the number of accident victims in commercial vehicles must be seen as a very positive one: despite a dramatic increase in the

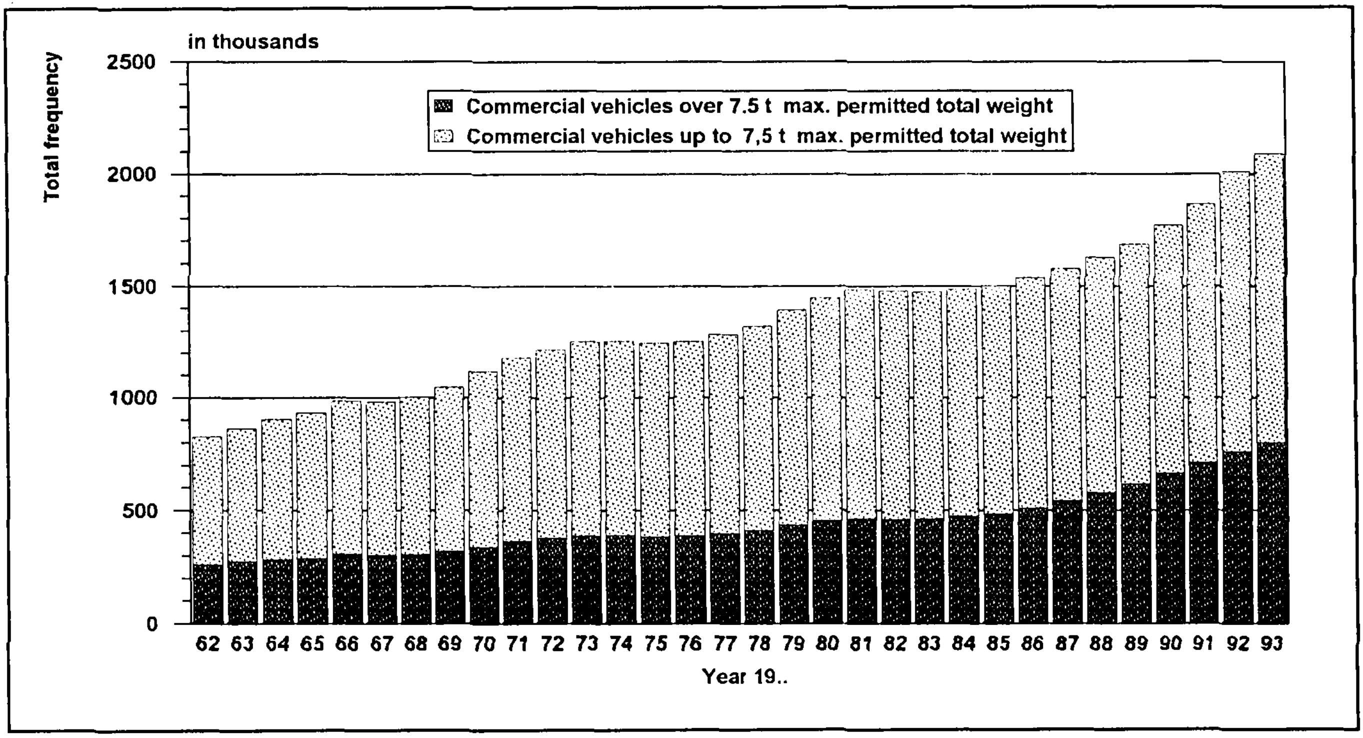


Figure 2. Number of commercial vehicles in the former countries of the Federal Republic of Germany (Source: German Federal Ministry of Statistics, 1994)

number of commercial vehicles the number of occupants killed or seriously injured in road accidents in commercial vehicles fell considerably, see figure 1. Endeavours should be made to ensure that this positive trend is also continued in the future. To this end particular attention should be devoted to accidents outside built-up areas involving commercial vehicles.

As with the number of vehicles, the distances travelled has also shown a marked increase. To this end we can see from the official statistics for example that in 1984 German and foreign commercial vehicles travelled a total of 28.4 billion km in the former countries of the Federal Republic Germany. In 1991 this figure had risen to 37.9 billion km.

Overall, passenger vehicles are seen as the most important other vehicle/party involved in accidents with commercial vehicles. In this context Figure 3 shows the absolute frequency rates of the other vehicles involved in fatal accidents with commercial vehicles in 1994 where two vehicles were involved. If we look purely at the accidents in built-up areas, we can see that the two-wheeled vehicle is most frequently involved with 147 cases, pedestrians with 131 and passenger vehicles only in third place with 79 cases. In the corresponding accidents outside built-up areas passenger vehicles are by far the most frequent with 515 cases, followed by two-wheeled vehicles with 91 cases and pedestrians with 62. It is only in accidents outside built-up areas that the commercial vehicle is a more significant factor as the other vehicle in accidents with commercial vehicles involving fatalities. Inside built-up areas these sort of accidents are very rare. The higher speeds on roads outside built-up areas play a major part in this respect.

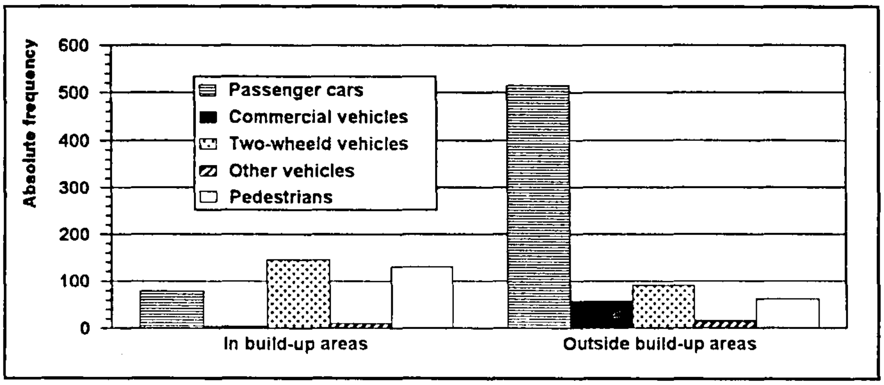


Figure 3. Other vehicles/parties involved with commercial vehicles in 1 114 fatal road traffic accidents involving two parties in the year 1994 in the Federal Republic of Germany (Source: German Federal Ministry of Statistics, 1995)

DEKRA Accident Surveys

Highly detailed examinations of accidents involving commercial vehicles are provided by special surveys of the type carried out by DEKRA Accident Research. Thanks to the structure of DEKRA, the specialist organisation, analytical reports on road accidents are available on a nationwide basis as a source of data (since 1990 in the new German countries as well).

Safety Analysis of Road Goods Traffic [6]. For this study a survey was carried out of 1 011 accidents from the period between 1986 and 1990 involving 1 170 commercial vehicles. Within this context accidents occurred most frequently between vehicles moving along in carriageway (Table 1). As befits their use, commercial vehicles were generally involved in accidents either fully or partially loaded, only 14.5 % of the towing vehicles (40.6 % of the towing vehicles were semitrailer tractors) were empty and 23.3 % of the trailers (Table 2). The most frequent load was general cargo (44.5 %), followed by bulk commercial (14.9 %) and liquid materials (9.6 %).

The drivers of the commercial vehicles were almost exclusively male (1 077 out of a total 1 089 occupants). In addition to the drivers there were a total of 95 passengers in the commercial vehicles. This represents on average one passenger in every twelfth commercial vehicle.

In only 99 cases was it possible to clarify whether a seat belt had been fitted for the driver, they had in fact been fitted in 10 cases. In the remaining cases it can be assumed in by far the vast majority of cases no seat belt had been fitted in the commercial vehicle. 13 out of 816 drivers of commercial vehicles had been catapulted out of the vehicle during the accident. In 10 of the 778 cases which were able to be analysed in this respect it was discovered that the driver had been trapped in the vehicle cab during the accident.

Internal safety of commercial vehicle cabs [7] The purpose of this in-depth study was to examine the commercial vehicle cabs damaged in the accident. To this end the study documented and analysed 99 accidents involving 110 commercial vehicles whose occupants had either been injured or there had been a high probability of injury to occupants

Table 1. Distribution of the type of accidents involving commercial vehicles [6]

Type of accident (acc.)	Relative frequency
Driving acc.:	13.0 %
Acc. caused by turning off the road:	11.4 %
Acc. caused by turning into a road or crossing it:	16.7 %
Acc. caused by crossing the road:	4.7 %
Acc. involving stationary vehicles:	5.0 %
Acc. between vehicles moving along in carriageway:	44.6 %
Other accident:	4.5 %

Table 2. Distribution of the load situations in commercial vehicles [6]

Towing vehicle	Relative frequency
Empty:	16.6 %
Approx. 1/3 loaded:	10. 6 %
Approx. 2/3 loaded:	6.8 %
Fully loaded:	14.0 %
Less than 10 % overloaded:	2.4 %
More than 10 % overloaded:	1.2 %
Loaded but no further details:	16.6 %
Articulated vehicle:	46.6 %
Trailer	
Empty:	30.5 %
Approx. 1/3 loaded:	10.0 %
Approx. 2/3 loaded:	10.5 %
Fully loaded:	33.5 %
Less than 10 % overloaded:	7.5 %
More than 10 % overloaded:	2.5 %
Loaded but no further details:	31.5 %

as a result of the damage to the cabs. Using the stipulated selection criteria as a basis, head-on collisions were predominant. 70 % of the vehicles documented had suffered distortion damage to the front.

One of the central findings of the study was the fact that the occupants were at very great risk of being killed when being catapulted out of or trapped in the cab: of the drivers and passengers in commercial vehicles who had been catapulted out of the vehicle during the accident 50 % suffered fatal injuries in the associated cases, those caught up in the cab died in 33 % of the cases. Of those commercial vehicle occupants not catapulted out of or caught up in the vehicle, 7 % died. As such, they were subject to a far smaller risk of being fatally injured.

Up to an internal cab deformation depth of 60 cm, the percentage of commercial vehicle occupants killed or seriously injured remained relatively constant. At internal deformation depths of more than 60 cm the percentage of occupants killed and seriously injured rose dramatically. Another interesting finding of the study came from the comparison of damaged parts and parts causing injury within the driver's cab (Figure 4): the steering wheel is clearly more frequently the cause of injury than being damaged itself, a fact which indicates that steering wheels on commercial vehicles do not have sufficient yield built into their design. Other conspicuous factors are the dashboard, foot/leg room and roof hatch. The restraint system is a particular feature. Although only a few vehicles were fitted with them, in 2 % of the cases they were acknowledged as being a cause of injury. This indicates that restraint systems (seat belts) have not yet been optimally adapted to the conditions in commercial vehicle cabs.

Accounting for 29 % of the recorded accidents, collisions against the rear of another commercial vehicle represent the focal point of the subject of the investigation. These kind of accidents are associated with very high risks of serious injury to or death of the occupants of the approaching vehicle. The underride safety bar on the rear of the vehicle in front provides very little resistance to the impact of the approaching commercial vehicle. Consequently the impact forces are transferred primarily to the raised area of the platform base and the tailgate as well as the chassis. In this

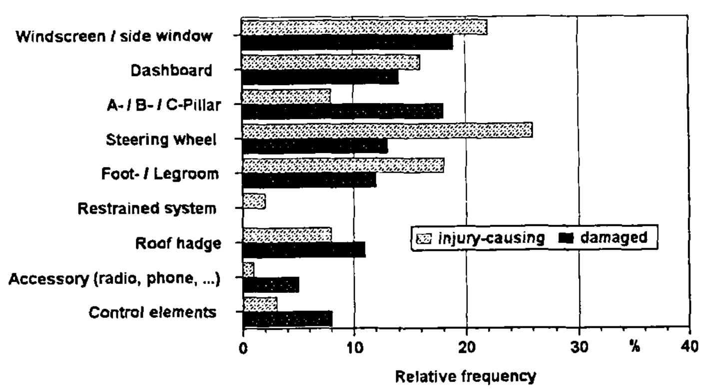


Figure 4. Causes of injuries and damage inside the driver's cab of the commercial vehicle [7]

context the driver's cab on the approaching vehicle is subjected to extreme impact pressure. This leads to major intrusions even at relatively low collision speeds (Figure 5). In such cases a load sliding forward during the collision can cause additional intrusions to the rear of the vehicle cab.

Figure 5. Driver's cab of a commercial vehicle (38 t) with considerable intrusions following an impact at approx. 35 km/h differential speed against the rear of another commercial vehicle of the same weight.

<u>Accidents involving road tankers [8].</u> Road accidents involving road tankers carrying hazardous goods pose special risks for the environment. In order to obtain additional data on these a wide ranging survey of information taken from the actual events of road tanker accidents was carried out as part of the THESEUS Project. The evaluated investigation data covered 231 accidents which had occurred between 1989 and 1993 on roads throughout the Federal Republic of Germany. These involved a total of 236 road tankers carrying hazardous goods. In 48 % of these accidents hazardous goods escaped.

Of the 231 cases documented, 104 (44 %) were accidents involving a road tanker alone. In 89 (86 %) of these accidents the road tanker tipped on to its side. 45 accidents where the vehicle tipped over had occurred on straight stretches of road, for example after leaving the motorway. 44 of such accidents occurred on bends, primarily where the critical tilt speed has been exceeded. Of the total amount of escaping hazardous goods during all the recorded accidents, accidents where the vehicle tipped over were in the majority with 68 %. The average speed being travelled when the vehicle started to topple over was 47 km/h.

132 (56 %) of the recorded road tanker accidents are those which involved collisions between vehicles. In 57 cases the road tanker collided with a commercial vehicle, in 55 cases a passenger vehicle and in 20 cases a different type of vehicle, for example a tram. The commercial vehicles impacted head-on with the road tanker in 18 cases, in 11 cases against the side and in 28 cases against the rear of the tanker. The passenger vehicles involved collided head-on in 26 cases, against the side in 19 cases and in 10 cases against the rear of the road tanker. The greatest risk of hazardous goods escaping therefore exists where a commercial vehicle collides against the rear or the side of a road tanker: hazardous goods escaped in 13 of the 28 cases involving a collision by the commercial vehicle against the rear of the road tanker and in 5 of the 11 cases involving a collision by a commercial vehicle against the side of the road tanker. In head-on /rear collisions at the beginning of the accident the average differential speed of the vehicles involved was 32 km/h.

Mercedes Benz Accident Surveys

By carrying out accident investigations Mercedes Benz is gathering information on vehicles manufactured by them as to how they behave in actual accidents. Independent surveys and analyses are being carried out to this end because commercial vehicles act in a fundamentally different way to passenger vehicles in this context.

The accident characteristics documented include the kind of accident, the collision speed of the vehicles involved, the extent of the remaining survival space, descriptions of intrusions into the cab area as well as the impact sites and damage. One of the initial primary tasks is to clarify the mechanisms of how injuries are caused to those involved in accidents. This will enable the possibilities for avoiding or reducing the injuries and their consequences to be analysed for each individual case. The categorisation of the accidents, for example according to the type of accident, illustrating associated common features, will help to highlight and assign priorities. Another key aspect of the analyses is to reproduce actual accidents using crash tests.

An important role in this respect is played by the head-on collision by the commercial vehicle. As in the general investigation findings ascertained by DEKRA Accident Research, at Mercedes Benz collisions against the rear of a commercial vehicle in front also represent a large proportion of the accidents which pose risks to the occupants of commercial vehicles.

In accidents occurring outside built-up areas, particularly on motorways in which the occupants of commercial vehicles were injured, the impact into the rear of a vehicle is a relatively significant factor. Another focal point is represented by the accidents where the vehicle have a roll over. In these type of accidents a large proportion of the occupants are fatally injured.

General overview of accidents involving commercial vehicles based on 400 cases

In order to gain a general overall picture on the course of events in an accident involving commercial vehicles a total of 400 accidents which had occured during the years 1985 to 1991 were taken from the data held at DEKRA Accident Research and analysed. Within this totaly the representation of the European vehicle manufacturers - amongst others Mercedes-Benz, MAN, Iveco, Scania, Volvo, MAN-VW - corresponded approximately to their distances travelled on German roads.

Of the 400 accidents, 137 (34 %) resulted in the death of the least one of the people involved. In 40 accidents occupants of commercial vehicles were killed, in 57 accidents occupants of passenger vehicles, in 22 accident two-wheel vehicle riders and in 19 accidents pedestrians. The most serious result of the accident in the remaining accidents was an injury to at least one of the people involved. Amongst the total of 344 injured, 50 % were occupants of commercial vehicles, 41 % passenger vehicles occupants, 6 % two-wheel vehicle riders and 3 % pedestrians. 60 % of the 400 accidents occurred outside built-up areas.

Accidents involving just one vehicle represented 9 % of the 400 accidents. In 64 % of these cases the commercial vehicle tipped over. Consequently the proportion of accidents involving single commercial vehicles tipping over, whilst not as prominent as in the case of road tankers [8], still however remains significant.

The speed of the commercial vehicle when it starts to tip over during an accident involving no other vehicle was on average 65 km/h. 60 % of the vehicles involved in single vehicle accidents collided with fixed objects. In this context the average collision speed was 73 km/h.

2 % of the occupants of commercial vehicles killed in the 400 accidents analysed were fatally injured in single vehicle accidents. 80 % of the single vehicle accidents occurred outside built-up areas.

Vehicle/vehicle accidents represented 72 % of the 400 accidents analysed. In this respect the other vehicle involved in the accident collided head-on in 59 % of the cases, in 25 % with the side and in 12 % with the rear of the commercial vehicle or its trailer.

In head-on collisions the other vehicle in the accident collided head on (accidents occurring in two-way traffic). 23 % of the vehicle/vehicle accidents were categorised as being of the head-on collision type. The average collision speed of the commercial vehicle in this context was 41 km/h.

By far the most frequent other vehicle/party involved the accident (80 % of the head-on collisions) was the passenger vehicle. It was travelling at an average 49 km/h. 39 % of the front occupants in the passenger vehicle did not survive the head-on collision with the commercial vehicle. Accounting for 73 % of the head-on collisions, this type of collision occurred most frequently in accidents outside built-up areas.

Side/front collisions are the kind where the front of the other vehicle in the accident hits the side of the commercial vehicle. 17 % of the vehicle/vehicle collisions were categorised as being of this type of collision. In these cases the average collision speed of the commercial vehicle was 31 km/h. Once again a passenger vehicle was most frequently the other party/vehicle involved in the accident, travelling at an average collision speed of 54 km/h. 19 % of the accidents involving side/front collisions resulted in fatal injuries for at least one occupant of the passenger vehicle. With 33 %, the angled impact of the passenger vehicle (angle of the vehicle longitudinal axes 15 to 45 °) against the side of the commercial vehicle was the most significant combination. 61 %, in other words the majority, of side/front collisions occurred outside built-up areas.

Front/rear collisions (impact by the front of the commercial vehicle against the rear of the other vehicle in the accident) represent 18 % of the vehicle/vehicle accidents. Passenger vehicles (27 %) and other commercial vehicles (71 %) were the other vehicles most frequently involved in the accident. The average collision speeds were 66 km/h for the approaching commercial vehicle, 22 km/h for the commercial vehicle in front and 29 km/h for the passenger vehicle in front. Where the collision was against the rear of a commercial vehicle 28 % of the occupants in the approaching commercial vehicle were fatally injured. 27 % of the front/rear collisions occurred outside built-up areas.

CRASH TESTS USING COMMERCIAL VEHICLES

Crash tests which use commercial vehicles are not subject to statutory regulations. The regulation of testing by way of binding standards does not appear to serve a purpose. The main reasons for this include the wide range of sizes and the diversity of the actual vehicle attachments as well as the potential influences provided by their load. One of the stimuli for carrying out manufacturer and vehicle-specific crash tests is provided by the actual accident course of events [10]. Secondly, we are seeing an orientation towards the international standards applicable to passenger vehicles and light commercial vehicles (EEC Regulations, FMVSS) and to the internal regulations of the manufacturers.

The results of the crash tests are incorporated in on-going development processes. It is standard in this context to back up the actual crash tests with computer simulations (Figure 6), [11, 12, 13].

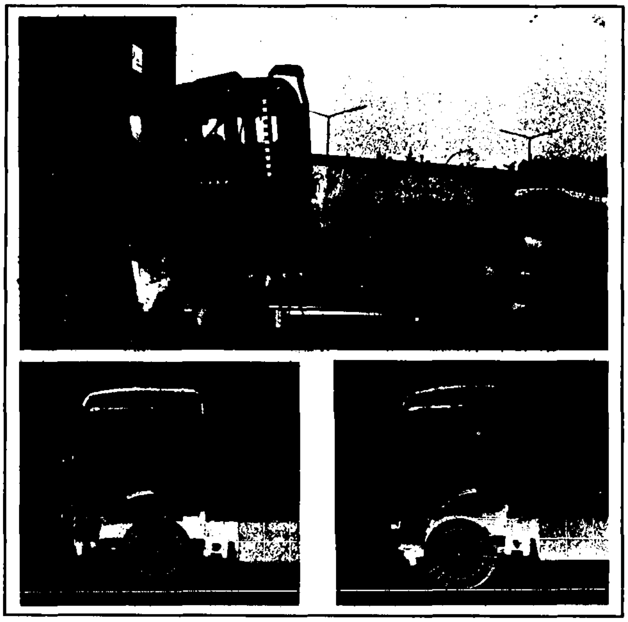


Figure 6. Actual crash test using a commercial articulated vehicle manufactured by Mercedes Benz (speed 35 km/h, full overlap, line of approach 0 °) and the associated computer simulation.

The computer simulation first of all helps in determining the crash conditions. Key factors in this respect are the results of the validation of the computer model in the speed range being studied. The upper limit of this range generally marks the ability of the occupants to survive the collision. As such, the calculations also help in forecasting risks in the test with regards to the potential destruction of equipment (dummies, on-board cameras, transient recorders and sensors) in cases of extreme intrusion or delay as well as in the adapted choice of dynamics ranges for recording the measurement values.

In addition, the simulation provides information on probable deformation and destruction of vehicle parts and assemblies in individual tests. On this basis it is possible to plan a series of crashes, as required, which encompass several tests using the same vehicle. This can be done if, at the beginning of the series, no major deformation or destruction of the vehicle occurs (and which can be fully repaired once again in the specific case by exchanging certain parts). This kind of approach, which optimizes both time and costs, can be used in tests for development purposes particularly if a prototype which is both costly and has only limited availability is used as a test vehicle.

Once the crash tests have been completed further studies can then be carried out using the computer model by varying the parameters within the validated range. This sort of method has already proven successful in passenger vehicle development and today represents state of the art technology in the commercial vehicle sector.

The appropriate crash test matrix for commercial vehicles remains a topical subject in relevant technical discussions. Setting aside the problem of load and attachments, a basic pattern has however already emerged (Figure 7).

As in the situation with passenger vehicles, the full overlap collision against the rigid barrier at a positional angle of 0 ° provides important basic data on collisions involving a sharp increase in and high level of delay (Figure 8). The costs of the computer model can be considerably reduced in this context by making full use of the available symmetries. It is primarily the collision speeds of 15 km/h (possibly firing a seat belt restrainer and not firing an airbag) and 35 km/h (possibly firing an airbag) which are relevant to most front wheel drive vehicles. The collision speed of 50 km/h can also be included in the analysis of vehicles with bonnets. The collision speed of 5 km/h may be of interest in particular for the purpose of validating the computer model and as a non-firing criteria for passive restraint systems (airbag, belt restrainer). As in the case of passenger vehicles, offset crash tests against rigid barriers with partial overlap (50 %, 40 %, 30 %) as well

as at an angled position (10 to 30 °) can also be included for analysing the structural pressure on commercial vehicles. However, the corresponding pattern of damage suffered by commercial vehicles is only comparable with the actual accident course of events in very rare cases.

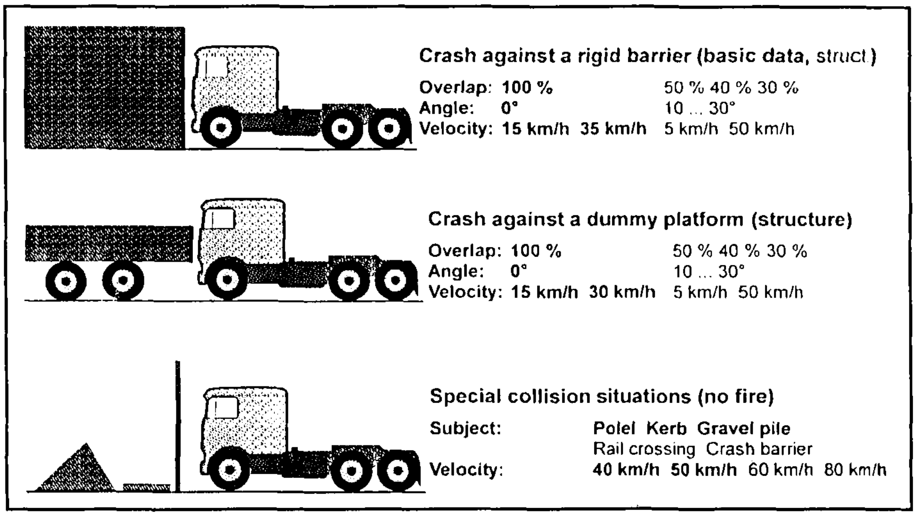


Figure 7. Basic pattern of a matrix for crash tests using commercial vehicles without attachment and without load.

In order to analyse the structural pressures on the commercial vehicle, the collision against a dummy platform is a far more relevant factor. In this context the delay level is markedly lower than in the impact against the rigid barrier (Figure 9). The impact by the front of the driver's cab above the chassis longitudinal support produces more extensive intrusions than are frequently found in the actual accident course of events. In this test combination it is primarily 15 km/h and 30 km/h impact speeds which are of interest. With full overlap and 0° angled position, the given symmetry conditions also enable the computer costs of the simulation to be reduced. As with the collision against the rigid barrier, using the dummy platform at an angled position (10 to 30 °) and with offset crashes (overlap 50 %, 40 %, 30 %) and at an impact speed of 5 km/h or 50 km/h (for vehicles with bonnets), tests can also provide further information.

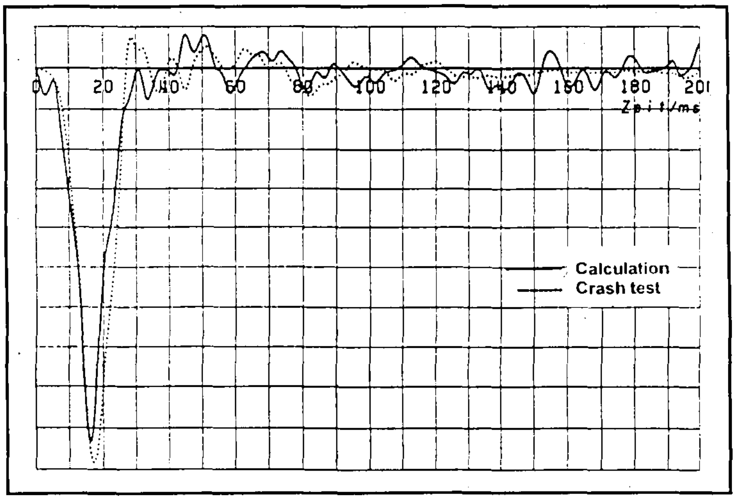


Figure 8. Longitudinal acceleration measured and calculated on the driver's seat casing in a head-on collision by a commercial articulated vehicle at a speed of 35 km/h and with full coverage [2].

Special collision situations are used to coordinate restraint systems. These have to release surely (must fire) in the event of specific accidents at a predefined minimum level of severity. In accidents with lesser severity or in special situations, the delays occurring must not result in the release of the restraint system (no fire). Differing releasing conditions for these passive safety mechanisms are standard for the combination of seat belt and airbag. The collision against a pole and driving over a kerb are two of the conventional no-fire situations. In the actual course of events of an accident the pole might for example be a traffic light or street light pole. Impact against a gravel pile as a no-fire situation is another relevant factor for commercial vehicles. Other possibilities include driving over railway lines on rail crossings and the low-angled, scraping impact against a crash barrier. The standard test speeds are 40 km/h and 50 km/h, whilst in certain situations, higher speeds for example 60 km/h (driving over a railway track) or 80 km/h (scraping contact with a crash barrier) might also be advisable.

As with the on-going development of passive safety in passenger vehicles, in commercial vehicles appropriate importance has also been attached to the need for compatibility with the other vehicle in the accident. Vehicle/vehicle crash tests are indispensable to the associated investigations. These kind of tests are consequently directly linked to the trials on the commercial vehicle's external safety mechanisms, reflecting their pre-defined aim to provide protection:

head-on collision with a passenger vehicle for testing the front underride safety bar, side collision with a two-wheeled vehicle for testing the side underride safety bar. These kind of tests for the restraint systems in commercial vehicles represent non-fire situations.

MEASURES DESIGNED TO REDUCE THE RISK OF INJURY TO THE OCCUPANTS

The occupants of commercial vehicles are comparatively well protected in many accident situations purely on the basis of the large mass and the dimensions of their vehicle. This is the reason why the process of fitting commercial vehicles with passive safety mechanisms such as seat belts or airbags, has not been implemented in the same sort of consistent manner as has been the case with passenger vehicles. Various analyses of the actual course of events of accidents however are revealing ever more clearly that restraint systems can also have positive effects in commercial vehicles. This involves the prevention of or reduction in collision contacts of critical significance to injuries in the driver's cab in the case of head-on collisions and preventing the occupants from being catapulted out for example through the openings in front windscreens or side windows.

Contemporary restraint systems, consisting of a three-point seat belt with tightener and if necessary belt force limiter, supplemented by an airbag, are therefore also being proposed for use in commercial vehicles. The task of current development work is to provide optimum adaptation and coordination of the components in these kind of systems to the specific general conditions applicable to commercial vehicles.

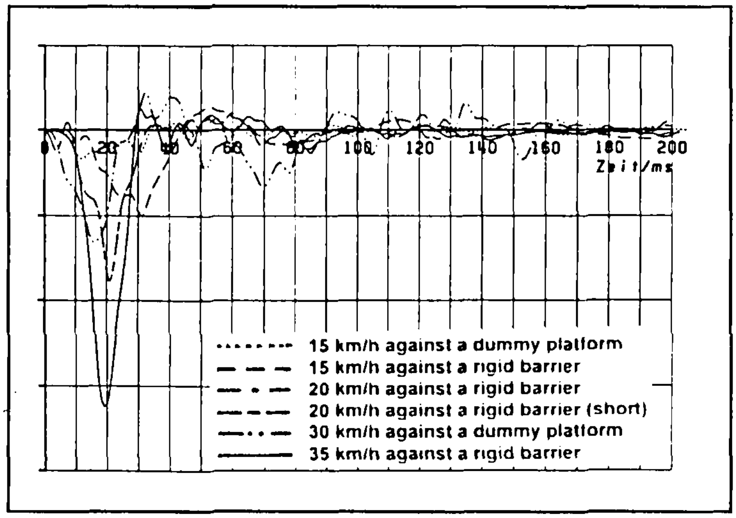
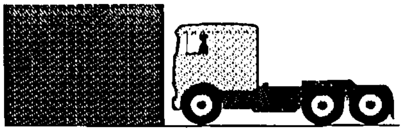


Figure 9. Longitudinal acceleration measured on the driver's seat casing of an articulated vehicle in a head-on crash at various speeds against a rigid barrier and a dummy platform [13].



Overlap: 100 %
Angle: 0°

Restraint system	Acceleration loadings			Force loadings			Velocity
	Head	Chest	Pelvis	Head	Chest	Neck	
None	#	#	#	#	#	+	50 km/h
	#	#	+	#	#	+	35 km/h
	+	+	+	+	-	+	25 km/h
Seat belt only	#	#	#	#	-	-	50 km/h
	+	+	-	-	+	+	35 km/h
	+	+	+	+	+	+	25 km/h
Airbag only	#	-	#	+	#	+	50 km/h
	+	+	+	+	#	+	35 km/h
	+	+	+	+	-	+	25 km/h
Seat belt and airbag	#	#	#	#	#	#	50 km/h
	+	+	+	+	+	+	35 km/h
	+	+	+	+	+	+	25 km/h

Load above the limit - Load near the limit + Load beneath the limit

Figure 10. Driver loadings ascertained through computer crash simulations by crashing a articulated vehicle against the rigid barrier at various speeds and using differing restraining systems [13]

Preliminary investigations with computer simulations as yet not validated on the basis of actual crash tests, showed that (unlike in passenger vehicles) the collision by a commercial vehicle of the cab-over engine configuration at 50 km/h and with full overlap against a rigid barriers is clearly not survivable by the occupants even using a restraint system (Figure 10) [13]. The main reason for this is the comparatively low deformation path on these type of vehicles. At the same time however, the computer simulations indicate a considerable potential on the part of the restraint systems being investigated to reduce the loadings on the occupants: without a restraint system in the collision at 35 km/h, apart from the force of pressure on the neck and acceleration in the pelvic area, all other simulated loadings exceeded the relevant biomechanical maximum limit. With a seat belt and an

airbag under the same crash conditions all the loadings remained below the critical limits. When making a comparison between the results of the simulations with seat belt only or with airbag only as a restraint system, the benefits of combining both sub-systems become clear: in the crash at a collision speed of 35 km/h, the addition of the airbag reduces the load on the pelvic area and the head compared with the seat belt system without airbag. With the airbag only, the computer simulation indicates a loading on the chest area above the limit in the same collision.

When interpreting these kind of results in more detail, it must also be remembered that as a result of the current position of the steering wheel in a commercial vehicle, a position which will also remain the same for the near future, less favourable conditions apply for the provision of the protective effect of the inflated airbag compared with those in passenger vehicles (Figure 11). Consequently, the possibility of the driver's chest or abdominal area impacting against the rim of the steering wheel cannot be totally ruled out. Although it would be technically feasible to reposition the steering wheel in the commercial vehicle - in the extreme case by replacing the mechanical transfer of the steering wheel movements to the wheels (drive by wire) - this cannot however be anticipated as a practical solution in the foreseeable future.

Improvements already realised in this area include the reduction in the diameter of the steering wheel and a collapsible-design steering wheel rim. Padding and removing sharp edges in the driver's cab in those areas relevant to injuries caused by collision contact, are two other features of the pioneering design of driver's cabs in commercial vehicles.

One of the key pre-requisites for the ability of restraint systems to reduce injuries is to preserve the

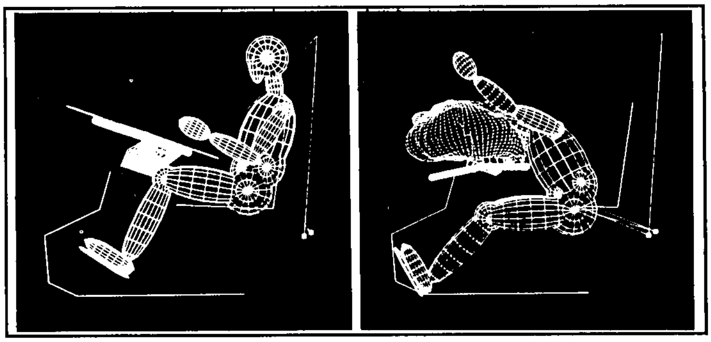


Figure 11. Computer simulation of the effect of restraining systems (seat belt and airbag) in a commercial vehicle at Mercedes Benz.

survival space in the cab. One of the basic measures for reducing the risk to occupants in the event of an accident therefore is optimization of the cab stability. To this end systematic series of trials with crash tests, backed-up by computer simulations, will increasingly expand the knowledge already available. Optimization processes which build on this basis are taking place, making a contribution towards minimising the intrusions in the relevant stress cases, simultaneously taking into account cost and weight aspects and the justifiable use of materials.

MEASURES DESIGNED TO REDUCE THE RISK OF ACCIDENT TO OTHER ROAD TRAFFIC USERS

As reflects its purpose of use, the commercial vehicle is large and heavy and as a result of its structure and external shape is not exactly compatible in collisions with other road users (which are generally smaller and lighter). Consequently, information gained from the actual accident course of events led to the introduction of underride safety devices at a very early stage. These are covered by statutory approval regulations and technical rules which stipulate the way they are designed. The attachments on the underride safety bar fundamentally produce an increase in the vehicle's unloaden weight and consequently, under both German as well as European law, a reduction in the useful load when the maximum permitted vehicle weight has been fully utilised. In addition, this can lead to higher fuel consumption if the attachments increase the air resistance. It is therefore appropriate to design the underride devices in such a way as to create an optimum situation in terms of protective effect and additional weight. In this context, by using aerodynamic designs, the underride devices can be constructed without having a detrimental effect on the air resistance, by contrast improving it and as a result contributing towards lower fuel consumption [14].

Rear underride safety bar

On certain types of heavy commercial vehicles the rear underride safety bar is subject to statutory regulations as specified in § 37 b of the German Road Traffic Licensing Act (StVZO). The European regulations ECE-R 58 and 70/221/EEC describe the technical design of this safety device. This is intended to offer effective underride protection across the entire width for a passenger carrying vehicle, with a maximum of eight seats, against collision from behind, or a commercial carrying vehicle with a maximum permitted total load

of up to 3.5 t colliding from behind. This definition encompasses for example passenger vehicles and smaller transporters but not commercial vehicles.

In older versions of the underride protection there was doubt about the adequate stability of the transverse bar and its link with the rear of the vehicle for meeting the defined objectives for protection [15]. This has no longer been the case since the load assumptions and inspection regulations under 70/221/EEC or ECE-R 58 which have been applicable since 1987.

However, there continues to be concern as to whether the stipulated maximum gap of 550 mm between the lower edge of the transverse bar on the underride protection and the road surface is small enough. As a pre-requisite for an effective transfer of force in the front structures of a passenger vehicle (crush zone) where it is involved in a head-on collision, its front longitudinal supports must be able to adequately support themselves.

In passenger vehicles constructed by German manufacturers however, the front longitudinal supports are positioned at a height range clearly below 500 mm (some 300 to 450 mm). Furthermore, it must be noted that the improvement in the air resistance led to a reduction in the upper edge of the bonnet on the bodywork shapes and that a head-on collision is frequently preceded by braking with the corresponding spring action of the front axle.

Against this background - and in view of collisions in which passenger vehicles went beneath the rear of commercial vehicles despite the underride protection, with fatal consequences for its occupants - it is becoming clear that there is further potential for improvement in the rear underride protection. This potential must be fully utilised, taking into account the minimum rear floor freedom required for the operation of the commercial vehicle.

The idea of energy absorption by the rear underride safety bar was looked at once again within the framework of the THESEUS Project [16]. Interesting findings on this topic had already been published in 1980 [17].

In the THESEUS trials the prime objective was also to use the underride protection on the road tanker to protect the rear tank bottom from deformation and in particular penetration caused by the front of an impacting commercial vehicle. The underride protection prototypes developed for this purpose and tested on actual crash tests, include a construction with friction wedge sleeves and additional wheel support (Figure 12).

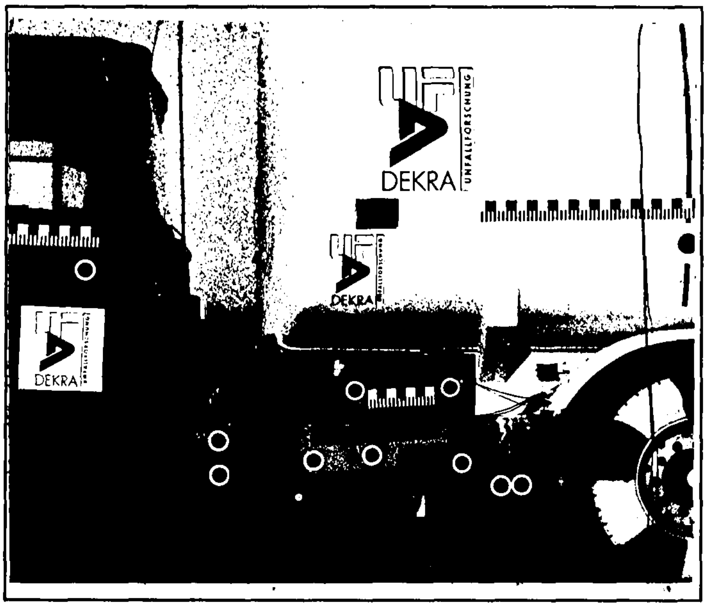


Figure 12. A prototype version of a rear underride protection and with wheel support and friction wedge energy absorber developed and tested as part of the THESEUS Project.

During a rear impact, the rear transverse bar, together with its movable longitudinal supports, is pushed against the friction wedge which is mounted permanently into the chassis. As the impact progresses it is then transferred to the wheel supports. Kinetic energy is than absorbed by the wheel supports in the friction wedge and the tyres being compressed together. This clearly reduces the strength of the impact. As a result, this first enabled the rear floor of the tanker to be effectively protected, secondly, through the displacement of the forces to the level of the front bumpers and the chassis longitudinal supports behind this on the impacting goods vehicle, the intrusions into the elevated driver's cab were also able to be drastically reduced. In the crash tests commercial vehicles weighting 16 t were driven against the rear of stationery road tankers (Figure 13) at speeds of 30 km/h.

Associated computer simulations of the crash tests showed that the wheel supports can be dispensed with in order to further reduce the weight of the underride protection whilst providing virtually the same protective effect. With just the friction wedge energy absorbers on their own, this would leave an underride

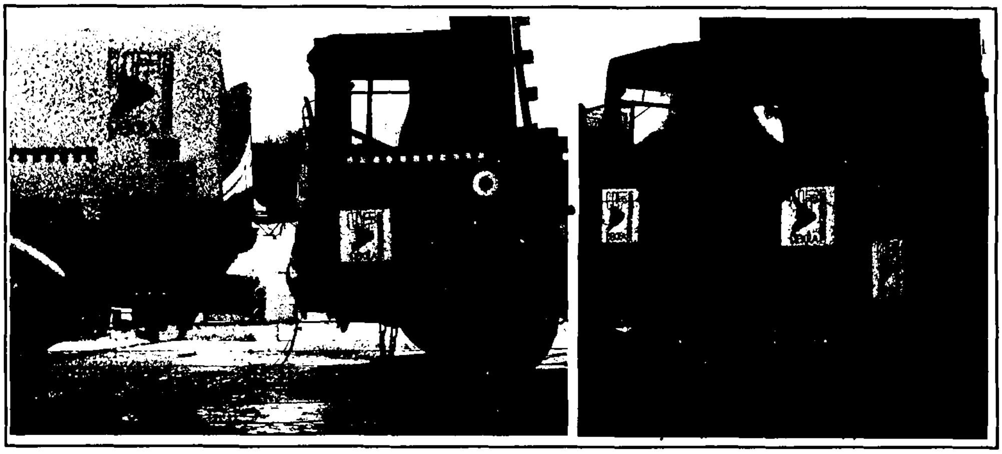


Figure 13. Commercial vehicle and road tanker in their final positions immediately after impact by the commercial vehicle at a speed of 29 km/h on an energy-absorbing rear underride protection prototype against the stationary road tanker as part of the THESEUS Project, and a view of the damaged front section of the commercial vehicle.

protection with the same weight range as already applies in current standard rigid constructions designed in accordance with the applicable specifications contained in ECE R 58 or 70/221/EEC. The accompanying calculations also showed that using a justifiable amount of materials, energy absorbing rear underride protection devices, able to withstand the impact of a 16 t heavy commercial vehicle at a speed of up to 60 km/h, can be achieved. This has enabled concrete objectives to be highlighted for the further development of rear underride protection, to include the occupants of the approaching commercial vehicle.

During the crash tests as part of the THESEUS Project, test were also carried out on a rear underride protection device which meets the current requirements, and an older version of rear underride protection (as per the versions of ECE R 58 and 70/221/EEC or § 37 b StVZO). Because there is no compulsory requirement to convert older commercial vehicles and trailers, versions of the rear underride protection which no longer reflect the latest state of the art can still be found on vehicles on German roads. These type of constructions do not provide any meaningful resistance to an impacting commercial vehicle (Figure 14).

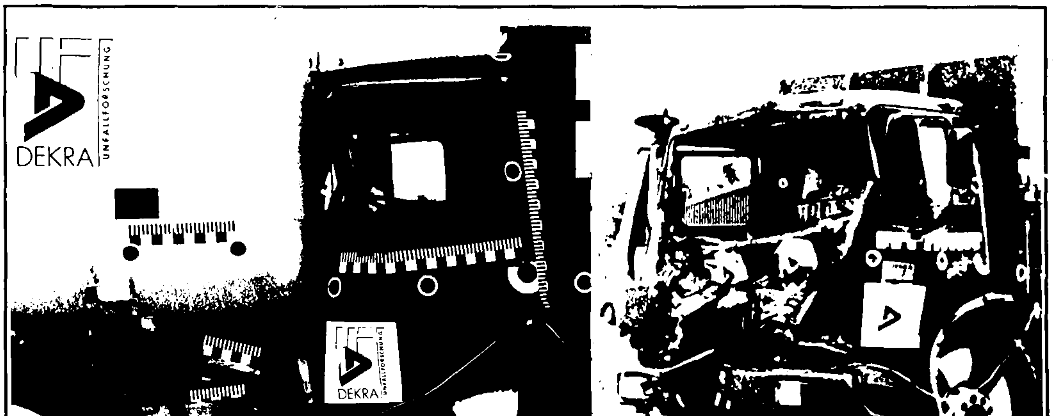


Figure 14. Commercial vehicle and road tanker in their final positions immediately after impact by the commercial vehicle at a speed of 27 km/h against an older type of rear underride protection on the stationary road tanker as part of the THESEUS Project, plus view of the damaged front section of the commercial vehicle.

Greater importance has been attached to the prevention of intrusions in serious collisions with the introduction of supplementary restraint systems (seat belt and airbag). These systems today give the front occupants a good chance of survival in many head-on collisions - providing no excessive intrusions in turn nullify the gain in safety. As such, the rear underride protection is an illustrative example of how the effect of other systems can also be decidedly improved upon or actually felt at all through the optimization of an individual system, taking an integrated approach to certain types of accidents.

Side Protection Devices

Side protection devices have been a statutory requirement in Germany under § 32 c of the StVZO for certain types of heavy goods vehicles first registered after the 1st January 1992. Older vehicles had to be adapted by the 1st April 1994.

The technical design of the side protective devices is governed by the European standards ECE R 73 and 89/297/EEC. The purpose of the design is to offer effective protection for unprotected road users against the risk of impacting beneath the side of the vehicle and being caught up by the wheels. The regulations consider pedestrians and two-wheel riders to be unprotected road users.

As the analyses of the actual course of events of the accident have shown, passenger vehicles are most frequently the other party involved in accidents with commercial vehicles, including in side collisions. Closer examination is therefore required as to whether the function of the side protection devices can also be extended to the impact by a passenger vehicle at justified cost.

POTENTIAL BENEFITS

The data collected from in-depth accounts of individual accidents can be used to forecast the benefit of measures designed to improve passive commercial vehicle safety. From the collection of cases held in the databases of DEKRA Accident Research, a random sample comprising 104 accidents involving 140 commercial vehicles was taken for this purpose. In this random sample the main collisions were distributed in approximately the same way as in a totality comparison comprising a total of 1 011 accidents involving commercial vehicles (Table 4).

Table 4. Distribution of the main collisions in a collection of in-depth accounts comprising 104 accidents involving 140 commercial vehicles for the purpose of forecasting the potential benefits of passive safety measures.

Main collision	Relative frequency
Comm. vehicle single-accident:	13 %
Comm. vehicle front / other vehicle front:	17 %
Comm. vehicle front / other vehicle rear:	14 %
Comm. vehicle front / other vehicle side:	17 %
Comm. vehicle rear /other vehicle front:	12 %
Comm. vehicle side /other vehicle front:	13 %
Comm. vehicle side /other vehicle side:	14 %

The in-depth accounts contained in the random sample made up of 104 accidents were first of all examined by two experts independently of each other to see whether specific measures designed to increase the passive safety of commercial vehicles could have helped reduce the personal injuries in each case. The description of the effectiveness was recorded on a scale of one to five: no, unlikely, possibly, very likely and definitely. The findings were then compared. Where the independent classifications by the two experts differed from one another, detailed discussions were held and a uniform assessment arrived at. In cases of uncertainty the more pessimistic forecast applied. Figure 15 shows one individual result using the example of the airbag. The question was: would an airbag (in conjunction with a seat belt system) have been able to help reduce the personal injuries in the commercial vehicle? In 57 cases the answer to this was clearly no. In 17 cases the assessment was that a reduction in the personal injuries would have been unlikely, in 14 cases this might have been possible and in 7 cases the reduction in personal injury if an airbag had been fitted was seen as very likely. The experts were unable to reach the view that the airbag would definitely have reduced any personal injury. The main reason for this is that in the past there was no data

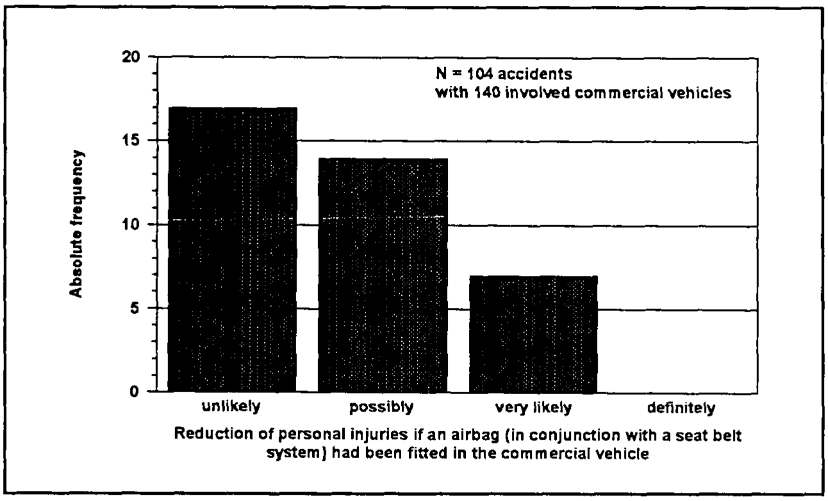


Figure 15. Forecast of the injury-reducing potential of an airbag in a commercial vehicle according to an expert assessment of 104 accidents involving 140 commercial vehicles based on in-depth accounts.

from the actual course of events of accidents on the effectiveness of airbags in commercial vehicles. Combining the assessments "possibly" and "very likely" gives a potential use of the airbag in commercial goods vehicles in a total of 23 cases. This represents 22 % of all the accidents investigated.

One interesting factor in this context is the new Volvo Report 4 which deals amongst other things with the potential effect of airbags as an integral part of supplementary restraint systems in Volvo trucks [17]. In this respect, on the basis of 94 accidents involving injuries to truck occupants, it was calculated that in 21 % of the cases an airbag would have had an injury-reducing effect additional to the seat belt already fitted.

The "passive safety package" for commercial vehicles as summarised in Table 5, was put together at DEKRA Accident Research on the basis of the safety elements described above.

Table 5. Combination of measures as a "passive safety package" for commercial vehicles.

Seat belt + airbag
Crash optimization of the driver's cab
Front underride protection
Optimized rear underride protection and side protection

The purpose of seat belt and airbag, as part of a complementary combination, as well as crash optimization of the driver's cab, is to protect the occupants.

Other road users are protected by a front underride protection as well as an optimized rear underride protection and side protection devices.

The associated assessments by experts based on the in-depth accounts contained in the random sample comprising 104 accidents, showed that in 6 % of the cases there was a definite reduction in the injuries to at least one of the persons involved in the accident. In 23 % of the cases this kind of reduction in injuries was categorised as being very likely. In a further 28 % of the cases, in the view of the experts, it was assumed that a reduction in injuries was possible. This gives a total potential benefit of the measures summarised in Table 5 of 57 %.

NEED FOR RESEARCH

The improvement in the safety of commercial vehicles requires on the one hand taking into account the special purpose of use and the transport tasks of the various types of vehicle. Secondly, specific requirements must be placed on the safety of commercial vehicle as a place of work. In addition, a large, heavy commercial vehicle should not create an excessive risk to other road users in the event of an accident. Current innovations, such as the airbag and crash optimization of the driver's cab, will contribute towards a further reduction in the consequences of accidents at what is already a high level of safety in commercial vehicles. Such processes are characterised by the fact that an ever reducing marginal benefit is all that's left for the additional cost. In order to reach sound decisions on the use of limited resources for future developments, high quality information will be needed. This represents the framework of conditions for further research and development as well as the need for research in the field of commercial vehicle safety.

There is an urgent need for research particularly into the sound implementation of benefit/cost analyses. This relates both to the costs as well as the forecast of beneficial effects. In view of the diversity of commercial vehicles it is questionable as to whether the generally available cost rates, accepted as being valid, reflect the actual situation to a sufficient extent for the purpose of detailed accident cost estimates. Data designed to help calculate the extent and structure of the costs of road accidents involving road tankers was collated and analysed for example as part of the THESEUS Research Project. There is a similar need for investigations for other commercial vehicles. In many cases there is insufficient awareness of the beneficial effects of measures designed to improve vehicle safety. First of all, the knowledge on potential savings in the consequential costs of fatalities and injuries is inadequate. Secondly, additional, cost-related effects and multiple benefits must be taken into account, such as for example in the side protection devices.

There is also a need for an expanded bio-mechanical basic research. At present the same dummies and measurement sensors as well as the associated biomechanical criteria and limits are used to analyse the loadings on occupants in crash tests using commercial vehicles as were originally developed and validated for corresponding trials with passenger vehicles. This may well have been sufficient for previous investigations. However, in view of the clearly different posture in the

commercial vehicle compared with a passenger vehicle, a thorough examination is required as to whether very demanding questions of a medical and bio-mechanical nature (of the kind which for example have to be posed for the comprehensive assessment of the various types of restraint systems) need to be answered with the necessary reliability, utilising the latest information.

The aim of the investigations in this context should not so much be the development of special dummies for commercial vehicles. From today's viewpoint it would seem sufficient to improve the adaptation of the existing dummies to the specific requirements in a commercial vehicle, requirements which are influenced in particular by the different posture. In addition, the question as to whether the bio-mechanical limits validated for the occupants of passenger vehicles can also be directly transferred to the occupants of commercial vehicles, should be examined.

With the increasing use of basic and supplemental restraint systems in commercial vehicles as well, associated new technical and medical features are becoming relevant to the purpose of actual accident research. These features should be documented appropriately and then evaluated in such a way as to enable them to provide the information required for the vehicle developers. A similar development has already begun in the passenger vehicle sector.

The problem of loads and attachments which has previously been excluded, must in future also be taken into account within the framework of crash test programmes. Worst case assumptions are a helpful factor in sensibly restricting the potential diversity of tests from the outset. It will be a question in this context of pushing ahead further with the process of evolution already commenced, without any statutory controls. This includes clearly defined objectives for protection which can be achieved at a justifiable technical cost.

In this process a rethink is also required on the current provisions relating to the registration, taxation and insurance of commercial vehicles. These should not hinder the further progress towards greater vehicle safety and can be utilised if necessary for its specific promotion.

REFERENCES

[1] Brenken, G.: Der Weg zum Sicherheitsautomobil. ATZ Automobiltechnische Zeitschrift 73 (1971) 5, S. 170 ... 178.

[2] Morschheuser, K.: Airbag im Rahmenfahrzeug. Grundsatzuntersuchungen zur Entwicklung eines Airbags für Nutzfahrzeuge der "Schweren Klasse". ATZ Automobiltechnische Zeitschrift 97 (1995) 7/8, S. 450 ... 457.

[3] Högström, K., L. Svenson, L. A. Weimar u. a.: Report 1, Heavy Commercial Vehicles / Unprotected Road Users. Volvo Accident Investigation, Göteborg, Schweden, 1973.

[4] Högström, K. L. Svenson u. B. Thörnquist: Report 2, Fatal Accidents, Heavy Trucks / Cars. Volvo Accident Investigation, Göteborg, Schweden , 1974.

[5] Högström, K. u. L. Svenson: Report 3, Accidents Involving Volvo Trucks Resulting in Personal Injuries. Volvo Accident Investigation, Göteborg, Schweden, 1974.

[6] Grandel, J. F. A. Berg u. W. Niewöhner: Sicherheitsanalyse im Straßengüterverkehr. Berichte der Bundesanstalt für Straßenwesen. Reihe Mensch und Sicherheit, Heft M 7, Bergisch Gladbach, April 1993.

[7] Grandel, J. u. W. Niewöhner: Untersuchungen zur inneren Sicherheit von Lkw-Fahrerhäusern. Forschungsvereinigung Automobiltechnik e.V. (FAT) Schriftenreihe Nr. 122, Frankfurt am Main, Juli 1994.

[8] Autorenkollektiv: THESEUS Tankfahrzeuge mit höchst erreichbarer Sicherheit durch experimentelle Unfallsimulation. Zusammenfassender Schlußbericht. TÜV Rheinland e.V., Köln, März 1995.

[9] Straßenverkehrsunfälle. Verkehr, Fachserie 8, Reihe 3.3. Statistisches Bundesamt, Wiesbaden.

[10] Grandel, J. u. F. A. Berg: Neue Wege zur Erprobung und Verbesserung der Nutzfahrzeugsicherheit. Verkehrsunfall und Fahrzeugtechnik 32 (1994) 7/8, S. 205 ... 212.

[11] Rubi, V., H. Geißler u. P. Alber: Numerische Simulation des Crash-Verhaltens von Nutzfahrzeugen. ATZ Automobiltechnische Zeitschrift 95 (1993) 10, S. 528 ... 535.

[12] McKellip, S. u. K. Morschheuser: Abstimmung der FE-Crashrechnung eines Frontlenker-Rahmenfahrzeuges der Schweren Klasse mit Crashversuchen. Berechnungen im Automobilbau, VDI Berichte Nr. 1153 (1994) S. 421 ... 440.

[13] McKellip, S. u. P. Alber: Passive Sicherheit von Lkw-Fahrerhäusern. Berechnungen im Automobilbau, VDI Berichte Nr. 1188 (1995) S. 239 ... 257.

[14] Göhring, E. u. W. Krämer: Verbesserung der aktiven und passiven Sicherheit bei Nutzfahrzeugen durch seitliche Fahrgestellverkleidungen. ATZ Automobiltechnische Zeitschrift 89 (1987) 12, S. 659 ... 666.

[15] Beermann, H. J.: Untersuchungen zum Aufprall von Personenkraftwagen auf Unterfahrschutzeinrichtungen. AI Automobilindustrie 25 (1980) 4, S. 47 ... 54.

[16] Grandel, J., F. A. Berg, B. Schmitt, J. Epple u. E. Günther: THESEUS - Tankfahrzeuge mit höchst erreichbarer Sicherheit durch experimentelle Unfall-Simulationen. Teilbericht Fahrzeug-Fahrzeug-Crash. DEKRA Unfallforschung, Stuttgart, März 1995.

[17] Persicke, G. u. J. R. Child: A development in truck rear end safety devices. VDI-Berichte Nr. 367 (1989) S. 317 ... 321.

[18] VOLVO Truck Corporation: Report 4, Accidents involving Volvo trucks resulting in driver injury, and estimated effect of the SRS-Airbag. Accident Investigation (1994).

CERTIFICATION OF ROLL-OVER PROTECTION SYSTEMS FOR HEAVY VEHICLES BY COMPUTER SIMULATION

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ABSTRACT

To boost workplace safety on mining and quarry sites in Victoria, the State Government has announced a new initiative, accompanied by financial support, to help operators to fit roll bars and seat-belts to their vehicles, and to assess them by computer simulation of the prescribed physical tests.

The procedure for compliance by computer simulation is demonstrated on one real case, involving a "one off", self-made ROPS. Static tests are simulated first, followed by the simulation of dynamic roll-over in order to evaluate a recent criticism on the adequacy of the AS 1224-1994 for the protection of drivers in real roll over accidents. Finally, the self-made ROPS design of the discussed case is evaluated and modified to demonstrate that not only a substantial weight reduction is possible, but also that a lighter ROPS may improve passive safety of operators.

INTRODUCTION

From January 1985 to December 1993, there were 362 work-related fatalities involving tractors in the Australian State of Victoria. This is, in relative terms, a large number in view of the fact that Victoria has a population of about 4.5 million.

Some 46% of the fatalities were caused by roll over of a tractor, ie about 166 fatalities, or in average 18.4 fatalities every year, to which the agricultural sector contributed 22%, and the other industries the remaining 78%. The statistics for other type of earth moving machinery is not available.

These alarming figures resulted in the implementation of Extraction Industries Regulations 1989, and Mineral Resources (Health and Safety) Regulations 1991, which require that all mobile equipment and vehicles manufactured after 1988 must be fitted with Roll Over Protective Devices (ROPS) that comply with the Australian Standard AS 2294; this standard is technically identical with the standards SAE J1040 APR 88 and ISO 3471/1. All three standards prescribe in detail physical tests and specify criteria the equipment has to satisfy in order to demonstrate compliance with the regulations.

It is relatively easy for commercial manufacturers to develop and implement satisfactory ROPS for their products; only one physical test is required for each type of machinery. However, there is a large number of older earth moving vehicles in service, which are mostly owned by individual operators who can hardly afford a destructive test on their usually self made ROPS. Therefore the Victorian Department of Agriculture, Energy and Minerals announced in 1995 a new State Government initiative to boost workplace safety on mining and quarry sites in Victoria by offering a $250 payment per vehicle to assist with computer simulation of self made or retrofit ROPS. Further, in 1996 the State Government announced another initiative for the development of generic designs of ROPS to serve as a guideline to individual owners. TAYMAR Pty Ltd has been appointed to develop such designs.

In the following, firstly a case study is presented which should demonstrate the procedure of computer simulation of the static test according to AS 2294, as applied to one self made ROPS. Then results of a dynamic simulation of a roll over of the same vehicle are shown and discussed, as a response to a recently expressed criticism of the adequacy of static tests for ensuring the operators' safety. This simulation is also used to demonstrate the importance of seat belts. Finally, a generic design of ROPS is presented, as the answer to the fact that the self made ROPS are usually over designed and, as a consequence, too stiff. The negative effect of over stiff structures on the safety of operators during roll over is also discussed.

For the reasons of a limited size of this paper, only lateral roll over tests are investigated and demonstrated.

STATIC LATERAL TEST

Figure 1 shows a photograph of a Crawler Dozer Caterpillar D6 (Model 58), owned by a prospector undertaking strip mining for gold, and equipped with ROPS designed and manufactured locally in a small work shop. The ROPS consist of a series of beams of

100x100x6 mm (about 4x4x1/4 inches) box-type cross section. The beam structure is attached on each side of the dozer to a plate of 12 mm (approx. 1/2 inch) thickness, the plates being welded to the dozer body and supported by three triangular stiffeners of 25 mm (approx. 1 inch) thickness.

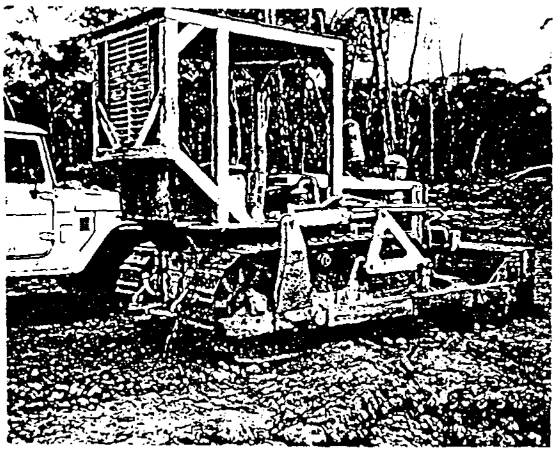

Figure 1. Photograph of the investigated Crawler Dozer Caterpillar D6.

A finite element model used for the simulation of the static tests according to the AS 2294 is shown in Figure 2. The finite-element program ABAQUS has been used for this simulation. As it can be seen, the plates are modelled in detail by a series of plate elements and connected rigidly to the dozer (not modelled). The ROPS is modelled by beam elements. These elements appear as lines in Figure 2, however these lines have all the necessary tension-compression, bending and torsional properties of the box cross-section, and also elasto-plastic properties of the used material.

The standard defines a so called deflection-limiting volume (DLV), ie a volume which must not be penetrated by the ground during a lateral impact (ground simulated plate - GSP - is used in static tests). The DLV and GSP are also shown in Figure 2.

For the tested vehicle, which has a total mass of 10,000 kg (22,000 lbm), the AS 2294 requires firstly that the ROPS have to sustain a force of 70,000 N (15,700 lbf) in lateral loading without the GSP penetrating the DLV. This is necessary for ROPS to penetrate unfrozen soil thereby giving a braking action to a roll.

The second lateral response requirement states that the deformation energy accumulated by the ROPS must exceed 13,000 J (9590 ft lbf). This ensures that the ROPS will deflect and provide run down when striking frozen soil, concrete, rock, or a similar rigid surface while retaining the capability to withstand subsequent impacts.

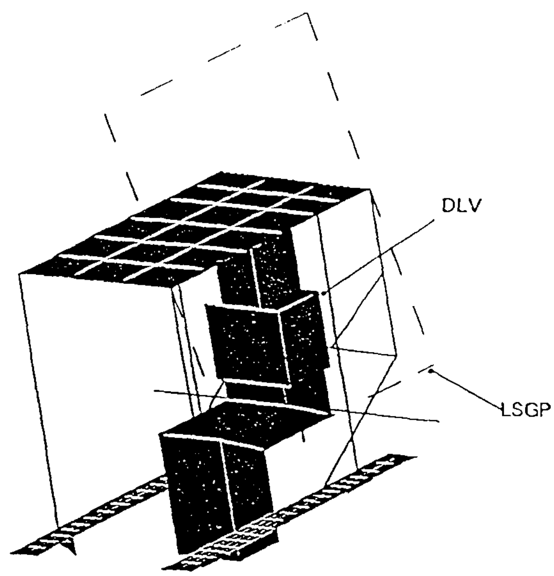

Figure 2. Finite-element model of the dozer.

Figure 3 shows the force-displacement diagram, as obtained from the simulation. The area below the curve represents the deformation energy accumulated in ROPS at the end of the loading.

The total energy is 280 J (206 ft lbf), which is substantially less then the required amount of 13,000 J (9590 ft lbf). Therefore the structure had to be loaded further until the energy requirement was satisfied (dotted line in Figure 3). A force of 240,000 N (54,000 lbf) was needed to achieve this, ie about 3.5 more than required by the force criterion only. These results indicate that the ROPS is too stiff.

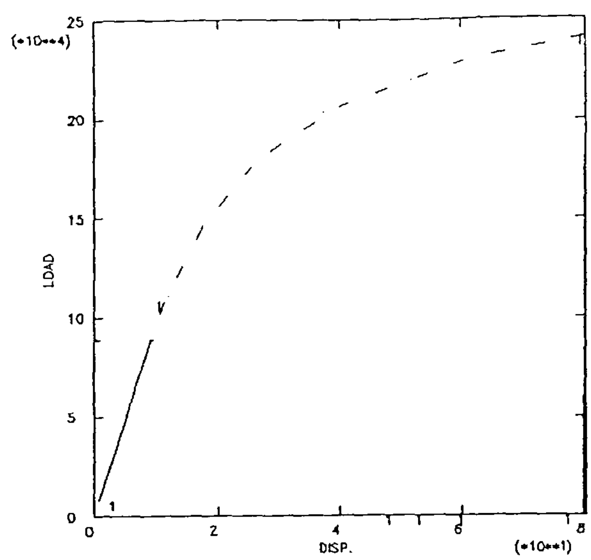

Figure 3. Force-displacement diagram from the lateral static test.

Figure 4 shows the ROPS model from Figure 2 after the application of the lateral force of 240,000 N (54,000 lbf). It can be seen that DLV was not penetrated by GSP.

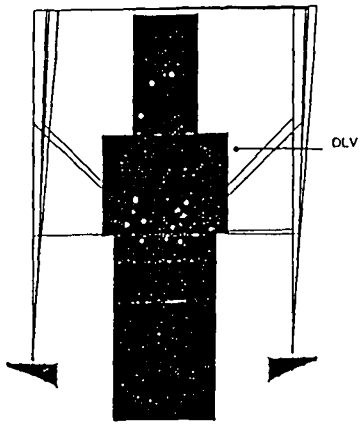

Figure 4. ROPS model from Figure 2 after static lateral test.

DYNAMIC LATERAL TEST

There has been an expert opinion expressed at a recent Coroner's Inquest in a fatal accident involving a haulpak roll-over, questioning the AS 2294 requirements in regard to the adequacy of resulting safety protection. To respond to this criticism, a dynamic model has been developed and the lateral roll over test, under the conditions on which the static test has been based, has been simulated by the computer program MADYMO.

Figure 5 shows the MADYMO model. The dozer itself is modelled as a series of rigid bodies, the ROPS, including the supporting plate, is modelled by finite elements. The stiffness of contacts between the structure and the ground is modelled by use of the known soil data.

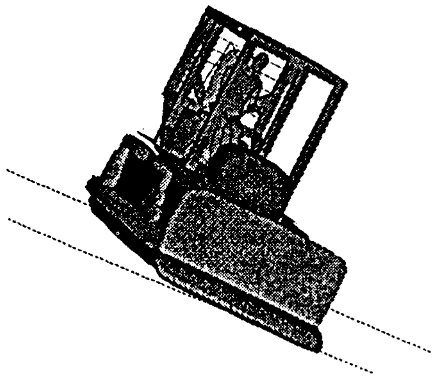

Figure 5. MADYMO model for the lateral dynamic test.

The model includes also a 50% Hybrid III dummy to demonstrate the importance of restraint systems for operator safety. Strain effects are not included in the model, but they should have little effect on the overall results.

Figure 6 shows the model at the moment of maximun ground penetration. It can be seen that the ground did not enter the DLV, however the unrestrained occupant has been catapulted from the DLV and has impacted the ground. Further more, the driver may be crushed by the dozer so that the chance to survive such accident is minimal indeed.

The average value of the impact force from the dynamic simulation of the lateral roll-over was found to be about 200,000 N (45,000 lbf), ie it corresponds not only well to the static value of 240,000 N (54,000 lbf), but also confirms that the ROPS are unnecessarily too stiff.

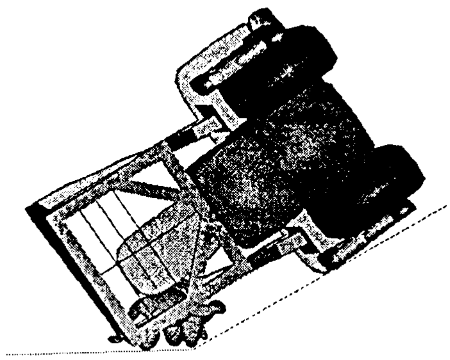

Figure 6. MADYMO model - Unrestrained occupant.

Nevertheless, it can be stated, at least for the presented case, that the static test according the AS 2294 adequately prescribes the necessary value of the lateral force.

MECHANICS OF OPERATOR RESTRAINT AND PROTECTION

The previous example of a dynamic roll over demonstrated that while the structure was stiff enough to resist intrusion into the original DLV, the DLV is neither fixed or constant due to the movement of the unrestrained occupant. It showed that the operator is likely to be ejected from the machine unless some form of restraint is provided for. Figure 7 shows the same roll over event as that shown in Figure 6, but with the addition of a lap belt for the operator. As this figure shows, the driver remains restrained approximately within the bounds of DLV. A second simulation (not shown here) of the same roll over,

but with the driver in a lap/slash three point restraint showed similar results. Despite this, some consideration must be given to the type of restraint installed in such machinery with regards to the mechanics of the roll over event.

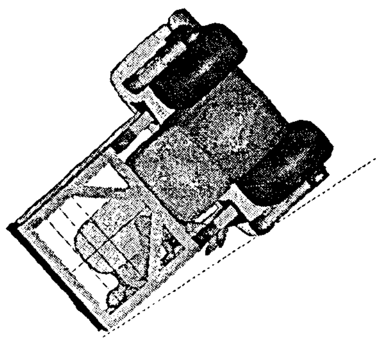

Figure 7. MADYMO model - Occupant restrained by a lap belt.

Firstly, as the vehicle rolls, it is highly likely that without any restraint the operator will be displaced from the seating position rather early in the event, ie well before any impact with the ground has occurred. Given that the rate of this roll over is initially relatively slow (low angular velocity), it is unlikely that the automatic retractor system would lock in time to stop the operator from spooling the belt out and sliding slowly off the seat. This locking problem would occur with standard inertia reel type and emergency locking type retractors in lateral roll overs. Hence the most effective option would be to have operator adjustable seat belts fitted to the vehicle, though the problems associated with poor tightness and geometry with this type of belts would be present.

Secondly, while the operator will be located at the pelvis/seat interface by the lap belt, there is no mechanism for fixing the upper body of the occupant. Without this, it would be possible for the operator to be thrown against either the ROPS or the ROPS glazing/cladding surfaces, which may result in head or thoratic injury of the type commonly seen in the occupants of passengers vehicles after side impacts. While three point belt would do something to prevent this occurrence, it is not likely that it would provide any protection when the operator is thrown away from the side of the vehicle which the sash belt is mounted on, allowing the operator to slide laterally out of it. Similarly, if the operator were to slide laterally towards the sash belt, a hazardous neck injury could occur. The best option, after having considered all these arguments, appear to be a tightly adjusted four point racing harness belt. While such belts do not provide the same ride down for the occupant as conventional passenger car seat belts, roll over impacts are typically at low acceleration levels so the need for elongating belts is not as critical.

Finally, some consideration in the ROPS design must be given to the way how the strain energy is stored during an impact. While the ride down provided by the deforming ROPS will serve to lower peak acceleration levels experienced by the occupant and hence any inertia based injuries, the impact velocity of ROPS is seldom high. The mechanism of death in most occupational accidents involving mining and agricultural equipment is being crushed beneath the vehicle. Hence if a ROPS is overly stiff, this may not adversely affect performance of the ROPS with regards to injury reduction. The main problem in this case is that in the event of a roll over, the ROPS may transmit all the load to the vehicle structure, causing damage to the expensive machinery rather than to the cheaper and replaceable ROPS.

SAFE DESIGN OF MINIMUM WEIGHT

As mentioned in the second chapter, the ROPS for the dozer shown in Figure 1 is too stiff. It is of interest to develop a generic design which would have optimum properties, ie minimum weight and still adequate safety.

The same model as shown in Figure 2 has been used for the study, however without the supporting plates. A preliminary hand calculation indicated that a cross section 50x50x6 mm (2x2x1/4 inches) should be adequate for the mass of the dozer. Figure 8 shows the deformed structure after the static lateral test. As it can be seen, the DLV has been just avoided by the GSP.

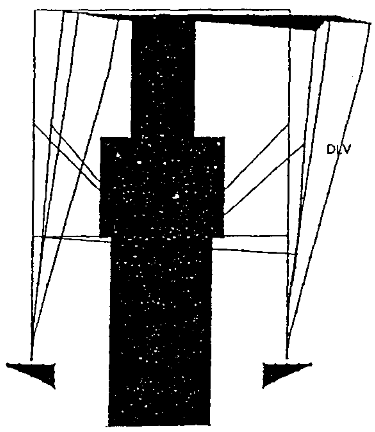

Figure 8. Lighter ROPS model after static lateral test.

Figure 9 shows the force-displacement curve of the lighter ROPS from the lateral static test. It can be seen that the lateral force is not reaching the prescribed value of 70,000 N (15,700 lbf), however the energy requirement is satisfied. It can be therefore stated that the ROPS design with the reduced cross-section, as shown above, is just below the level of acceptance, and that a slight increase of the cross-section would be beneficial.

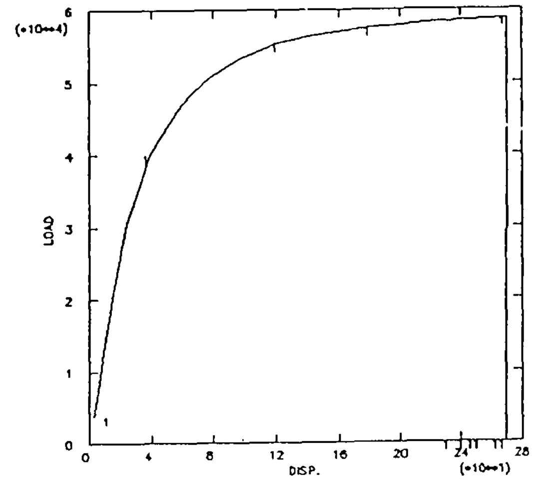

Figure 9. Force-displacement diagram from the lateral static test.

Figure 10 shows the deformation of the lighter ROPS as obtained from MADYMO dynamic simulation. The DLV was not penetrated, however, the braking effect to roll-over, as required by the standard, may not be adequate.

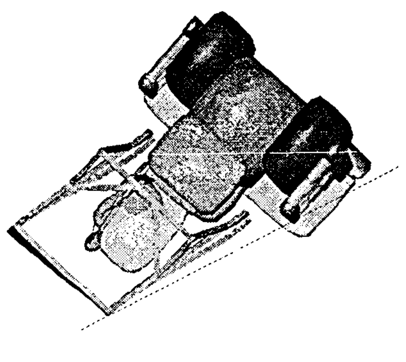

Figure 10. MADYMO model of lighter ROPS-Occupant restrained by a lap belt.

CONCLUSION

This study has demonstrated that either dynamic or static computer models represent a viable alternative to experimental testing of ROPS. The finite-element method is accurate method for assessing ROPS performance and a useful tool for developing generic designs for a variety of types and sizes of earth moving vehicles. Further more, it has been shown that the physical static test is a good method for compliance testing over more expensive physical dynamic tests. Lastly, the need for adequate operator restraint in conjunction with a suitable ROPS has been shown to be critical for real world injury reduction in the area of heavy vehicle safety.

ACKNOWLEDGMENTS

The authors express their appreciation for the financial and in-kind support by the Department of Agriculture, Energy and Minerals of the State Government of Victoria.

REFERENCES

Danger - Tractors & Other Farm Machinery, Occupational Health and Safety Authority, Department of Business and Employment Industry Service, Melbourne 1995.

News Release, Office of the Minister for Energy and Minerals, State Government of Victoria, May 4, 1994.

Circular MDS:kn ME/63, August 31, 1995, Standard Australia, POB 1055, Strathfield, NSW 2135.

ABAQUS User's Manual, Version 5.5, 1996, Hibbitt, Karlsson and Sorensen, Inc., Providence, R.I., USA.

MADYMO User's Manual, Version 5.1.1, 1995.

ROLLOVER ANALYSIS METHOD OF A LARGE–SIZED BUS

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Paper Number 96–S11–O–05

ABSTRACT

Remarkable progress has been made in the safety technology of a car, and in recent years there has been strong demand for a safety sight–seeing bus. For this reason, safety bus structure is essential to reduction in casualties, and computer simulation is indispensable for developing a safety bus. However, the structural analysis of a bus is so time–consuming because of the enormous number of elements of a vehicle model.

This paper deals with structural analysis method for a bus in the event of rollover to reduce the calculation time to a reasonable one. A common crash analysis solver is modified in our method by reducing the number of integration cycle with respect to time in the explicit finite element method.

Rollover test and computer simulation have been performed based on the ECE R66 regulation which specifies European rollover test standards. Deceleration and displacement of critical points on the bus have been measured during the time the vehicle is being deformed. As a result, quite a good agreement has been achieved between the test results and the simulation ones.

INTRODUCTION

First of all, the outline of the rollover crash test is explained before the new numerical analysis method is discussed. Our test method is based on the European regulation, ECE–R66.

A rollover crash tester shown in Fig.1 is used. The test vehicle is placed on a platform, 0.8 m high from the ground. This platform turns on a pivot in one side of the platform, and is tilted by pulling up the other side of the platform until finally the test vehicle lies on its side on the concrete ground. The test vehicle used in this study is a high–floor–type heavy–duty sight–seeing bus, 12.0 m in overall length, 2.5 m in overall width and 3.7 m in overall height. Fig.2 shows the outlook of the rollover crash test.

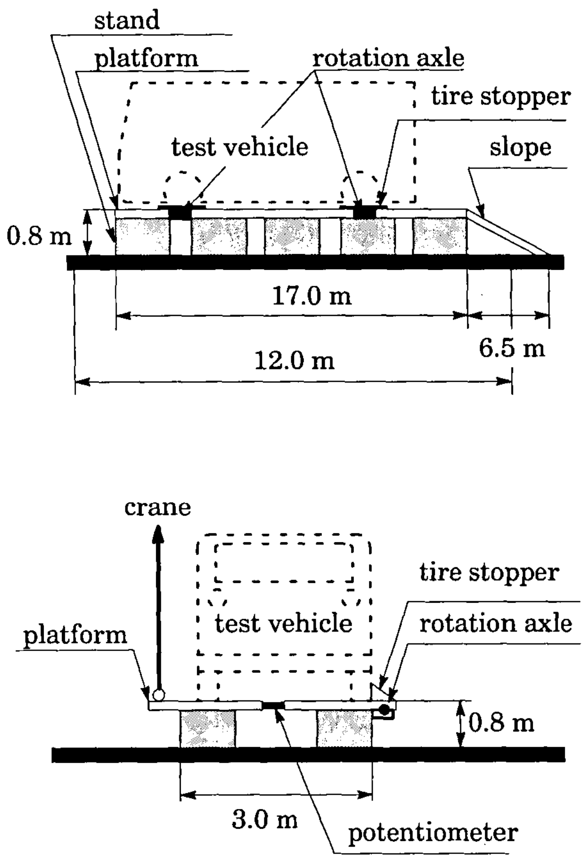

Figure 1. Rollover Crash Tester.

Fig.2 Outlook of Rollover Crash Test.

The objective in this evaluation test is to confirm that the fall on the ground does not cause the vehicle deformation which intrudes into the life area specified by the regulation. In order to confirm this, Styrofoam plates, what we call 'templates', as shown in Fig.3, are used at several locations to simulate the life areas inside the bus. Needles are stuck on the templates, and the amount of intrusion into the life area is measured by the lengths of the needles sunk into the templates, which is caused by the deformation of the bus wall. Fig.4 shows the locations of templates.

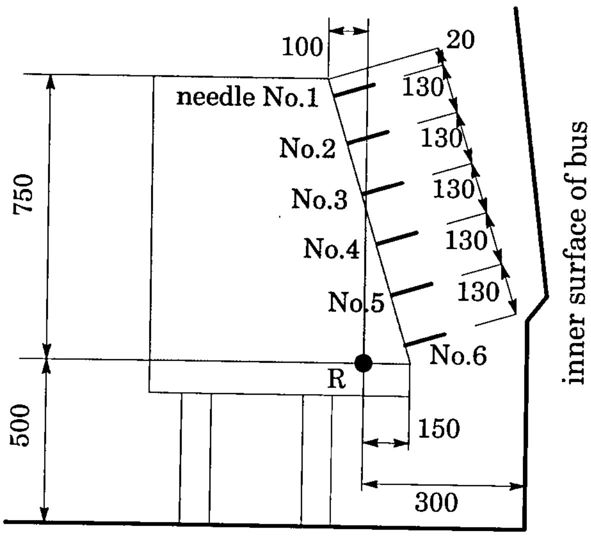

Fig.3 Template of Life Area.

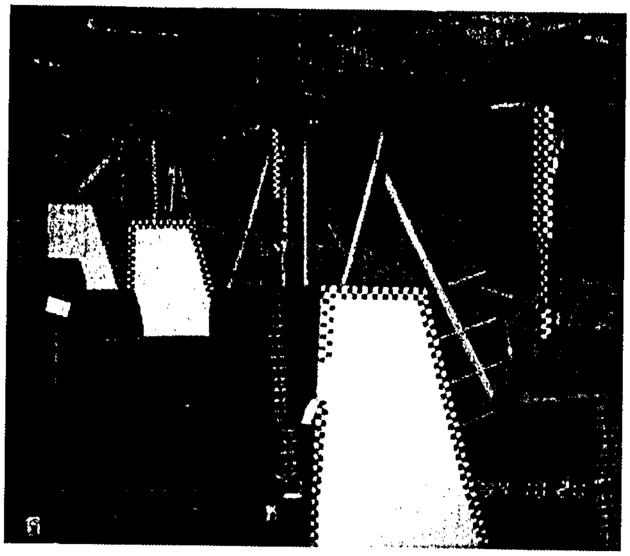

Fig.4 A picture of Template

The other objective of this rollover test is to obtain data required in the calibration of a numerical analysis model, such as acceleration characteristics, displacement in the suspension, and deformation mode, by using accelerometers, potentiometers and high–speed cameras, respectively.

TEST RESULT

The following data were obtained from the time when the platform started tilting to the time when the vehicle initially hit the ground:

- Angular velocity of tilting platform: 1.4° /sec (measured by the potentiometers on the platform)
- Angle at which the test vehicle starts rollover under the force of gravity alone: 41°
- Crash speed: 24 km/h (6.67 m/sec) (measured by micromotion film analysis method using high–speed camera)

The outlook of the test vehicle is shown in Fig.5. These photographs were taken with the vehicle viewed from the front, from the top and from the bottom respectively. These photographs demonstrate the following facts:

- The photograph of the frontal view shows that deformation in the vehicle front occurred mainly in the pillar–to–floor joint structure with the side pillars and

the roof left intact, and in a mode in which the front windshield was deformed in a shape of parallelogram. Also, the photo–graph shows that the pillar–to–floor joint structure in the not–struck side was broken near the side center of the bus.

- The top view demonstrates that the roof was little deformed.
- The bottom view shows that the engine and suspension were free from significant damage. Also, the vehicle was free from fuel leak and damage to electrical wires.

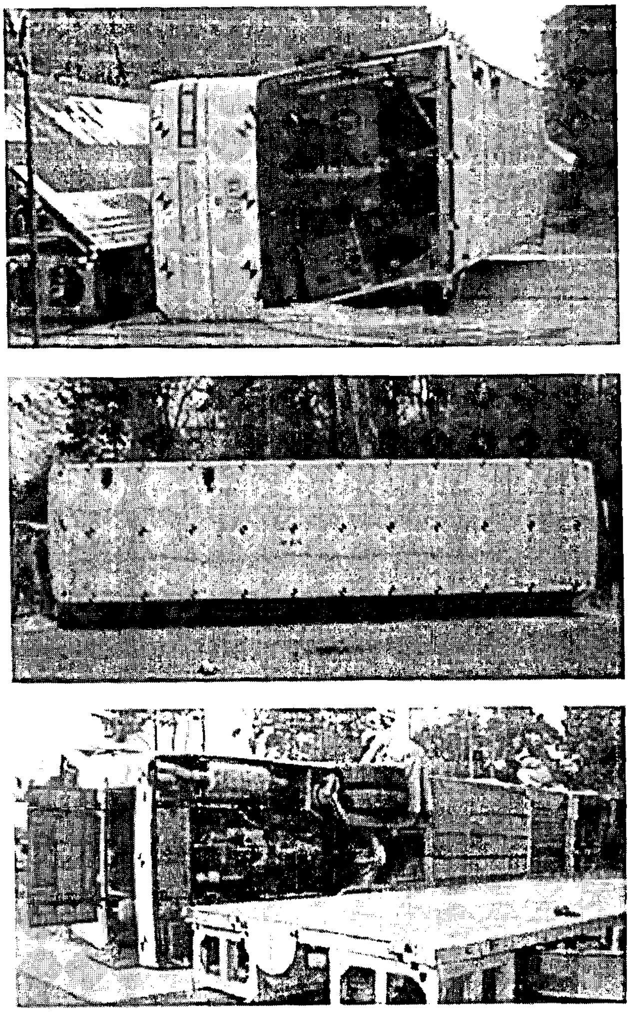

Fig.5 Deformation of Body

The measurement of accelerations on each part of the vehicle reveals the following facts:

- The roof rear first hit the ground, and 6 msec after that, the roof front did.
- When the roof rear hit the ground, an acceleration of – 85 G was produced in Y direction.
- The acceleration of the roof in Y direction was – 4 to – 5 G, far smaller than that for the roof.
- When the resultant accelerations on the right and left middle parts of the vehicle are compared, the acceleration on the right side of the roof is larger than that on the left side, while the acceleration on the left side of the floor is larger than that on the right side.

Fig.6 shows the results of measuring suspension movement using the potentiometer in the rollover event. The measurement is performed to prepare an analysis model by obtaining mass balance data, including those of unsprung mass.

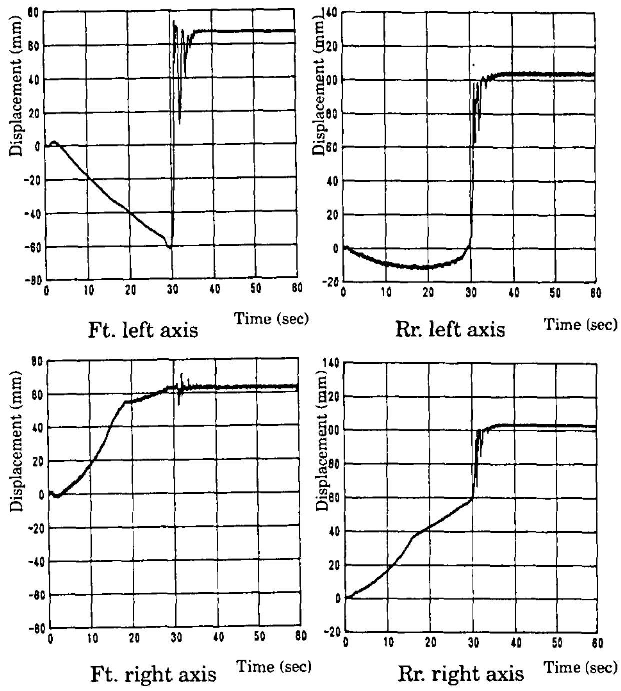

Fig.6 Movement of the Suspension

This measurement reveals that the left front wheel shrank as the vehicle was tilted to the left side, while the left rear wheel scarcely shrank. The maximum displacements immediately before the vehicle starts rollover under the force of gravity alone, and the maximum returns of springs

in reaction for the wheels are within the range from 60 mm to 127 mm, 1/29 to 1/62 of the vehicle overall height of 3.7 m, which are extremely small. This indicates the possibility of neglecting the effects of change in mass balance and dealing with the sprung and unsprung masses as an integrated one.

The movements of the points marked on the vehicle were measured by the micromotion film analysis using the high–speed camera. The film analysis was performed for 62.5 msec from 18.75 msec before the crash to the ground with time increments of 6.25 msec.

Fig.7 shows the analysis results of the vehicle front and rear, indicating the characteristics of the deformation mode. These figures are obtained by connecting with lines the marked points on the vehicle immediately before and after the crash, showing that the largest displacement occurs in different places from the vehicle front to the vehicle rear. The photography reveals that the deformation in the vehicle becomes maximal approximately 200 msec after the crash, and then the fall on the ground reduces the deformation in the chassis, and finally the deformation remains as permanent set.

These results indicate that investigation into deformation behavior in the transient period is essential to the confirmation of intrusion into the life areas and the analysis of deformation behavior.

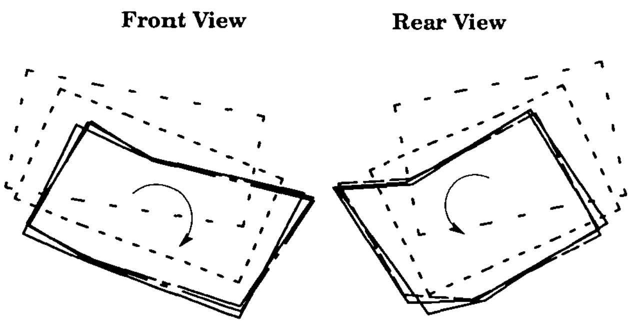

Fig.7 Film Analysis Result of Actual Test

NUMERICAL ANALYSIS METHOD

As explained so far, the vehicle test is such a large–scale one that the test cannot be repeated so often at the development stage. Also, information about the deformation behavior during the transient period is indispensable to engineering, but is difficult to obtain only from the vehicle tests. Therefore, simulation is very effective in determining the specifications of a bus at the initial stage of engineering.

However, a large–scale model is required in analyzing the deformation behavior of a bus structure in an rollover event because the vehicle itself is very large, and the entire vehicle is affected by deformation. The duration of the deformation behavior is around 2000 msec, much longer than that in the normal case of collision. If all the procedures for the explicit analysis method are exactly carried out on the entire area with time increments for one cycle restricted by the Courant conditions, an enormous calculation time is required. Therefore, the most essential to the analysis technique is the reduction of calculation time, and, in order to save the calculation time, the following two methods are proposed:

- Reduce the number of elements by restricting the modeling of vehicle parts to be analyzed.
- Reduce the duration of behavior by restricting the range of time to be analyzed.

These methods, however, have the following drawbacks:

For the first proposed method, the number of elements is reduced in making a full model by combining parts which can be roughly modeled because of slight deformation in beam elements, and those which should be modeled in detail because of heavy deformation in the elements. However, in reality, structural stiffness is locally reduced by joining parts, and the hardness of a plastic material depends on strain rate. Therefore, proper stiffness reductions are very difficult to give to the joint structures. Also, a preliminary vehicle test is required in restricting the area of deformed parts. Moreover, the results obtained cannot be applied to a

case with different test conditions, such as vehicle model and rollover method.

With the second proposed method, the duration of the overall rollover behavior is reduced. In restricting time range in behavior analysis, the time during which deformation occurs cannot be neglected. Therefore, calculation starts immediately before the vehicle hits the ground. In this method, however, performance of a vehicle test is required in order to estimate the initial velocities at the event of crash as in the case of determining loading conditions in the general analysis. Even with the velocities estimated in the rollover event where the vehicle rotates while it falls down, the magnitude and direction of the velocity are different from part to part of the vehicle, and therefore, complicated procedures are required for inputting the velocity data from the measurement results. Other possible simple method is to assume the magnitude and direction of velocity constant at any part of the vehicle, but the dominant direction of deformation behavior is difficult to identify.

Fig.8 shows the calculation results of both horizontal and vertical components of velocities at the event of the vehicle front hitting the ground, where accelerations caused by the gravity force are given to the model with weight distribution in simulated shape. The calculation reveals that velocities at the center of gravity and at the marked points on the corners have respective characteristic components.

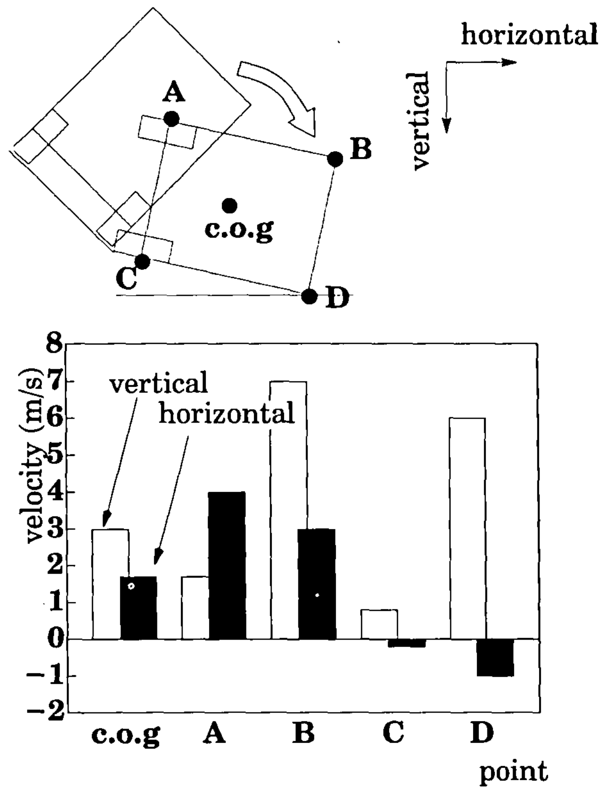

Fig.8 Vertical and Horizontal Velocity at the impact event

Explanation so far in the rollover event indicates that a large–scale model should be fully calculated over the entire period of deformation behavior.

Another aspect of the numerical analysis to deal with is discrete quantity of time. Time should be discretized to as small increments as possible according to the Courant conditions in order to obtain proper elemental forces produced by external ones in the case of using an explicit analysis solver, which is appropriate for dealing with deformation behaviors in collision. In the case of rollover, however, such a discretization condition is not always required, especially during the time of the vehicle falling down before it touches the ground. The duration of the falling–down event is approximately 1600 msec, taking most of the total time of the rollover event, around 2000 msec. Therefore, saving

calculation for the period of the falling–down event will be effective.

The abovementioned ideas are materialized in our calculation method. As shown in Fig.9, the entire model is considered as an ideal rigid body, and thus long time increments are provided during the time when the vehicle falls down from the platform. Immediately before the vehicle hits the ground, the conventional crash analysis begins with the rigid body conditions replaced with the original ones. In such a way, the material conditions are optional in our method.

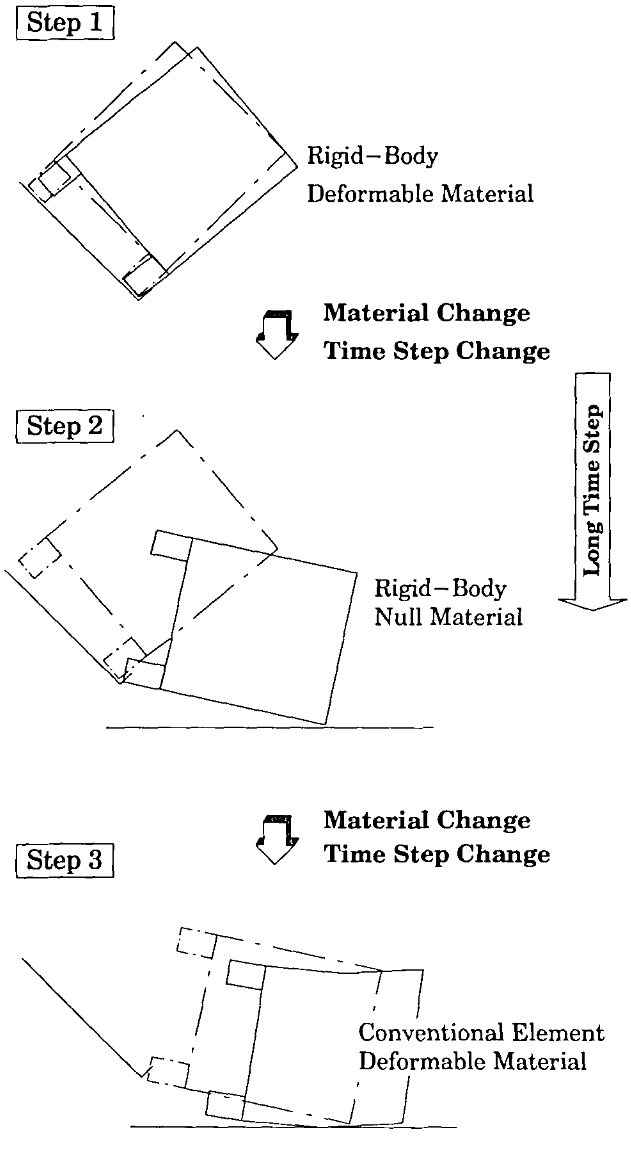

Fig.9 Material Change

The analysis model is shown in Fig.10. As seen from this figure, the entire vehicle model is made from almost equal shell elements. The total number of elements is approximately 65,000, including the beam elements for the suspension and wheels. An approximate platform angle at which the vehicle starts rollover under the force of gravity alone is calculated from the height of the center of gravity and the tread width. The elements for the front windshield glass are eliminated as broken pieces when the magnitude of strain exceeds a certain limit.

Number of nodal points	61,998
Number of shell elements	65,563
Number of beam elements	186

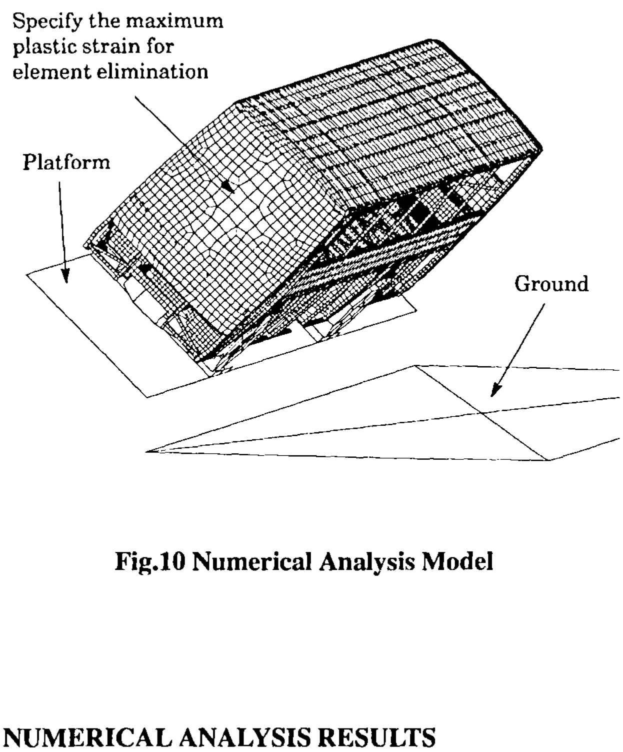

Fig.10 Numerical Analysis Model

NUMERICAL ANALYSIS RESULTS

Fig.11 shows the results of applying the numerical analysis method to a representative deformation case. With this analysis method, the form of the vehicle can be continuously expressed from the time when the bus starts toppling over to the one when the bus is on its side.

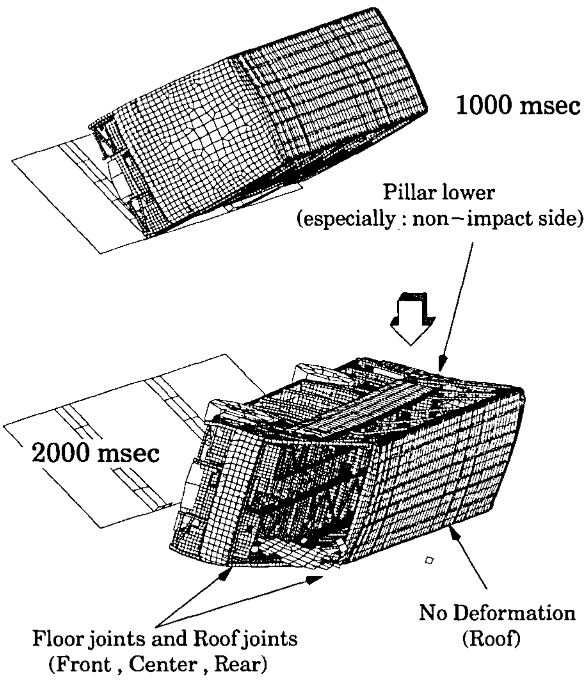

Fig.11 Numerical Analysis Result of Rollover

The following characteristics are shown in the simulation results, which agree well with the test results:

- In the vehicle front and rear ends where beam stiffness are comparatively high, deformation occurs mainly in the pillar–to–floor and pillar–to–roof joint structures both in the struck and not–struck sides.
- In the center of the vehicle, deformation occurs in the pillar–to–floor joint structure in the struck side, and the pillars in the not–struck side are heavily deformed.
- The roof as a whole is little deformed, and thus out–of–plane deformation scarcely occurs.

Fig.12 shows cross sections of the vehicle front, which are arranged from top to bottom as time elapses. These results indicate that the deformation in the vehicle is the heaviest at 1800 msec, about 200 msec after the crash event. Then, the deformed parts tend to spring back as the chassis falls down. Finally, the deformation becomes permanent set. This tendency is also confirmed by the micromotion film analysis. Therefore, the timing when the deformation reaches the maximum is critical in determining the life area and analyzing the deformation of the vehicle.

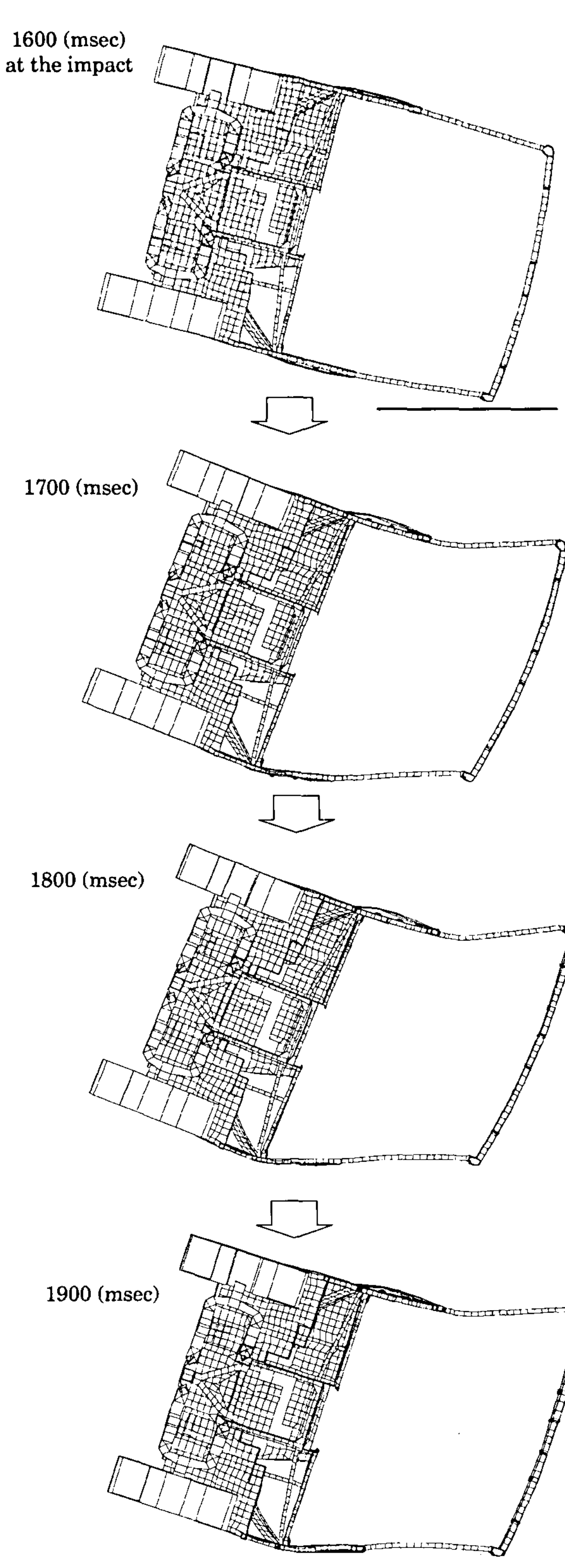

Fig.12 Deformation of cross sections

Fig.13 shows an example of evaluating the life area of passenger compartment based on the numerical analysis results. The template for the life area is shown in the cross section of the being–deformed vehicle. From this figure, clearance between the life area and the pillar is numerically determined at the time of the heaviest deformation of the vehicle.

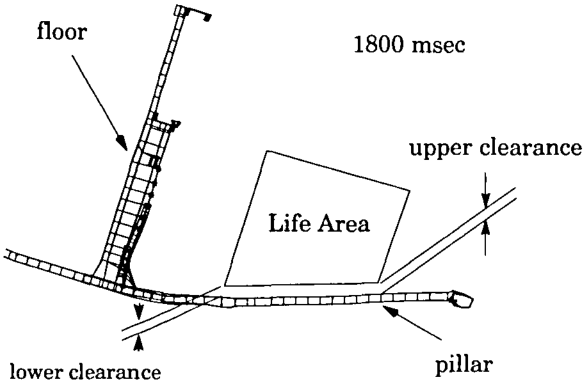

Fig.13 Numerical Analysis Result of Life Area

Fig.14 shows numerical analysis results of the roof and floor speed changes. The roof speed reaches maximum of 6.67 m/sec at the event of crash, which completely agrees with the vehicle test results obtained by the micromotion film analysis. The maximum passenger floor speed is around 4 m/sec at the event of crash, and then is attenuated over a period of 300 msec.

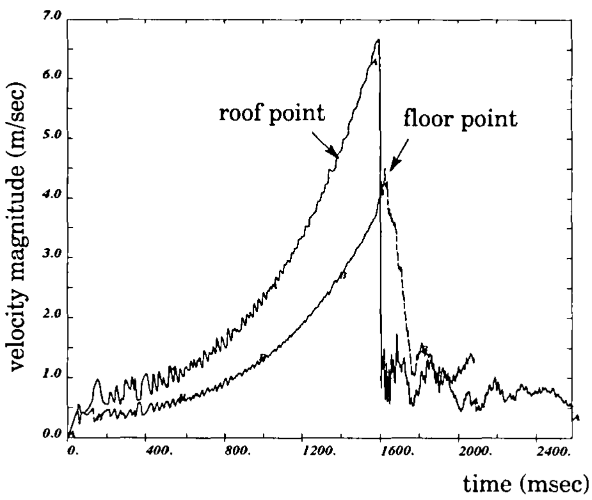

Fig.14 Numerical Analysis Result of Velocity

In Fig.15, comparison is made between the test results and numerical analysis ones of the change in the passenger floor speed immediately after the crash, obtained by integrating the output from the accelerometer using the SAE filter, with respect to time. In the numerical analysis, calculation noise is made in the event of the vehicle coming into contact with the ground, and is included in the acceleration wave. Therefore, complete agreement is not achieved, but quite a good correspondence is observed in the tendency.

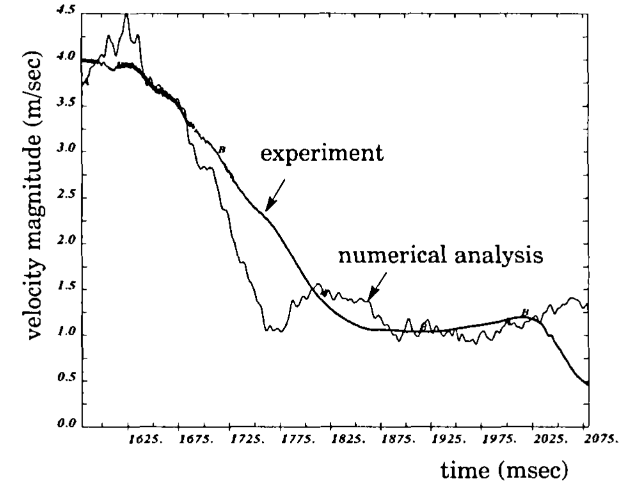

Fig.15 Comparison of Velocity Magnitude Between Experiment and Numerical Analysis

Fig.16 shows the outlook of the deformed bus after deformation behavior ends. In this figure, the numerical analysis results of permanent set of deformation are superimposed on the photographic results of the vehicle test. The differences in the broken part between the vehicle front and rear, which are also observed in the micromotion film analysis results, are characteristic of the deformation. The numerical analysis results correspond well with the test results in such a characteristic.

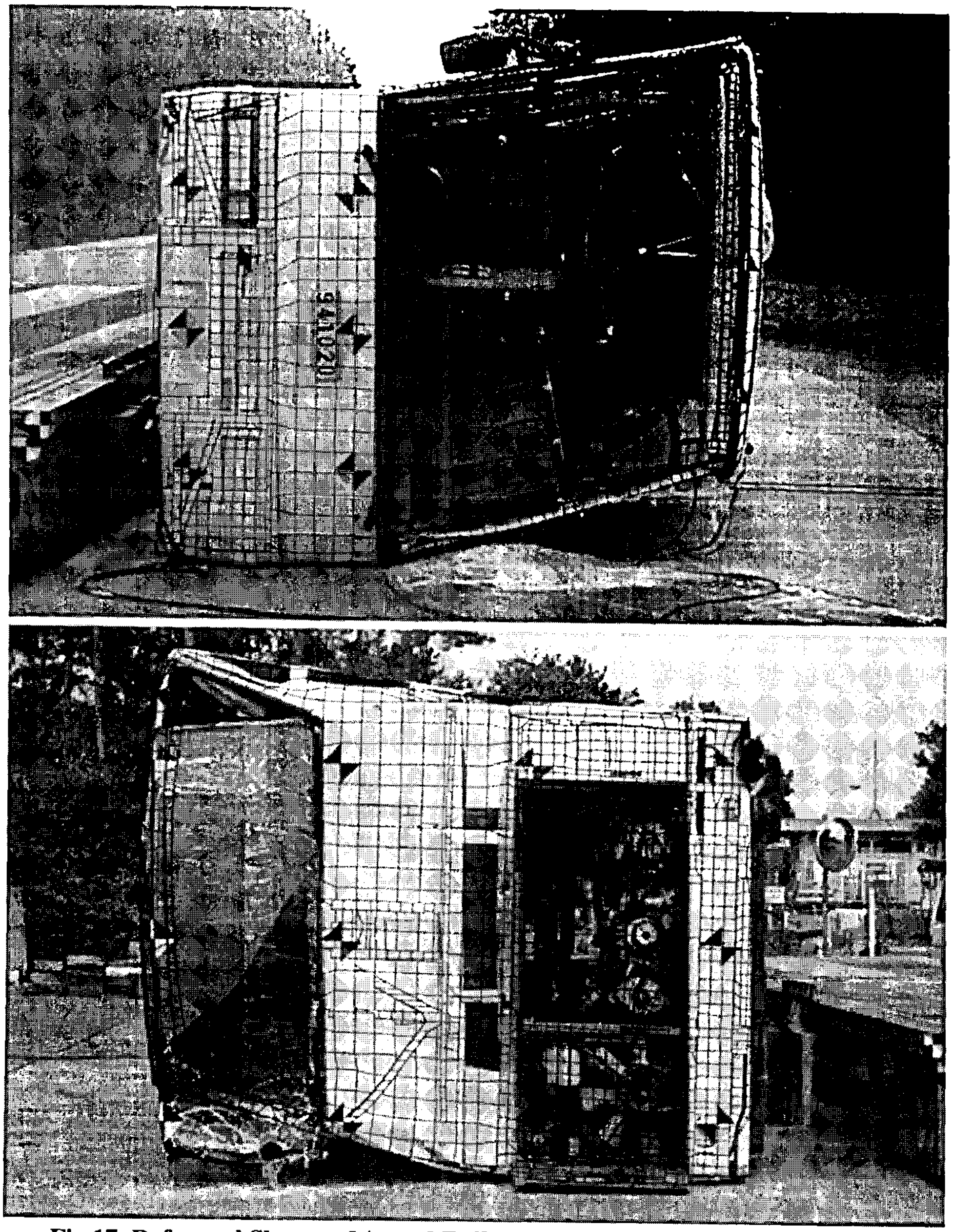

Fig.17 Deformed Shapes of Actual Rollover Test and Numerical Analysis

CONCLUSION

In simulating the rollover event of the heavy–duty bus, the calculation time is reduced to a practical length of time by increasing the length of time increment in the event of the bus falling down to the ground.

The abovementioned simulation results agree well with the vehicle test results.

REFERENCES

Research and Study on Safety Bus, Japan Automobile Research Institute (JARI), Inc., 1994

RESEARCH ON THE EVACUATION READINESS OF BUS CREWS AND PASSENGERS - INVESTIGATION OF CURRENT BUS EXIT PERFORMANCE AND EFFECT OF EASY-TO-UNDERSTAND EMERGENCY EXIT DISPLAY-

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Paper No. 96-S11-O-07

ABSTRACT

The purpose of this research is to investigate the performance of current bus emergency exits and the effect of a new type of exit based on the results of the current bus exit performance. Tests employing human subjects were conducted to measure the time required to evacuate current buses through the emergency exit, regular door, window and new type exit. The subjects' psychological responses during evacuation were also investigated to identify any evacuation problems with current buses.

The results show that it is important to improve the safety of emergency exits located above the floor and to provide an easy-to-understand display of the opening procedure. Moreover, it is important to have an easy-to-understand display.

INTRODUCTION

In 1995, there were four accidents involving death of bus crew members and passengers. This is an increase over previous years in Japan. Furthermore, according to available 1992 commercial-use vehicle accident statistics, a total of 23 major bus accidents occurred in Japan over the past 40 years, or a little more than one every two years. This can be considered an extremely small number of cases among all the traffic accidents. Of this total, 70% were accidents in which buses fell into rivers or the sea, or caught fire. Fatalities in bus accidents can be numerous, with as many as 30 lives being claimed in a single bus accident.

The US and Europe have taken active measures to facilitate the evacuation of bus crews and passengers in case of accidents. For instance, Europe provides detailed requirements such as UNIFORM PROVISIONS CONCERNING THE CONSTRUCTION OF PUBLIC SERVICE VEHICLES, in ECE36. This defines the number and type of emergency exits according to passenger capacity. For example, there should be six emergency exits for a bus with a capacity of 46 to 60 persons. In the US, FMVSS NO. 217 contains requirements for school buses and provides for bus window retention and release. This provision considers both preventing crews and passengers from being ejected from buses in an accident and ensuring evacuation in an emergency. It also provides that the emergency exits should be distributed on each side of the bus since one side may be blocked if a bus rolls over. In Japan, however, practically no new measures have been introduced since 1951 when the safety standard for emergency exits was established. The 1951 standard primarily requires installation of an emergency exit of the specified size on the right or back side of buses. The number of local bus passengers has decreased slightly in recent years, but the number of passengers on chartered buses, mainly long-distance buses, has increased noticeably. As a result, there is a growing demand for larger buses with more horsepower and higher floors, which will entail changes in the bus body shapes. Therefore, evacuation equipment for bus crews and passengers should now be reviewed so it can better respond to recent changes in the body shape of buses. Better evacuation readiness of crews and passengers could also probably save lives.

The purpose of this study is to propose appropriate evacuation equipment for bus crews and passengers. This study is being made according to the three-year plan outlined in Figure 1. We already reported on the result of the survey executed in the step 1 [2][3]. The following were clarified:

(1) Bus passengers do not know how to open the emergency exit.

(2) Passengers believe there is a lower possibility of evacuation.

(3) Therefore, bus passengers and drivers would like to

1994	1995	1996
Step 1 Investigation of Bus Passengers' and Drivers' Understanding of Evacuation Procedures	**Step 2 Investigation of Current Bus Exit Performance**	**Step 3 Evacuation Equipment Proposals**

Figure 1. Three-year plan

improve the evacuation readiness.

In this report, we report on the result of the survey executed in step 2 in which we investigated the current bus exit performance.

METHOD

Tests employing human subjects were conducted to measure the time required to evacuate current bus types through emergency exits, regular doors and windows. The subjects psychological responses during evacuation were also investigated to identify any evacuation problems with current buses. Moreover, we improved the display of the opening procedure of the emergency exit based on current bus evacuation test results, and investigated the effect of the evacuation readiness.

Subjects and Test Vehicle

For the current bus test, the subjects were 6 schoolchildren 8 to 12 years old (average age 10.2, SD 1.3), 12 adults 20 to 28 years old (average age 24.0, SD 2.9), and 6 aged persons 66 to 73 years old (average age 68.5, SD 2.3), for a total of 24. For the emergency exit display improvement test, the subjects were 16 schoolchildren 7 to 12 years old (average age 10.4, SD 1.7),12 adults 21 to 39 years old (average age 29.4, SD 4.9), and 13 aged persons 65 to 71 years old (average age 66.6, SD 2.0), for a total of 41 subjects. These subjects did not overlap with the subjects for the current bus and the display improving test. The test was performed with a chartered bus on a road in our institute as shown in Figure 2. For the emergency exit display improvement test, the type of bus was almost the same as the current bus test. We did not consider the local bus as the test vehicle because the evacuation readiness is comparatively better, it is easier to open all windows, and the floor is lower than for the chartered buses.

Test Exit

The test exits were the emergency exits, the window

Figure 2. Test bus

and the regular door as shown in Figure 3. The emergency exit is shown in Figure 4. The emergency exit is installed in accordance with the safety standard in Japan. In the emergency exit test, the subjects stand up after sitting on the seat, remove the cover of the lever, turn the lever, and open the emergency exit. For the

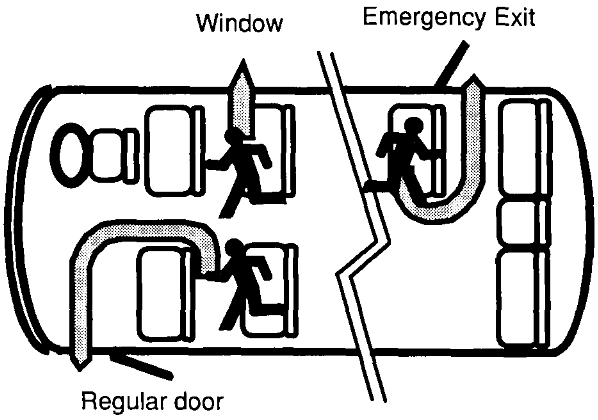


Figure 3. Test exits

Figure 4. Current bus emergency exit

window exit, the subjects stand up after sitting on the seat, open the sliding window and evacuate to outside the bus. For the regular door, the subjects stand up after sitting on the seat, pass 2m along the aisle, go down the spiral stairs (about 2m), and evacuate to outside the bus.

Figure 5 shows the improved emergency exit display which was developed based on the result of the current bus test. We adapted the display by installing an arrow in the aisle to indicate the location of the emergency exit as shown in Figure 6. We also adapted the emergency exit display for the public architecture provided in ISO (see Figure 7). We thought that this mark is easy to understand because we often see this. It will also become very important to use ISO aggressively in the future. Furthermore, we adapted Japanese "hiragana" characters instead of Chinese characters in the emergency exit because we found in our previous investigation that some schoolchildren couldn't read the display using Chinese character in the emergency exits of current buses.

We didn't cover the lever for opening the emergency exit. The subjects were better able to understand the

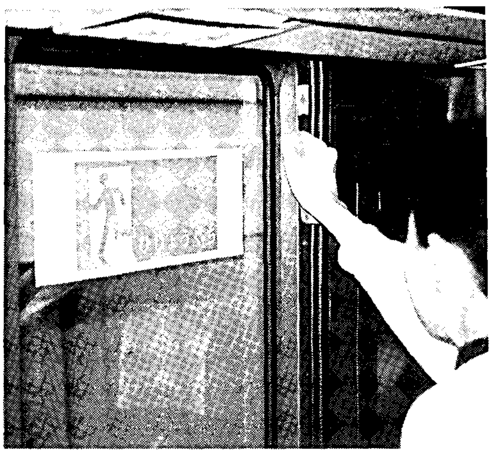


Figure 5. Improved emergency exit display

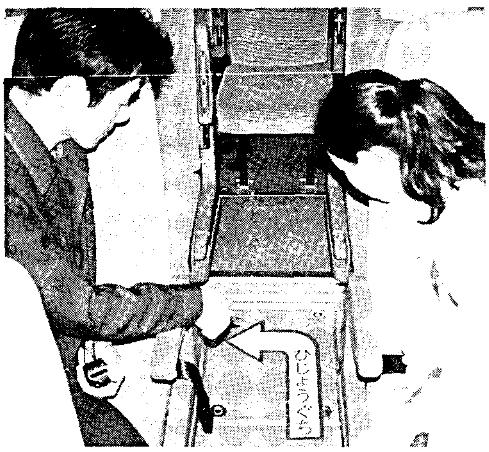


Figure 6. Arrow display in the aisle

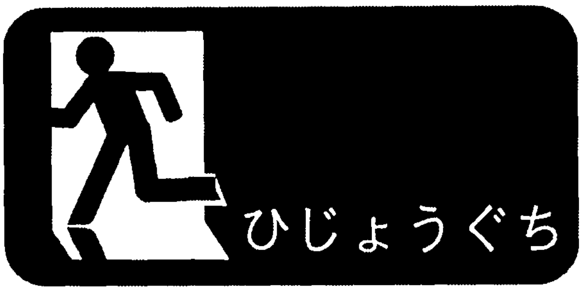


Figure 7. Display of emergency exit

operating procedure if they could always see the lever from the outside (Figure 5). In addition, the red arrow was displayed clearly to show the direction of turning the lever.

Instructions to the Subjects

(1) Subjects select the evacuation speed almost equal to walking in a bus aisle under ordinary conditions. They also open the window at normal speed.
(2) Subjects who think it is dangerous to jump to the ground when evacuating from the emergency exit or the window may use the step ladder for secure the work stand of the 150cm height.
(3) The maximum allowed time for evacuation is three minutes. Subjects taking longer are considered unable to evacuate.
(4) Subjects who can't understand the emergency exit opening procedure the first time are taught how to open it by one of the experimenters.

Measurement of Evacuation Time

We measured the evacuation time using a video camera with timer to record the subjects behavior. We mounted cameras inside and outside of the bus. We conducted the test three times under the same evacuation conditions.

Measurement of Psychological Responses

The subjects' psychological responses about evacuation readiness were investigated after each test. 35 adult subjects were added to this investigation (in addition to the above-mentioned test subjects). We also evaluated the ease of understanding the improved display on a five point scale as shown in Table 1.

Table 1.
Five point scale

5 Very Good
4 Good
3 Just Acceptable
2 Poor
1 Bad

RESULTS AND DISCUSSION

Evacuation from the Emergency Exit on the Current Bus

Figure 8 shows the evacuation time. All schoolchildren, half of the aged persons, and one adult failed to evacuate in the first test. The first evacuation times of adults and aged persons were the longest in the three times (average time of adults 36.7 seconds, SD 28.0, from 11.4 to 101.5, average time of aged persons 25.5 seconds, SD 6.0, from 20.0 to 31.7). Moreover, times for the third test (average time of adults 10.1 seconds, SD 3.6, from 5.6 to 18.1, average time of aged persons 11.1 seconds, SD 3.8, from 6.9 to 17.9) are shorter than those for the first test (significant with a significance level of 5%).

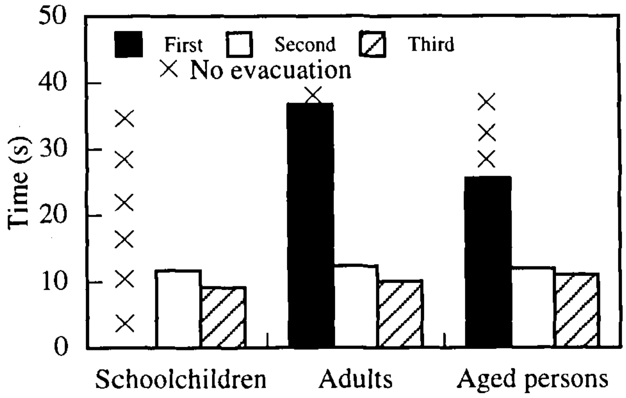


Figure 8. Evacuation time from emergency exit

Figure 9 shows the percent of the time of each activity during evacuation by adults. The percent of time for lining up in front of the emergency exit for the first test exceeded that of the second and third tests. This may be because subjects didn't know the location or meaning of the emergency exit display used in the current bus the first time.

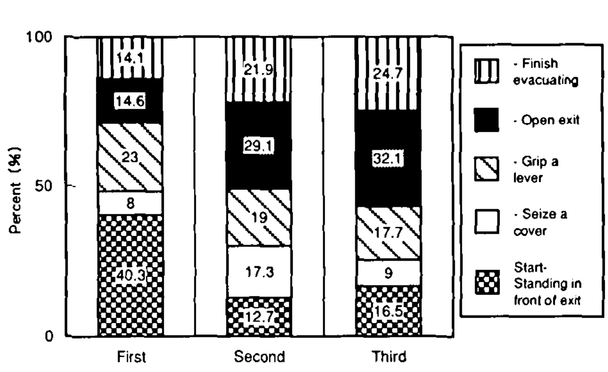
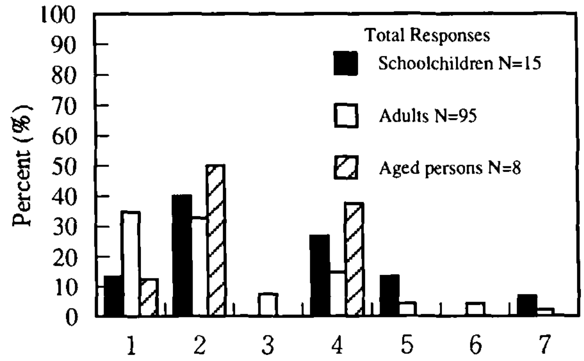


Figure 9. Percent of total time for each task in evacuating from emergency exit (Adults)

Figure 10 shows the result of the subject' psychological response investigation. Aged persons and schoolchildren said, "Passengers can't understand the opening procedure" and "It is dangerous due to the higher floor." According to our investigation (2)(3), about 90% of the bus passengers do not know how to open the emergency exit. Moreover, the reason for schoolchildren not evacuating is that they might not be able to be read the Chinese characters used in the emergency exit of current buses, according to the investigation result. Therefore it is necessary to provide emergency exits that are easy to find and an easy-to-understand display of the opening procedure. The current buses in which floor height in the emergency exit exceeds 150cm have already been equipped with evacuation assistance devices such as folding ladders. However, we think that it is important to improve the emergency exits



1. Passengers can't open quickly.
2. Passengers can't understand the opening procedure.
3. Passengers don't recognize an emergency exit as an exit.
4. Dangerous due to higher floor.
5. Passengers are afraid to get out.
6. Passengers can't see the groud due to darkness.
7. Others.

Figure 10. Evacuation readiness from an emergency exit
(Subjects: 59 persons (multiple responses))

located at higher floor levels when the passengers and crews are evacuating to the ground.

Evacuation from the Window

Figure 11 shows the evacuation time. The evacuation times are shorter for the windows than for the emergency exits in all age groups (first time, average time 12.1 seconds, SD 5.6, from 5.7 to 28.0). There are no significant differences among age groups (with a significance level of 5%). This may be because all subjects have experience opening an exit using the easy procedure.

Figure 12 shows the psychological response results. All age groups responded that evacuation was "Dangerous due to higher window position." This may be because the test bus used this time had a window height of 230cm from the ground.

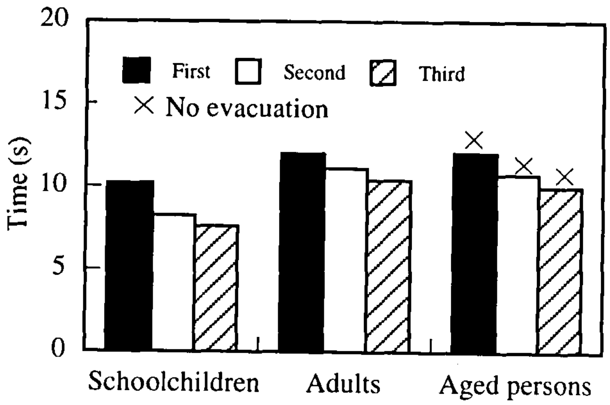
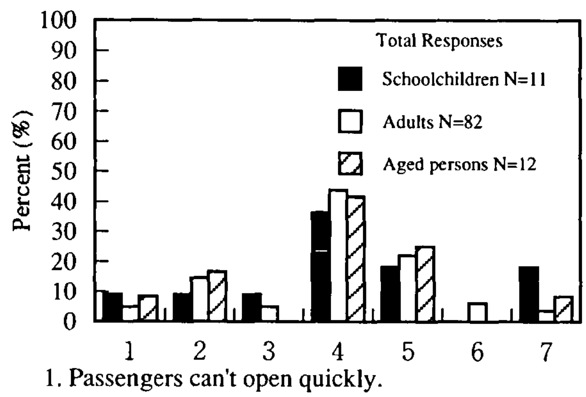


Figure 11. Evacuation time from a window



1. Passengers can't open quickly.
2. Passengers can't understand the opening procedure.
3. Passengers don't recognize a window as an exit.
4. Dangerous due to higher window position.
5. Passengers are afraid to get out.
6. Passengers can't see the ground due to darkness.
7. Others.

Figure 12. Evacuation readiness from a window (Subjects: 59 persons (multiple responses))

Evacuation from the Regular Door

Figure 13 shows the evacuation time. The evacuation times from the regular door are shorter than those for the emergency exit in all age groups (first time, average time 7.7 seconds, SD 1.4, from 5.7 to 11.2). By age group, schoolchildren and adults show almost the same tendency, while aged persons take about 30 percent longer than the other two groups (significant with a significance level of 5%). The reason may be that aged persons walk more slowly than the schoolchildren and adults due to loss of body function from aging.

Figure 14 shows the result of the psychological responses. All age groups responded that "The aisle is too narrow," especially aged persons. This may be because subjects must pay attention while evacuating, because the spiral stairs in front of regular door are comparatively narrow and descending. This evacuation time is about 1/5

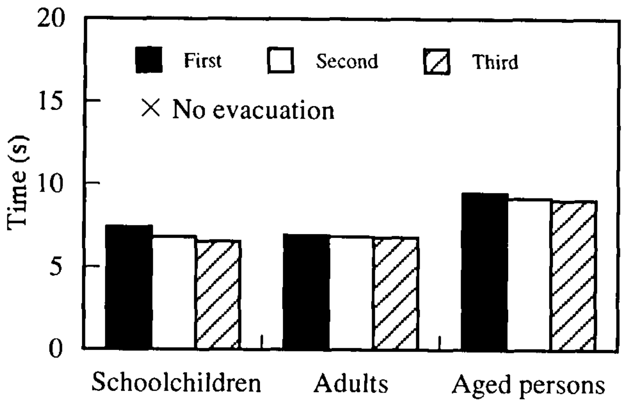
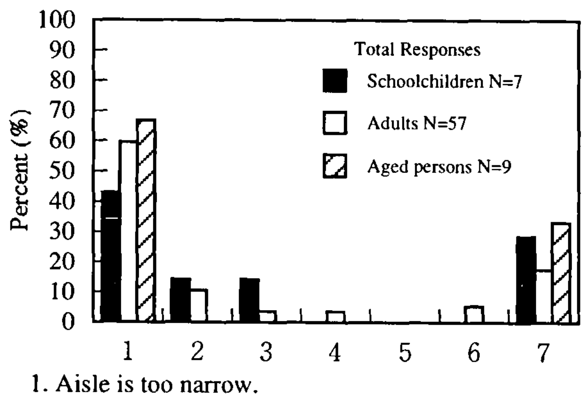


Figure 13. Evacuation time from a regular door



1. Aisle is too narrow.
2. Steps are too high.
3. Passengers don't recognize a regular door as an exit.
4. Top of the stairs is too high.
5. Passengers are afraid to get out.
6. Passengers can't see the ground due to darkness.
7. Others.

Figure 14 Evacuation readiness from a regular door (Subjects: 59 persons (multiple responses))

of the evacuation time of emergency exit. This tendency is the same as that of the window. We think that the regular door is effective if we can use this in an accident. However, we should consider that the door may be inaccessible or inoperative due to being damaged in the accident.

Improved Display versus Current Bus Display for Emergency Exit

Figure 15 shows the results. None of the schoolchildren (0 out of 6) could evacuate by following the current bus display. However, 87% (14 out of 16) could evacuate by following the improved display. Half of the aged persons (3 out of 6) couldn't evacuate by following the current bus display, but all aged persons (13 out of 13) could evacuate by following the improved display. For the adults, about 8% (1 out of 12) couldn't evacuate following the current bus display, but all (12 out of 12) were able to evacuate using the improved display.

Figure 16 compares the percent of time for each activity during evacuation for the improved display and the current bus display. For the improved display, the percent of time required from starting to standing in front of the emergency exit is about 1/4 that required for the current bus display. This may be because the subjects could understand the location and display meaning of the emergency exit. Therefore, we think that improving the display is a very effective way to improve evacuation readiness.

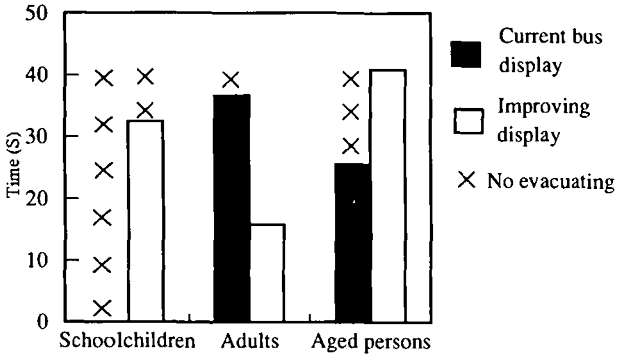


Figure 15. Comparison between improved display and current bus display

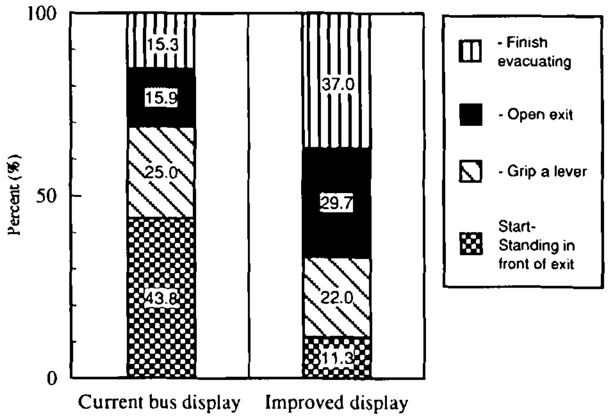


Figure 16. Comparison between improved display and current bus display (Adults)

Subjects' Psychological Responses for New Type Display

We evaluated the ease of understanding for the new type display on a five point scale. Figure 17 shows the results of the arrow in the aisle which indicates the route to the emergency exit. All age groups gave a high subjective rating (schoolchildren 4.3, adults 4.6, aged persons 4.1) for the display. We think that the arrow in the aisle is very effective because it is readily visible, especially to shorter schoolchildren.

Figure 18 shows the results for the emergency exit display. All age groups gave a high subjective rating (schoolchildren 4.3, adults 4.0, aged persons 4.0) for this display. This may be because we adapted a picture display

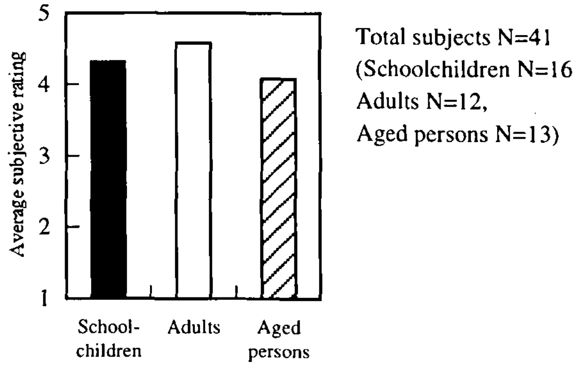


Figure 17. Arrow display in the aisle

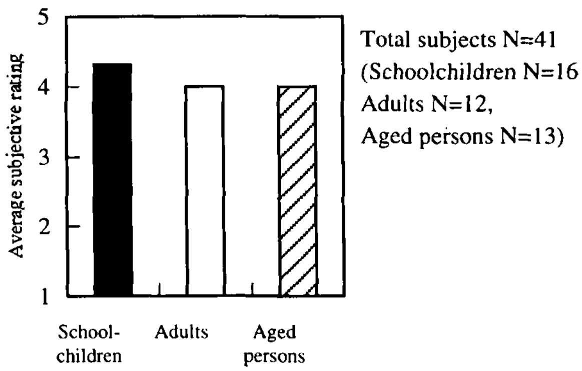


Figure 18. Emergency exit display

especially for schoolchildren and aged persons. We also adapted Japanese "hiragana" instead of Chinese characters for the schoolchildren.

Figure 19 shows the results for the improved opening procedures for the emergency exit. All age groups gave a high subjective rating (schoolchildren 4.6, adults 4.8, aged persons 4.5) for this display and procedure. This may be because the lever for opening the emergency exit is always shown from the outside, and the red arrow was displayed clearly near the lever to indicate the direction of operating. (The lever is hidden by a cover on current buses.)

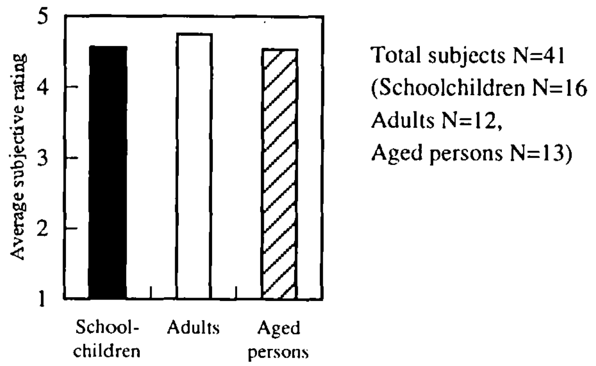


Figure 19. Display of opening procedure

CONCLUSION

Tests employing human subjects were conducted to measure the time required to evacuate current buses through emergency exits, regular doors and windows. The subjects' psychological responses during evacuation were also investigated to identify any evacuation problems with current buses. We improved the display of the emergency exit based on current bus test results, and investigated the effect of the evacuation readiness. The following were clarified:

(1) No schoolchildren and only half of the aged persons could evacuate from the current bus emergency exit.
(2) For the current bus emergency exit, the aged persons and the schoolchildren responded "Passengers can't understand the opening procedure" and "Evacuation is dangerous due to the higher floor."
(3) For evacuation from windows, all age groups responded "Evacuation is dangerous due to the higher window position."
(4) For evacuation from regular door, the aged persons took about 30% longer than schoolchildren and adults.
(5) None of the schoolchildren could evacuate following the current bus display, but almost all of them could evacuate following the improved display.
(6) All age groups gave a high subjective rating for the improved display.

FUTURE RESEARCH

In this research, we conducted evacuation tests using human subjects to investigate the performance of the current bus emergency exits and devices. We improved the display of the emergency exit based on current bus test results, and investigated evacuation readiness.

We will next investigate the relation between evacuation time and the number of exits using group evacuation tests. We will also develop a new type of emergency exit which considers the safety of evacuation and will then verify its practical use as an appropriate emergency exit.

REFERENCES

(1) Road Transport Bureau, The Ministry of Transport, Japan (1992) Commercial-Use Vehicle Accident statistics
(2) Shiosaka, Y, Research on the Evacuation Readiness of Bus Crews and Passengers - Investigation of Bus Passengers' and Drivers' Understanding of Evacuation Procedures, Journal of Japan Automobile Research Institute, JIDOSHA-KENKYU, Vol. 17, No. 6, June, p14-17
(3) Shiosaka, Y, Research on the Evacuation Readiness of Bus Crews and Passengers - Investigation of Bus Passengers' and Drivers' Understanding of Evacuation Procedures, SAE Paper 952670.

DESIGN OF AN ENERGY ABSORBING TRUCK-FRONT BUMPER BAR

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ABSTRACT

This paper reports on an experimental investigation aimed at reducing fatalities and injury associated with head-on collisions between passenger vehicles and trucks, or other heavy vehicles. In such collisions the truck typically overrides the front structure of the passenger car causing extreme occupant compartment intrusion. This is due in part to the relative rigidity of the trucks structure, and to the incompatibility in the heights of the bumper bars. In addition, the strength and stiffness of the truck front means that very little energy in the collision is absorbed by the truck. This paper focuses on the design and testing of a mechanism, mounted to the truck front, designed to prevent underride and to absorb a significant portion of the crash energy.

Full-scale truck-to-car crash tests were performed using a prototype energy absorbing, underride resisting, bumper bar system, at impact speeds ranging from 56 to 100 km/h.

From these initial tests it is concluded that it is possible to significantly reduce the severity of head-on collisions between cars and trucks at significant closing speeds. Further work is being conducted to examine other collision modes and means of reducing the bulk of the truck bumper bar components.

INTRODUCTION

Approximately 38 fatal accidents and 135 injury causing accidents occur each year in NSW - Australia, as a result of frontal impacts between heavy vehicles and cars. The problem is much worse in other countries (1), for example, in the European Community 13 000 people die and 300 000, on average, are injured in accidents with trucks. Of these, some 4 200 car occupants are killed in frontal collisions with trucks every year.

Truck development in Australia over the years has focused on economy (load capacity, dimensional constraints, fuel consumption and aerodynamics) and styling while little progress has been evident with respect to reducing their potential to harm other road users. There are currently no regulations or standards in Australia addressing the installation of front underride protection systems on trucks.

Australian and overseas research (2,3) has shown that the enormity of damage resulting from this type of collision comes about by the difference in the heights and mass of the two vehicles. This is made worse by the truck being of rigid construction, offering no energy absorbing mechanism. As a consequence the high rigid structure at the front of trucks intrude into the car occupant space. Occupants have little chance of survival in these crashes where gross intrusion into the occupant space is involved, and direct occupant contact with the truck is likely. Figure 1 shows a full-frontal head-on crash between a prime mover and passenger vehicle which occurred in NSW. The truck has climbed over the vehicle. Generally bullbars on trucks do not prevent underrun. The lower tubular member separates from the bullbar structure with the main horizontal section being mounted too high to prevent underrun. Gross intrusion results, Figure 2.

The benefits of a truck front underride protection system to the truck industry is the potential to save, not only the car occupants from serious or fatal injury, but also the truck driver. For instance:

- head-on accidents often result in damage to the truck's steering subsequently causing the truck to roll over.
- an underrun device has the potential to prevent undercabin damage to the steering box and other hardware, with the truck being able to be driven away from the accident site,
- a reduction in personal trauma experienced by the truck driver,
- and stemming from the reduction in personal injury and structural damage, is the reduction in interruption to the flow of traffic.

To improve survivability a truck front underrun system must address three primary objectives:

- the device must reduce or limit the degree of underride,
- it must effectively utilise the energy absorbing zone of the passenger vehicle during the impact,
- and the device must incorporate an energy absorbing component to the front of trucks.

Figure 1. Head-on collision

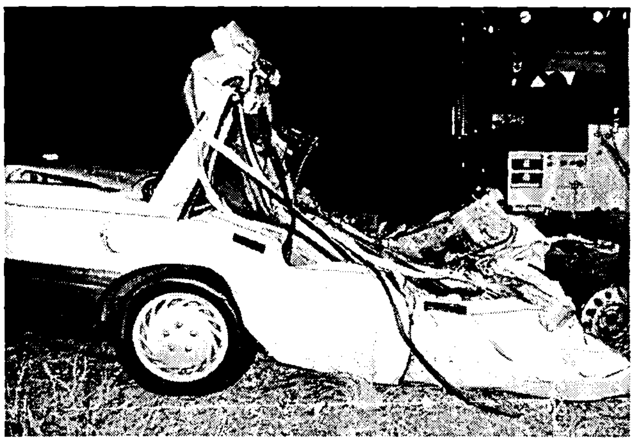


Figure 2. Vehicle removed from under truck

ENERGY ABSORBING UNDERRIDE DEVICE

The prototype truck underride mechanism consists of a rigid bumper bar or barrier constructed from steel rectangular hollow sections, Figure 3. This large contact area allows for the energy absorbing front zone of the car to be effectively loaded and crushed. The barrier is supported in front of the truck by four telescopic struts using ball joints at each end, making the assembly a pin jointed mechanism. The use of a pin jointed mechanism largely eliminates bending moments, which if resisted would require very large and heavy components. The upper struts are parallel to the truck's chassis rail, with the lower two struts angled away from the truck's centre line. This mechanism was designed to accommodate full frontal, offset and angled impacts.

The front underrun system has a ground clearance of 320 millimetres and projects 300 millimetres in front of the truck's leading face.

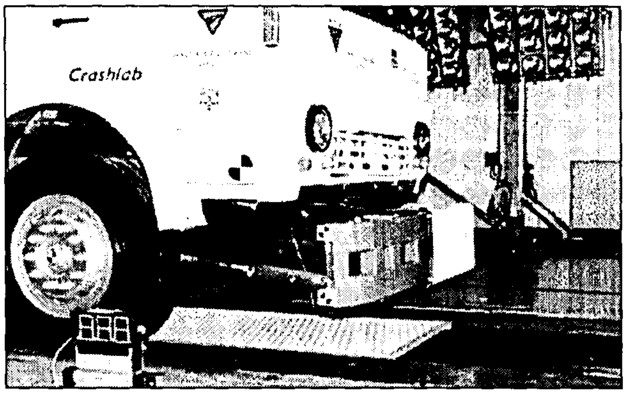


Figure 3. Truck-Front Underride System

ENERGY ABSORPTION

An energy absorbing component was incorporated to absorb the crash energy, reduce the high decelerations to protect the occupants, and reduce occupant compartment intrusion.

Energy absorption, in the telescopic struts, is by the plastic deformation of thin wall seamless steel tubing undergoing the inversion mode of collapse (4,5). Inversion involves turning a thin wall tube inside out under compressive load. This mode of collapse occurs for a restricted range of tube thickness to diameter ratios and only for ductile materials. Outside this range the tube assymmetrically or axisymmetrically buckles.

Considerable experimental work was conducted in order to ascertain this inversion range and the geometry of the tube. An investigation was also conducted to determine whether the rate of straining influences the inversion load (6). Quasi static compression tests were conducted using a conventional tension/compression machine at a rate of 20 mm/min. Dynamic tests were conducted on the RTA's crash sled simulator (6) where impact speeds ranging from 9.3 to 29.3 km/h were achieved. It was concluded from these tests that the material was not to any practical degree strain rate sensitive under this process of deformation, Figure 4.

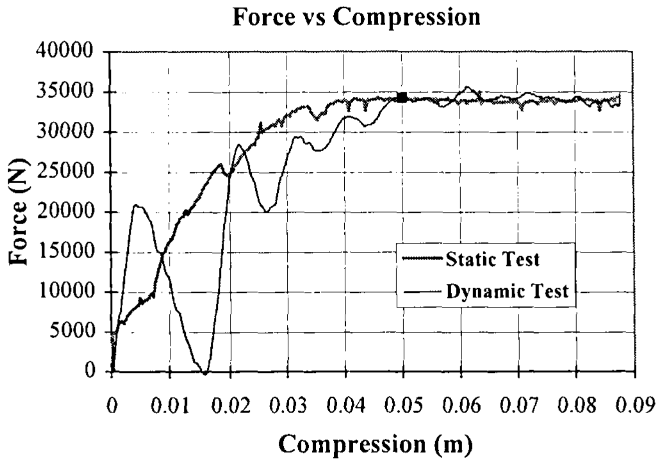


Figure 4. Inversion - Static and Dynamic test of a 0.8 mm tube

Within each telescopic strut there were four crushable tubes separated by forming dies. Except for the first crash test, the tubes were preformed 50 mm before being placed inside the unit. That is, the ends of the tubes were inverted reducing the length of the tube by 40 mm (tube was inverted at both ends on a 5 mm radius). Without some preforming the force-displacement graph shows a steady build up to a nearly constant inversion load, as shown in Figure 4. Preforming removes that portion of the curve, from the origin to the mark ■. This initial softness allowed the front underrun device to collapse unevenly and stroke at very low loads in the first test. Furthermore, the energy absorbed per millimetre of displacement is low for the early part of the inversion process.

PASSENGER CAR-FRONT STIFFNESS

With an energy absorbing component integrated on the truck front it is important to determine the load at which the device should collapse or stroke. If the load to collapse the device is underestimated then it may collapse without absorbing a significant portion of the crash energy. However, if overestimated it will act like a rigid barrier, absorbing little energy, producing high decelerations and resulting in a reduction in occupant space.

Ideally the load to collapse the bumper bar should be comparable with the load required to crush the front structure of passenger cars. The difficulty in achieving this is that the stiffness of passenger car fronts vary considerably between makes and models, as well as varying with crush displacement.

Since small cars are more vulnerable to underrun and intrusion the device was tuned towards smaller cars. This is justifiable since larger cars have longer front geometries, more occupant space therefore provide their occupants with a measurable better chance of surviving.

Researcher's (7) have established a method for quantifying stiffness coefficients from full-scale crash test data. However, the analysis is too simplified for this application and not able to provide adequate design data. The method adopted in determining the stiffness characteristics of car fronts was from data which was made available from the Australian New Car Assessment Program (NCAP). The force-displacement data was derived from accelerometers located at the left and right rear member of the vehicle (floor pan acceleration). This provided a representative average deceleration of the relatively undeformed portion of the car.

Table 1 below shows forces calculated from the vehicle's instrumentation. Figure 5 shows force-displacement characteristics for two vehicle types. Note the significant difference between the stiffnesses of the two vehicles. However, this provided average design loads for the collapsing tubes.

Table 1. Vehicle Crash Data

Vehicle Type	Average Force (kN)	Peak Force (kN)	Average Force after 400 mm of crush (kN)
Type 1	234.8	534.8	351.2
Type 2	214.8	426.4	364.3
Type 3	156.9	422.1	251.1
Type 4	175.6	394.2	294.2
Type 5	150.3	490.8	328.2
Type 6	196.7	552.8	329.8

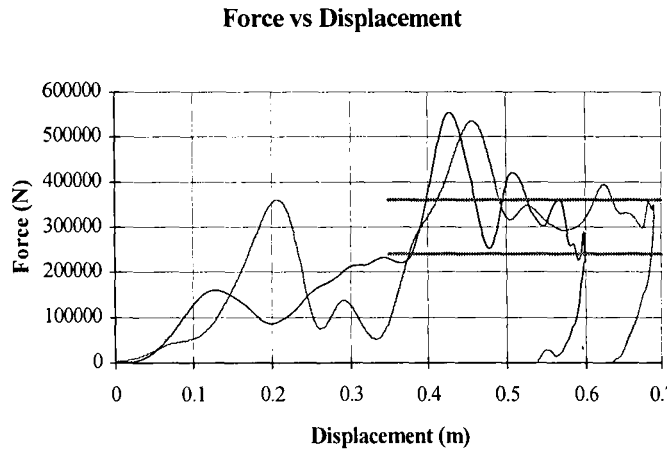


Figure 5. Car front Force-Displacement

The average force to crush the front structure of a car is 190 kN but after the first 400 millimetres of crush (relative soft zone) the average force is 320 kN. The two horizontal lines in Figure 5 represent the region over which the telescopic struts collapsed.

TRUCK-TO-CAR CRASH TESTS - Development Program

The first two phases of the truck underrun testing program will be discussed in this paper. These phases include a total of five full-scale crash tests. Test speeds ranged from 56 km/h to 100 km/h. The first four tests were all full-frontal truck-to-car crash tests. The fifth test was a full-frontal rigid barrier test. The truck in all cases was stationary and backed against a concrete barrier, simulating the worst possible mass difference.

Phase 1

The first crash test was conducted at 56 km/h into the truck underrun protection system. Tapered crushable tubes were predominantly used in this test to provide, on the truck, a progressive crush behaviour which matched that of the car. The tubes were not preformed at this stage. The bumper bar as a whole was designed to stroke at 216 kN (once the ramping stage to inversion load had been overcome) to a maximum of 330 kN. Maximum stroking distance of the struts was approximately 400 mm with an energy absorbing capacity of 80 kJ.

Figure 6 is an overlay plot comparing the car's average deceleration trace of the full-frontal NCAP barrier test to the 56 km/h truck underride test. Two Hybrid III dummies were used in these tests to provide occupant injury risk information. The NCAP test was used as the benchmark test and can be considered equivalent to a car impacting a truck with a rigid, low clearance, barrier.

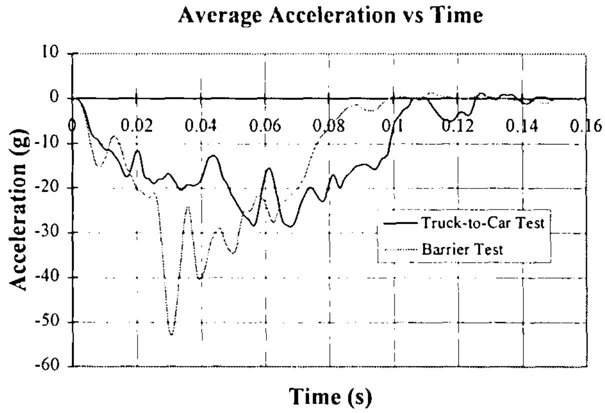


Figure 6. Average acceleration of benchmark and truck underride test.

It can be seen that the inclusion of an energy absorbing component on the truck significantly reduces the car's deceleration, with peak values nearly halved, 53.1g and 28.6g for benchmark and truck underride test respectively. The duration of the impact is also significantly increased. These two features have resulted

Table 2. Test Results (56 km/h)

Parameters		Barrier Test	Truck Underrun
Impact Velocity (km/h)		56.1 (15.58m/s)	56.16 (15.60m/s)
HIC (≤1000)*	Driver [f]	1645.0	976.2
	Passenger	1192.6	417.6
Head Resultant Acceleration (g)	Driver [f]	115.2	104.7
	Passenger	76.2	51.7
Head Acceleration 3ms max (g)	Driver [f]	129.6	83.3
	Passenger	74.3	48.6
Chest Compression (mm) (≤76.2mm)*	Driver [f]	44.4	32.6
	Passenger	44.1	34.5
Chest Resultant Decel. 3ms (g) (60g)*	Driver [f]	54.9	59.4
	Passenger	-	35.1
Femur Load - max (kN) (10 kN)*	Driver [f]	-2.3 (L), -0.9 (R)	-3.8(L), -1.4(R)
	Passenger	-1.3 (L), -1.7 (R)	0.9(L), 0.8(R)
Seat Belt Load - Sash (kN)	Driver [f]	8.1	4.2
	Passenger	8.8	7.1
Seat Belt Load - Lap (kN)	Driver [f]	9.2	5.4
	Passenger	8.6	7.0
Vehicle Peak Deceleration Rear Member (g)		53.1	28.6
Vehicle Average Deceleration (g)		18.9	14.2

* FMVSS 208 limits L - Left R - Right
[f] seat belt failure - resulting in high outputs

in the dummy responses being well below the predicted biomechanical limit for serious injury, Table 2.

The seat belt loadings for the driver are lower than for the passenger due to the driver's seat belt failing during the impact. This failure caused the driver's head to heavily contact the interior components of the car, resulting in a high HIC value of 976.2. Inspection of the seat belt revealed a failure of the seat belt axle resulting in excessive reeling out of the belt. The driver responses cannot be used to compare the two crashes but has been included here just for completeness.

The passenger dummy responses show the clear benefits of a low clearance, energy absorbing truck bumper bar. Most significant measure is the HIC value which is 35% of the barrier test. Head accelerations and chest compression have also been significantly reduced.

Following the test the energy absorbing struts were disassembled and tube compression measured to estimate the energy. The lower struts stroked an average of 348 mm while the top struts stroked 160 mm, absorbing 41 kJ or 32% of the initial kinetic energy. The system had the potential to absorb approximately 80 kJ of energy.

Following this test a number of issues were reconsidered and changes were incorporated to the system. Briefly these were:

- excessive rotation or unequal stroking of the telescopic struts during the impact event,
- tube stiffness configuration,
- and test speed.

Phase 2

The significant reduction in vehicle deceleration, the relatively little structural damage, no intrusion into the occupant space, together with low dummy (passenger) instrumentation outputs indicated that the system should work at speeds closer to those of actual road collisions. Therefore the next series of tests were performed at 80, 90 and 100 km/h.

To overcome unequal stroking between the lower and upper pairs of struts a stiffness distribution of approximately 60-40 was introduced. Tube stiffness configuration and length was changed to cope with the need for higher energy absorption. The tubes were machined to a length of 220 mm and preformed 50 mm. A preformed tube has a greater energy absorbing capacity with a square shaped force-displacement pulse remaining. Tapered tubes were no longer used.

Preforming the tube has the added benefit of making the bumper bar device rigid up until the force equal to the inversion load is reached. This feature allows the soft zone of the car front to deform significantly before the struts begin to stroke, reducing the rotational tendency of the bumper bar.

The objective of this series of tests was to perform three low cost experiments and focus attention on the articulation and stroking of the bumper bar during impact. No test dummies or instrumentation were used and cheap second hand cars (1150 kg) were purchased. Two of the vehicles were station wagons of the same make/model and the third was a sedan version. The tests were full-frontal tests. Peak decelerations were calculated by digitising the high speed footage. This method was verified by applying it to the test results obtained from cars with accelerometers. This demonstrated that reasonably accurate information was generated, Table 3.

The 80 km/h test represents a doubling in the energy of the previous test conducted at 56 km/h. The two horizontal members (125x75x5 mm) of the rigid bumper bar bent at the midpoint (approximately 30^{o}) which resulted in the bumper bar failing to stroke completely. The lower struts collapsing only 180 mm and the upper struts collapsing 260 mm. A contributing reason behind the bar bending in this test and not bending in the first test was that this vehicle was fitted with a longitudinal engine (previous vehicle had a transverse engine). On impact the longitudinal engine applies a concentrated load at the midpoint of the simply supported bumper bar.

Even though the energy absorbing device only absorbed approximately 63 kJ of energy, or 22% of the initial kinetic energy, the damage to the vehicle was concentrated to the front area only with the occupant compartment remaining relatively intact, intrusion was mainly concentrated at the footwell. The footwell was pushed back approximately 120 mm. The average and peak deceleration was calculated to be 18g and 40g respectively.

To prevent the bumper bar from bending it was reinforced between the left and right front strut mounts with a similar length of rectangular hollow section welded to the back face. Only minor changes were made to the tube stiffness configuration.

Crash test number 3 was conducted at 90 km/h. This represents two and a half times the energy of test number 1 and 25% more energy than test number two. The lower struts collapsed an average of 426 mm and the upper struts collapsed an average of 408 mm. A total of 123 kJ of energy was absorbed by the system, 100% more than in the previous test. This represents approximately 34% of the total energy.

Figure 7 shows the movement of the bumper bar at time intervals of interest. The bumper bar remained reasonably vertical and follows a smooth path down towards the ground (t=90 ms), preventing underrun.

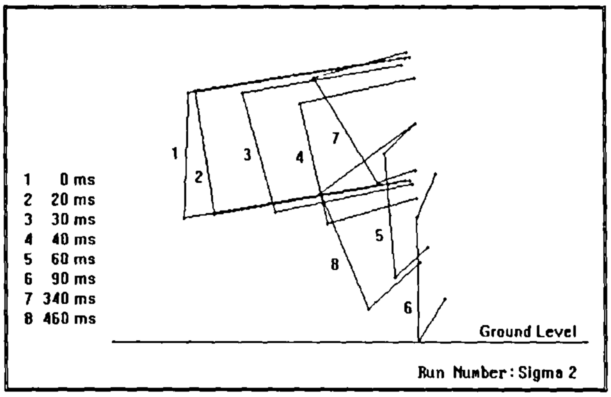


Figure 7. Bumper bar movement

Time step 7 occurs on the rebound stage and step 8 is where the bumper bar drops towards the ground after contact with the car is lost.

Average and peak decelerations were 21.3g and 44g respectively. Once again the vehicle experienced relatively little damage with the extent of damage being similar to that of the 80 km/h test, Figure 8.

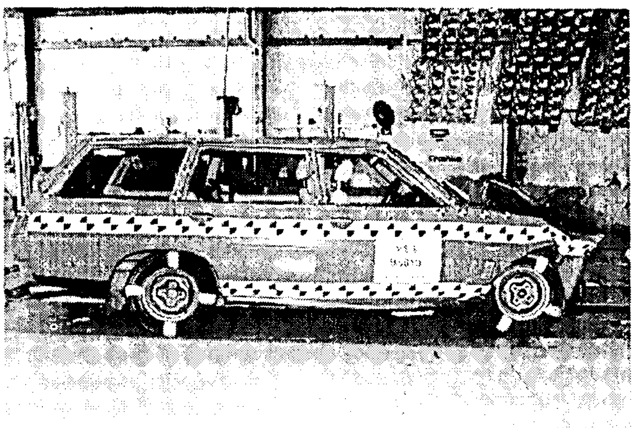
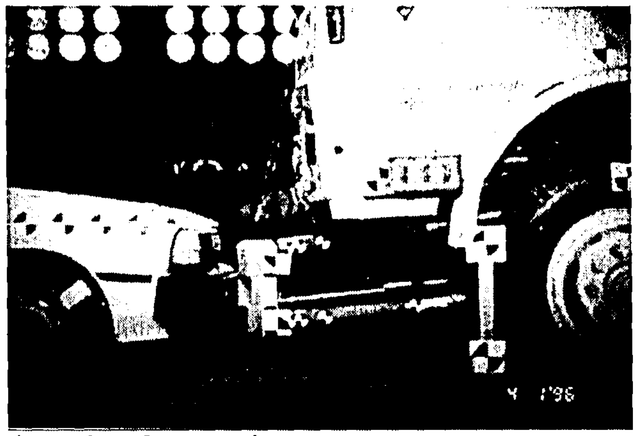
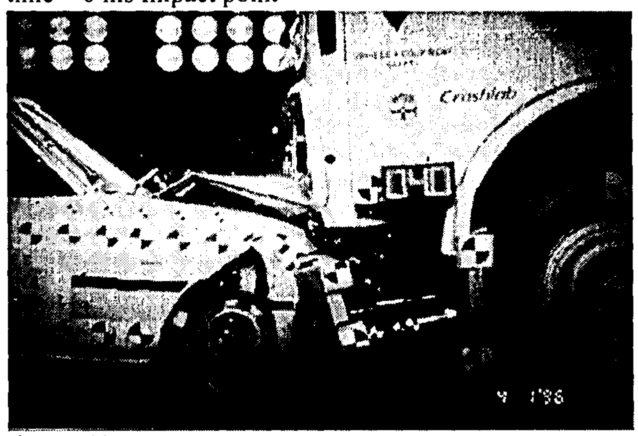


Figure 8. Crash test vehicle - 90 km/h

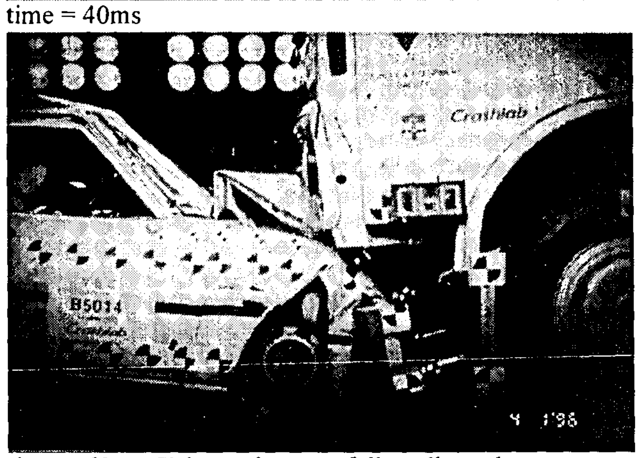
The final test in the second phase of testing was conducted at 100 km/h, which represents approximately three times the energy of test 1. The lower struts stroked an average of 482 mm and the top struts stroked an average of 378 mm. A total of 130 kJ of energy was absorbed by the energy absorbing system. The bumper bar followed a similar stroking path as illustrated in Figure 7. Figure 10 is a photograph of the vehicle after the 100 km/h test. It should be noted that the occupant survival space remains reasonably unchanged with approximately 120 mm of intrusion at the footwell and firewall. The average and peak deceleration was calculated to be 20.7g and 65g respectively.



time = 0 ms Impact point



time = 40ms



time = 60ms Telescopic struts fully collapsed

Figure 9. Frames taken at 0, 40 and 60ms from high speed film

All parts of the energy absorbing unit were reusable (not damaged) throughout the testing program. The crushable tubes were the only components which were replaced.

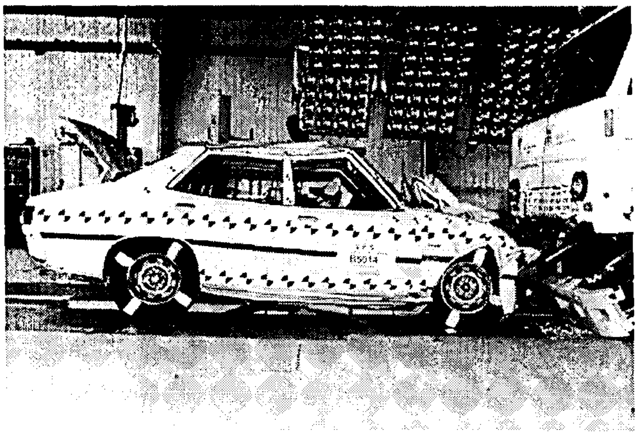


Figure 10. Crash test vehicle - 100 km/h

The final test discussed in this paper involved a similar model second hand vehicle being tested at 56 km/h against a rigid barrier. This test was conducted to establish the validity of the results obtained from phase 2. It was used to compare deceleration levels and compare the extent of structural damage with the underride tests. Two accelerometers were located on the rear member of the vehicle. The high speed film was then digitised and instrumented and digitised results compared, Table 3. Figure 11 shows the extent of damage to the vehicle for a 56 km/h rigid barrier test. The peak deceleration of the vehicle was 63.5g.

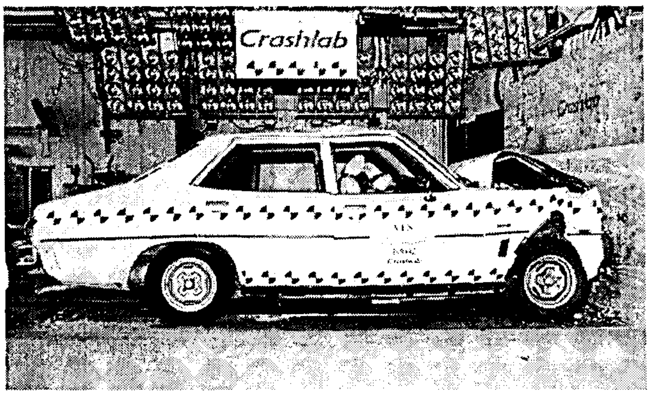


Figure 11. Rigid Barrier Test - 56 km/h

Table 3 is a summary of vehicle decelerations for the tests discussed. The table also validates the digitised results by their close comparisons with instrumented outputs.

Table 3. Summary Test Results

	Average Deceleration (g)	Peak Deceleration (g)
Truck-to-car underride tests		
Test 1 56 km/h	14.2, 12.0*	28.6, 29.0*
Test 2 80 km/h	18.0*	40.0*
Test 3 90 km/h	21.3*	44.0*
Test 4 100 km/h	20.7*	65.0*
Benchmark tests		
56 km/h (for test 1)	18.9, 24.8*	53.1, 50.8*
56 km/h (for test 2 3 4)	20.6, 22.7*	63.5, 60.1*

* digitised values

DISCUSSION AND CONCLUSIONS

This research project encompassed the prototype design, development and testing of a truck-front protection system. Primary considerations of the design were to prevent passenger vehicles from underriding the rigid exposed front structure of trucks, and to incorporate an energy absorbing component to the front of trucks to absorb crash energy.

The bumper bar device was successful in preventing underride in full-frontal impacts for all tests, keeping the truck structure away from the passenger compartment.

Structurally the vehicles sustained relatively low levels of damage, considering the speeds involved, with greatest damage being limited to the front structure of the cars. The extent of damage resulting from the 100 km/h test was estimated to be comparable to the 56 km/h rigid barrier test. Passenger compartment intrusion was essentially limited to the firewall and footwell and was in the order of 120 mm.

The four truck-to-car crash tests demonstrated that a low ground clearance, energy absorbing bumper bar can significantly reduce structural damage and decelerations, demonstrating a potential for improved occupant survivability even at high collision speeds. These are very encouraging outcomes, particularly for truck to car head-on impacts that result in serious and fatal injuries.

The energy absorbing system dissipated approximately 130 kJ of energy in the higher speed tests of phase 2, with a stroking distance of up to 500 mm. The load required to collapse the device was determined from instrumented crash tests. The device remained rigid up to a force of 240 kN and collapsed in a controlled manner up to 360 kN. The distribution in stiffness between the lower and upper pairs of struts was 60% and 40% respectively.

Further work has commenced, aimed at evaluating the device under offset collisions, and with more modern representative fleet vehicles.

ACKNOWLEDGMENTS

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REFERENCES

1. Goudswaard A.P., Nieboer E.G., Janssen E.G., *Truck Front Underrun Protection*, 1991 International IRCOBI Conference on the Biomechanics of Impacts.

2. Rechnitzer G., *Truck Involved Crash Study - Fatal and Injury Crashes of Cars and Other Road Users with the Front and Sides of Heavy Vehicles*, Monash University Report No. 35.

3. Riley B.S., Farwell A.J., Burgess T.M., *Front Underrun Guards for Trucks*, Proceedings of the Eleventh International Technical Conference on Experimental Safety Vehicles.

4. Al-Hassani S. T. S., Johnson W., Lowe W. T., *Characteristics of Inversion Tubes Under Axial Loading,* The Journal of Mechanical Engineering Science Vol 14 No. 6, 1972.

5. Al-Hassani S. T. S., *Tube Inversion: A Process for Obtaining Gross Expansions in the Diameter of Thin-Wall Tubes*, Proceedings of the Fifteenth International Machine Tool design and Research Conference.

6. Wasiowych A., Lozzi A., Griffiths M., *Mechanism for an Energy Absorbing, Underride Resisting, Truck-Front Bumper Bar*, Proceedings of the First Australasian Congress on Applied Mechanics 1996.

7. Neptune J.A., Blair G.Y., Flynn J.E., *A Method for Quantifying Vehicle Crush Stiffness Coefficients,* Accident Reconstruction: Technology and Animation II.

QUANTITATIVE TRUCK SPRAY MEASUREMENT

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ABSTRACT

When trucks drive down wet roads they usually generate a spray cloud around the wheels which can be hazardous to other drivers. Various methods of reducing truck wheel spray are in existence but a method to accurately determine and rank the performance of spray suppressing devices had yet to be established. In order to remove the subjectivity from measuring the spray cloud, research was carried out to develop a system to objectively measure truck spray and hence quantify the effect of truck spray on the visual impairment of other road users.

INTRODUCTION

The system designed and developed measures spray by digitising images of spray as a truck drives along a wetted track. The system used a CCD camera to display a sequence of spray images, with a road-side target board as the background, on a PC monitor. The images were then digitally recorded and processed by a custom-developed analysis program. The quantitative results from the mean spray area and density readings can be made immediately available at a test site. This system has distinct advantages over alternative methods of measuring spray. These include: ease of use, relatively low costs, the ability to average variance in readings by rapidly acquiring and processing several images, and most importantly, it measures the decrease in driver visibility by relating it to the brightness change recorded in the spray image. The measurement system utilises the effect of spray scattering ambient light which increases the apparent brightness of an image. This was measured as an increase in grey value of a black target board - the denser the spray, the greater the grey value increase.

EXPERIMENTAL TESTING

Laboratory Development and Testing

Since on-road ambient light levels are subject to uncontrollable change, and the visual perception of the spray cloud changes with ambient light levels, laboratory testing was carried out to determine the effect of spray density on various types of target boards under various ambient light intensities. It was established that a target board with a black surface must be used for measuring the spray. A checkered target board (with black and white alternating squares) produced unpredictable contrast changes, with a low level of sensitivity when the ambient light level and spray density were varied. When the black target board was used, the program output consistent readings of mean spray density and area, across the varying ambient light levels which would be experienced in an outdoor environment.

A fine mist of spray can be easily seen through by a driver and does not pose a great danger to other road users, but as the spray becomes denser it becomes more difficult to see through, and when it gets sufficiently dense, nothing can be distinguished through it. This critically-dense level was represented by a specific level of contrast increase. In the laboratory the equipment for generating the spray was limited to producing low levels of spray. However, trucks on wetted roads easily create very dense and dangerous levels. Therefore, road testing was required to determine this critical density of spray. It was found that a contrast increase above 30% was too dense to distinguish any object from its background. Any contrast increase above this level was then categorised as "unacceptable", while any level below a 30% increase was categorised as "acceptable". This criteria was then used to assess the percentage area of the target board obscured by both unacceptable and acceptable levels of spray.

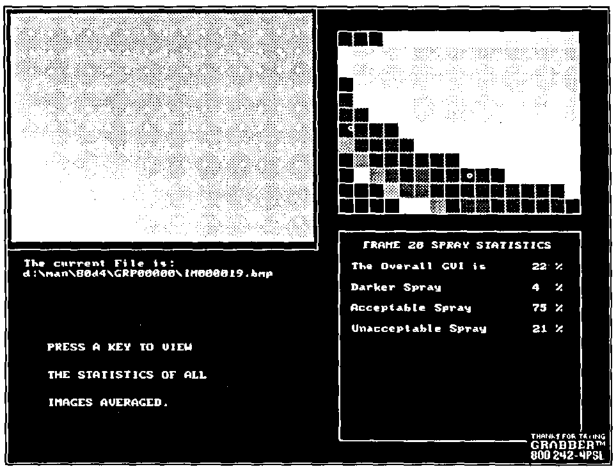

Figure 1. Sample program output displaying an image of truck spray area and density across a sequence of images.

If a spray reduction device was to make a quantifiable decrease in the level of spray the system would show a marked decrease in the area of "unacceptable" spray. Figure 1, shows a typical image of truck spray on the top left, with its computerised simulation on the top right. The spray statistics are also output to the screen. The accuracy of the data produced by the analysis was validated by counting the number of white dots remaining visible on the black target board. The results returned from the digital image analysis were found to be accurate to approximately four per cent when compared with human evaluation of the spray density.

On Road Evaluation

The spray measurement system was tested by evaluating the spray generated by an 8-Tonne tip truck driven down a wet runway. Thirty-five test runs were made at 80 km/hr to determine the variation in results when only a baseline configuration was evaluated. The long term consistency of results between on-road runs showed a turbulence intensity (standard deviation/mean) of 13%. This level of variation was caused by the random affects of variables which could not be controlled, such as the water depth on the road, (only a manual watering system was available), and the effects of changing ambient wind conditions. Therefore, to accurately evaluate the performance of a spray suppressant device many runs would be required before the variation in results due to the application of the device could be confidently quantified.

Limitations - For any given run of a test truck on a wetted track, the spray measurement system will analyse a sequence of images and return the area obscured by both "acceptable" and "unacceptable" levels of spray. The measurement system however, cannot guarantee consistency in results between runs unless extreme care is taken in the set up procedure and test conditions before any spray measurements take place. Variations in mean spray area and density between runs were shown to be caused by the inability to control certain test variables throughout the testing procedure. Precise control of the water depth on the road, and most importantly methods of coping with mean and transient variations in ambient wind are critical. Without adequate control of these factors, the results can be highly variable which can greatly increase the number of test runs required to obtain statistically useful data. Any spray measurement system can only be used to quantify spray cloud size and density, and hence rank the performance of the various spray suppressant devices, under these ideal conditions if a large number of runs are not performed.

Recommended Testing Procedure

The procedure outlined below must be carefully followed to obtain long term repeatability in test results.

Test Vehicle. Any comparisons between the effectiveness of various spray suppressing devices must be carried out on one vehicle. A control run should be made to periodically check the consistency of results.

Test Track. All testing of spray suppressant devices must be carried out on the same section of test-track.

Wetting Track. Small variations in water depth have been recognised to cause large variations in spray cloud size and density, therefore the track must have an even depth of water for each test run. This will most likely require a pumping system to provide and even surface level of water, and a means of damming up the edge of the road to entrap the water. An established settling time must be consistent between runs.

Vehicle Speed. The test vehicle must be driven at a precisely constant speed. Small increases in speed can produce large increases in spray cloud size.

Ambient Wind. The wind conditions during testing are critical when the objective is to obtain consistent results. Any level of ambient wind affected the results. Therefore accurate measurements require testing be carried out either in a sheltered environment, or on a completely still day. Even small gusts of wind have the potential to completely disperse the phenomenon to be measured on the upwind side, with a corresponding increase on the downwind side. Duplicate spray measurements on either side of the test truck can be utilised to measure the crosswind effect.

Image Acquisition. Care must be taken to ensure that the image of the target board is perfectly framed on the computer monitor to ensure that none of the unwanted surroundings are analysed. Also, the images of the spray must be recorded only when the truck has completely passed the camera, otherwise the analysis will not be assessing the fully developed spray exclusively.

With the above testing conditions and procedure strictly followed, the developed spray measurement system can be applied to assess the effectiveness of various spray suppressant concepts.

CONCLUSIONS AND RECOMMENDATIONS

The digitised image technique allows for relatively simple, fast and economical analysis of truck wheel spray. Therefore the developed spray measurement system should be further utilised, in a controlled testing environment, to compare the effectiveness of various spray suppressing devices in reducing the vision impairment caused by trucks driving down wetted roads. It may also be worthwhile to carry out spray measurement under simulated real world wind conditions to attempt to discover if the performance ranking's still remain true.

The system could be improved by using an electric eye to trigger the recording system as the truck passed the camera, this would eliminate any variation in data between runs caused by manual miss-timing.

A substantial improvement could be made by using two CCD cameras - one along each side of the test track. The two independent sets of results could then be automatically compared from each side of the truck for each run. For any given run the difference in the average value of spray area and density between the two sides must be due to the effect of ambient wind. This system would give a better understanding of the relationship between the effect of ambient wind and changes in spray measurement data.

Other time-varying optical phenomenon can also be studied using this system. These include, the measurement of smoke from industrial chimney stacks, exhaust plumes from trucks and remote bushfire detection. Little extra work would be required to modify the system to quantify other phenomenon which cause a perceived change in the grey value of a black background surface.

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BIBLIOGRAPHY

Maycock G., (1966) The Problem of Water Thrown Up By Vehicles On Wet Roads., Harmondsworth Road Research Laboratory. Road Research Laboratory, Ministry of Transport, UK, TRRL Report No. 4.

Ritter, Thomas E. (1974), The Development of Techniques to Measure Vehicle Spray on Wet Roads. Combined Commercial Vehicle and Fuels & Lubricants Meetings, Chicago, Ill.

J.W. Allan., (1979) A note on the Reduction of Water Spray from Heavy Lorries and on the Measurement of Spray During Trials., AASU Memorandum 79/1, Department of Aeronautics and Astronautics, University of South Hampton, UK.

Stroebel, Leslie., Todd, Hollis., and Zakia, Richard D. (1980), Visual Concepts for Photographers. First Edition, Published in Great Britan by Focal Press Limited. Printed and bound by A. Wheaton & Co. Ltd., Exeter.

J.W. Allan and G.M. Lilley., (1983) The Reduction of Water Spray from Heavy Road Vehicles, International Journal of Vehicle design, Special Publication SP3. Printed in U.K (pg 270-307).

Esser, R. and Neil, A., (1984), Effectiveness of Spray Suppression Devices. National Highway Traffic Safety Administration, East Liberty, OH, USA. Vehicle Research and Test Centre.

McConnell, Carl C., (1985), The MVMA Investigation Into the Complexities of Heavy Truck Splash and Spray Problem. International Technical Conference on Experimental Safety Vehicles (10th), Oxford, UK.

Tromp, J.P.M., (1985), Splash and Spray by Lorries. Institute for Road safety Research SWOV, Leidschendam, The Netherlands.

Mortimer, R.G., (1986), Effect on Visibility of Wet Weather Spray from Heavy Goods Vehicles. Proceedings of the conference on Vision in Vehicles, Nottingham, U.K., 9-13 Sep, 1985. A.G. Gale (Editors).

Koppa, Roger J, and Pendelton., Olga. J. (1987) Splash and Spray Test Results., SAE Technical Paper Series

872279, Texas Transportation Insititute, Texas A&M University System College Station, Texas, USA.

Scheltens, J. and Luyombya, A., (1987), Spray Cloud Measurement System Based on Computer Analysis of Video Images., SAE Technical Paper Series 872277, Truck and Bus Meeting and Exposition, Dearborn, Michigan, USA, Nov 16-19, 1987.

Wright Bruce, Koppa Rodger J. and Huchingson Dale R., (1989) Measurement of Visibility Through Spray, SAE Technical Paper Series 902274, Truck and Bus Meeting and Exposition, Detroit, Michigan, October 29 - November 1, 1989.

Mortimer, R.G. (1991), Effects of Spray Suppressing Devices on Large Trucks on the Visibility of Passing Drivers. University of Illinois, Champaign, IL 61820, USA. Published in Vision in Vehicles III, A.G. Gale et al (Editors).

Baughan C.J., (1991) Water Spray From Road Vehicles: Measuring The Effectiveness Of Spray Reductions., Transport and Road Research Laboratory, Crowthorne, Berkshire, England. Vision in Vehicles - III pg 275 - 282., A.G. Gale et al. (editors). Elsevier Science Publishers B.V. (North-Holland).

Sagerer, R., (1992) Effectiveness of Wheel Guards on Lorries., SAE Technical Paper Series 925212, TUV Bayern, Germany.

FATIGUE DETECTION IN TRUCKS IN NORMAL OPERATIONS

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Paper Number 96-S11-O-10

ABSTRACT

This paper describes some initial investigations of the feasibility of development of a driver fatigue warning system for trucks. Extensive measurement of drowsiness and vehicle control variables was undertaken on trucks and drivers in normal operation. The result suggests that the phenomenon of less frequent but larger steering wheel movements which underlies the Renault system for detection of drowsiness in car drivers is also present in trucks. The steering wheel angles observed are larger, however, and this may require revision of the algorithms to more effectively detect fatigue in truck drivers.

INTRODUCTION

While much of the earlier research in detection of drowsiness focussed on car drivers, the benefits of a driver fatigue warning system are likely to be greater in trucks, particularly in articulated trucks, than in cars (Knipling and Wierwille, 1993 agree). Articulated trucks travel about five times further per year than cars (76 versus 14 thousand km, Australian Bureau of Statistics, 1991) and much more of their travel is long-distance where fatigue is more likely. The initial purchase price of an articulated truck is about ten times that of a car, making the cost of a driver warning system a smaller fraction of the purchase cost. Importantly, the average cost of truck crashes, resulting from death and injury and from damage to the vehicle and its load, is greater than the average cost of car crashes. Finally, truck driver fatigue has been identified as a particular problem in countries such as Australia where trips often extend for several days.

An earlier literature review showed that the Renault system for detecting lapses in driver alertness was currently the most advanced example of a driver fatigue warning system for cars (Haworth, 1992). The system is based on analysis of steering wheel movements. It utilises the observation that the small directional corrections necessary because of surface irregularities, wind etc. are much more frequent when the driver is alert than when the driver is drowsy (Petit, Chaput, Tarrière, Le Coz and Planque, 1990).

This paper describes the collection and some preliminary analyses of driver drowsiness and vehicle control data for truck drivers on long trips. The research program reported here had two objectives:

1. to establish the feasibility or otherwise of use in trucks of Renault's published system for detecting car driver fatigue
2. to collect data on the relationship between truck driver fatigue and steering wheel movements, to enable improved algorithms to be developed in the future.

CHARACTERISTICS OF A FEASIBLE DROWSINESS WARNING SYSTEM

A number of researchers have outlined the necessary characteristics for a feasible drowsiness warning system (e.g. Haworth, 1992; Knipling and Wierwille, 1993; Petit, Chaput and Tarrière, 1990). Petit, Chaput and Tarrière (1990 - translated) stated that:

- the index detected must be inherent to the task of driving and the indicator must not disturb the driving process
- the indicator must measure both the driving task and the psychophysiological state of the driver
- the system must be capable of detecting sufficiently any deterioration of the "vigilance" of the driver
- the system must be capable of taking into account the individual differences among drivers; it must be personalised
- the system must be capable of informing the driver of any deterioration in his driving.

Knipling and Wierwille (1993) stress the issues of cost and compatibility with other systems as well.

However, there is not universal agreement about the importance of credibility to the driver of the output of the system. The goal of most working in this area has been the early detection of driver impairment due to fatigue and the presentation of a warning signal to the driver. Yet if the driver is not experiencing subjective fatigue (or is only experiencing it at a low level), the driver may not find the warning to be credible (even if it is objectively valid).

However, credibility may be a necessary characteristic only for those warning systems which require the cooperation of the driver (see discussion by

Ward and Fairclough, 1994). More "aggressive" interventions are possible. It may be that the alarm is accompanied by the need to perform a diagnostic task (e.g. reaction time) or the vehicle's power system is disabled in some way. Other alternatives involve directly disabling the vehicle (perhaps for some types of vehicles only) or storing or transmitting the signal in addition to presenting it to the driver.

ISSUES IN THE ESTABLISHMENT OF FEASIBILITY

The characteristics of a feasible driver fatigue warning system listed above relate to drowsiness detection, regardless of the type of vehicle involved. There are additional feasibility issues which relate to the application of drowsiness detection developed in cars to trucks. Several of these issues are listed below:

1. whether the underlying pattern of change from frequent, small steering corrections to less frequent, larger movements with increasing fatigue which is found in cars is also found in trucks. Given that this is assumed to relate to the central process of driver drowsiness, it is expected that it would be so, but little experimental evidence exists.
2. whether the particular vehicle control variables which predict drowsiness most clearly in cars also do so in trucks. For example, it may be that the frequency of lane exceedances is a useful measure of driver drowsiness in cars but it is not in trucks because of their greater width resulting in a higher frequency even when drivers are alert
3. whether, even if the same variables are predictive of driver fatigue, the levels of thresholds would be the same in trucks as in cars.

These issues were addressed in an on-road study of truck driver performance in long-distance driving.

PROCEDURE

All tests took place on drivers of semi-trailers in normal operation. The trucks travelled between Melbourne and Sydney (or vice versa), a distance of approximately 870 km. All trips commenced in the evening (between 5 pm and 1 am) and finished in the morning or early afternoon (between 3 am and 1 pm). Most trips lasted between ten and twelve hours.

Truck drivers drove alone during testing because it was considered that the presence of an experimenter would affect the normal development of drowsiness and possibly also affect driving performance.

The experiment comprised 78 on-road trips, undertaken between late August and mid-November 1993. Fifty-four trips involved drivers from one transport company who operated Scania prime movers and fibreglass trailers loaded with parcels. An additional 24 trips involved drivers from a second company who operated Ford prime movers and loaded car carrying trailers. All trucks were fitted with 100 km/h speed limiters.

During driving, the face of the driver was videotaped to record eye closure and facial expressions (the measure of drowsiness) and the vehicle control variables of steering wheel angle, speed and yaw rate were measured. A video recording of the road ahead was also taken to assist in the interpretation of speed, steering and yaw data.

Measurement of vehicle control data

The vehicle control parameters measured were steering wheel angle, speed and yaw rate. Steering wheel angle was measured 10 times per second using an Omron digital shaft recorder which was attached to the steering column just below the steering wheel using a pulley system. Speed was measured using a road wheel hall-effect sensor. Speed was recorded twice per second with a resolution of about 0.2 km/h. Yaw rate was measured to assist in detection of curves (in conjunction with the video recording of the road ahead). A piezoelectric vibrating gyroscope (Murata Gyrostar ENV-05S) was used to measure yaw rate. Yaw rate was measured five times per second.

The vehicle control data (as well as heart rate and auditory reaction time) were recorded by a data logger designed and built for WORKSAFE Australia. The data logger contained sufficient memory for approximately 15 hours of continuous recording. Equipment was built to encode elapsed time output from the data logger onto the audio track of the video tape (and decode this onto a computer screen). This enabled synchronisation of the video and vehicle control data.

EXPERIMENTAL DESIGN

Testing was conducted in cooperation with the WORKSAFE Australia study of the role of work practices in influencing levels of driver fatigue (Williamson, Feyer, Friswell and Leslie, 1994). Each driver was measured on three types of trips undertaken as part of WORKSAFE's data collection needs. During one trip, the driver travelled from the capital city to Tarcutta (the half-way point), changed trucks and returned to base. This trip was termed "staged driving" and was the normal mode of operation for the companies involved. On the "control" trip, the driver drove from Sydney to Melbourne in

compliance with the driving hours regulations which that a rest stop of at least 30 minutes duration be made after a maximum of five hours of driving. On the "flexible" trip, the driver drove from Melbourne to Sydney with an exemption to the driving hours regulations and was instructed to stop as often or as little as he wished.

RESULTS

Observer judgements of alertness levels

Given the considerable cost and difficulties of automated processing of eye closures from the video recordings, it was decided to undertake a more preliminary assessment of the likely relationship between drowsiness and steering wheel movement patterns. This was done by comparing steering wheel movement patterns during "drowsy" and "alert" periods for the same driver.

The video recordings for those trips with at least five hours of adequate video of the face were viewed and the level of alertness rated by an observer at the beginning of each hour of driving. The ratings ranged from 90% (above average alertness) to 40% (rather tired). Sufficient duration of video recording was available to allow examination of changes in alertness level with time spent driving for 16 trips (8 control and 8 flexible). The mean alertness ratings were very similar for control and flexible trips. There is a decline in judged alertness from commencement of the trip to about seven hours into the trip, but no marked decline in the overall means after that time.

While changes in mean alertness ratings with time spent driving are of interest, it is the occurrence of very low levels of alertness which are likely to be of road safety concern. Ratings of 50% or below occurred most commonly in the fourth to tenth hours of driving.

Speed

Vehicle speed was measured primarily because it affects steering wheel movements and is a variable in the Renault drowsiness detection algorithms. However, speed variability has also been reported to increase with driver fatigue (Khardi and Vallet, 1994; Knipling and Wierwille, 1993). The trucks instrumented in this study were fitted with speed limiters which nominally prevented travel above 105 km/h. While this is true of many trucks in similar operations, this may have reduced overall speed variability and reduced the increase in speed variability with increasing driver fatigue.

In real world driving, both speed and steering wheel angle variability are strongly influenced by the road geometry, traffic conditions etc. For this reason, data from a relatively large number of alert and drowsy periods are needed to draw strong conclusions about the effects of driver fatigue.

Table 1 presents the characteristics of vehicle speed for a small number of driving periods for two drivers. While large differences existed, in general the mean speed was somewhat lower and the variance greater during drowsy periods.

Table 1.
Selected summary statistics for speed (km/h) for a number of 400 second periods (elapsed time in seconds in brackets) during trips V20F and N15F. Drowsy periods are shaded

Time period	Mean	Variance	Minimum	Maximum
Alert period 1 V20F (1639-3238)	97.1	86.1	51.8	105.1
Alert period 2 V20F (5654-7253)	102.0	1.3	91.3	107.7
Alert period 1 N15F (7209-7608)	96.1	101.2	68.7	105.9
Alert period 2 N15F (7609-8008)	100.2	23.5	88.1	108.8
Drowsy period 1 V20F (29981-30380)	95.7	91.1	62.8	109.1
Drowsy period 2 V20F (32025-33624)	89.7	354.4	7.2	112.7
Drowsy period 1 N15F (28809-29208)	102.8	4.1	95.6	109.6
Drowsy period 2 N15F (29209-29608)	95.1	87.1	64.4	129.7

Steering wheel angle

<u>Detection of curves</u> - It was expected that the relationship between driver alertness and steering wheel movement pattern would differ between straight stretches of road and curves. The Renault algorithm applies only to straight roads. Thus it was necessary to detect curves and treat steering wheel movement data from these periods differently.

The data collected allowed curves to be detected by visual inspection of the video recording of the road or from the output of the yaw rate sensor. An initial

examination was made of the yaw rate at times that the video recording of the roadway indicated that the vehicle was in a curve. The examination suggested that curves were commonly present when yaw rate was greater than 10. In analysing the data, straight sections were identified as time periods when yaw rate did not exceed 10. This criterion may have missed lane changes, however.

Location of straights and curves has been completed for several trips. A small number of lengthy straights (greater than 1000 seconds) were identified, in addition to a large number of shorter straights. The lengthy straights comprised about 20% of the total duration of the trip.

Steering wheel angles during alertness and drowsiness - The steering wheel angles reported here are from straight line segments of road and were "justified" before further analysis. Justification involved subtraction of the mean for the previous 80 observations in order to remove the spurious continuous component of the recording.

Figure 1 shows an example of the justified steering wheel angles for alert and drowsy periods during trip N15F. Large steering wheel movements appear to be considerably more common during the drowsy period.

The variance of steering wheel angle was calculated for a number of 400 second periods (see Table 2). While the variances differed among alert and drowsy periods, they were generally higher during drowsy periods.

Table 2.
Selected summary statistics for justified steering wheel angle (degrees) for a number of 400 second periods (elapsed time in seconds in brackets) during trips V20F and N15F. Drowsy periods shaded

Time period	Variance	Minimum	Maximum	Range
Alert period 1 V20F (1639-3238)	148.0	-62.6	57.1	119.7
Alert period 2 V20F (5654-7253)	64.8	-50.3	46.1	96.5
Alert period 1 N15F (7209-7608)	202.9	-59.2	50.0	109.2
Alert period 2 N15F (7609-8008)	67.2	-33.0	42.8	75.8
Drowsy period 1 V20F (29981-30380)	199.9	-76.5	59.4	135.6
Drowsy period 2 V20F (32025-33624)	234.0	-161.8	79.4	241.2
Drowsy period 1 N15F (28809-29208)	99.1	-38.4	32.5	58.9
Drowsy period 2 N15F (29209-29608)	162.7	-41.8	58.9	100.7

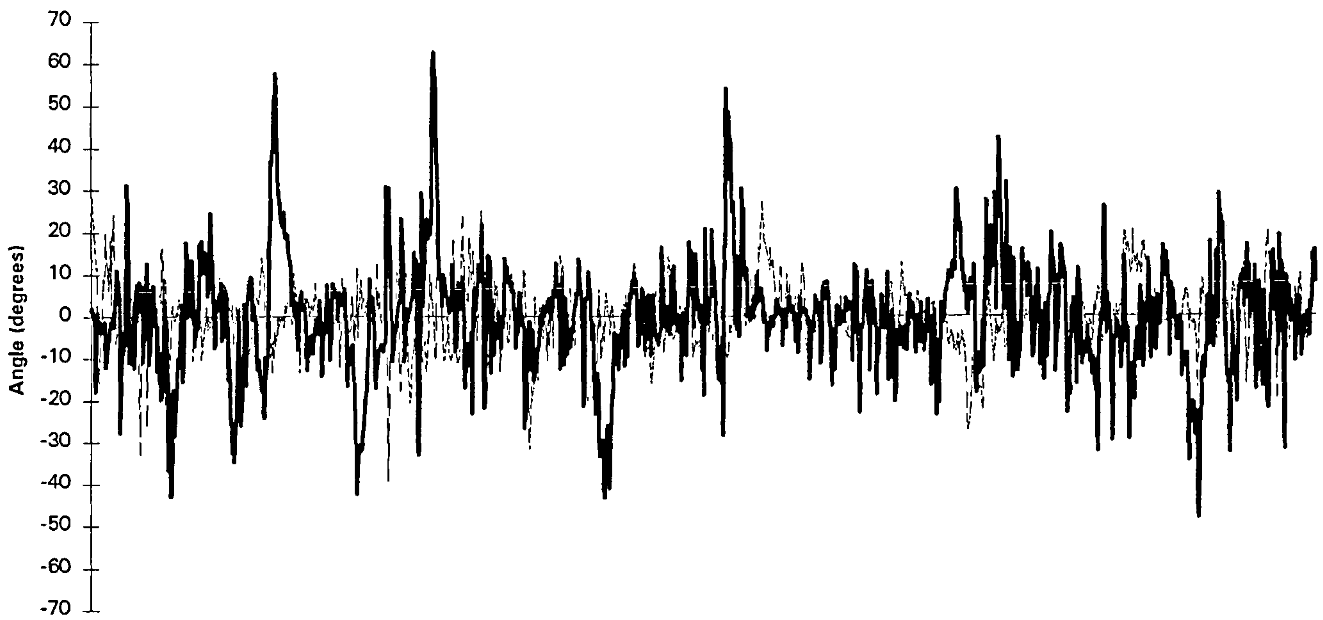

Figure 1. Justified steering wheel angle in alert (heavy) and drowsy (light) periods. Both recordings from trip N15F, duration 4000 seconds.

Comparison of car and truck steering wheel angles

While no direct comparisons of car and truck steering wheel angles were made, the frequency of large steering wheel angles observed during city and highway driving during one truck trip (N07C) was compared with data derived from a Renault on-road experiment which utilised a Renault 25 car (Chaput and Planque, 1991). These data are necessarily crude, but give an indication of the relative magnitudes of steering wheel angles for the two vehicle types.

The upper panel of Figure 2 shows that, in city driving, 55% of truck steering wheel movements exceeded 5 degrees, compared with about 15% of car steering wheel movements. In highway driving (lower panel of Figure 2), the number of large steering wheel movements was similar to that found in city driving for the truck but was much reduced for the car.

Despite its preliminary nature, this pattern of results suggests that there may be a need for defining "small" steering wheel movements differently for cars and trucks. This would be likely to lead to differences in fatigue detection algorithms.

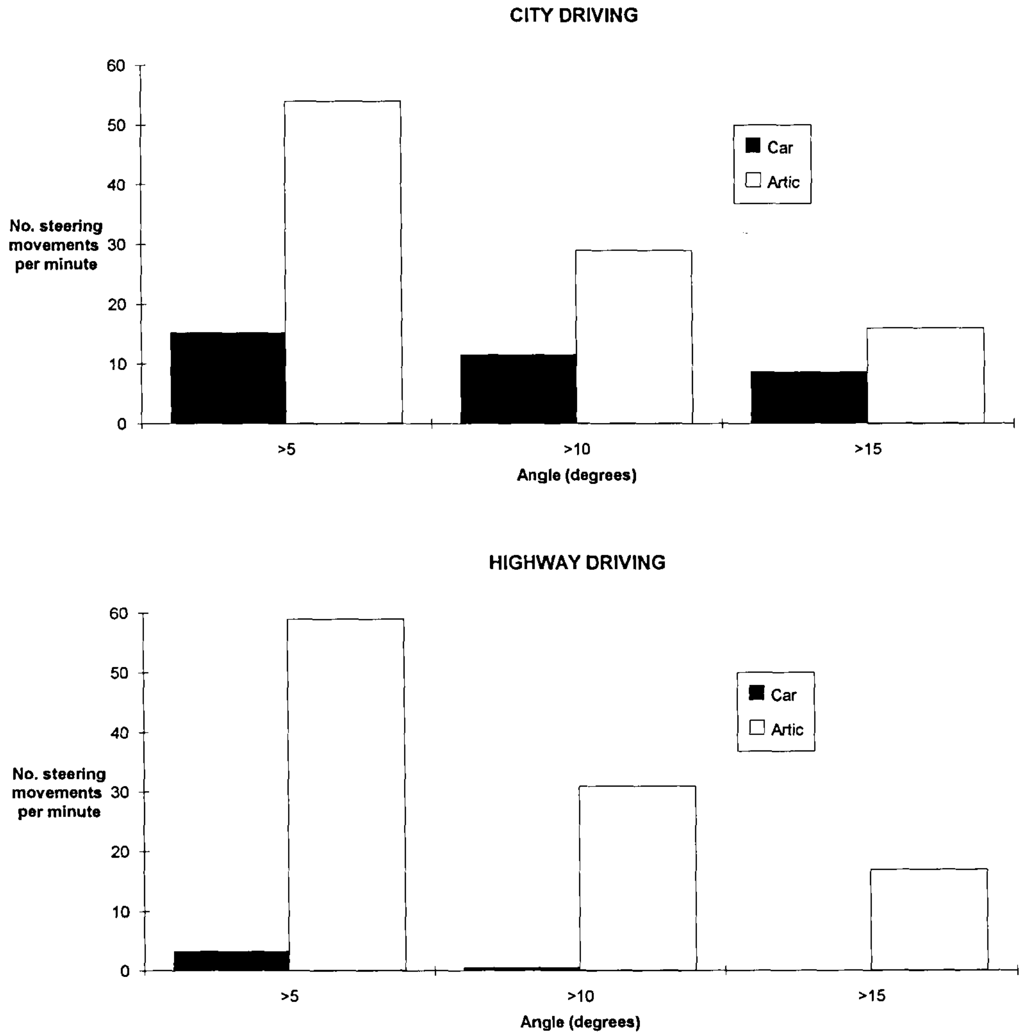

Figure 2. Comparison of frequency of large steering wheel angles observed in trucks (experimental data for trip N07C) and cars (data derived from Chaput and Planque, 1991). The upper panel refers to city driving and the lower panel refers to highway driving.

SUMMARY OF RESULTS

The mean alertness ratings were similar for control and flexible trips. There was a decline in judged alertness from commencement of the trip to about seven hours into the trip but no marked decline in the overall means after that time. Very low levels of alertness (ratings of 50% or below) occurred most commonly in the fourth to tenth hours of driving.

Speed and steering wheel data for a selection of straight-line sections of road were analysed. In real world driving, both speed and steering wheel angle variability are strongly influenced by the road and traffic conditions. While large differences existed among the selection of alert and drowsy periods analysed, in general the mean speed was somewhat lower and the variance greater during drowsy periods. Large steering wheel movements appeared to be considerably more common during the drowsy periods. The variances of steering wheel angles were generally higher during drowsy periods.

A comparison of a limited amount of data collected in this study with that collected in an on-road car study by Renault showed that large steering wheel angles were much more frequent in trucks than cars, in city driving and particularly in highway driving. Further analysis is required to assess whether the patterns of speed and steering data differed between the two types of trucks used.

CONCLUSIONS

This initial investigation of the feasibility of development of an impaired driver warning system suggests that the phenomenon of less frequent but larger steering wheel movements which underlies the Renault system for detection of drowsiness in car drivers is also present in trucks. The steering wheel angles observed are larger, however, and this may require revision of the algorithms to more effectively detect fatigue in truck drivers.

There is considerable international interest in impaired driver warning systems. The major issues relating to feasibility appear to be the need for high detection and low false alarm rates and whether this can be achieved at a realistic cost. While recent Renault and NHTSA papers have favoured collecting multiple driver or vehicle control variables to improve detection and reduce false alarms, the increase in validity and reliability from moving to the multiple variable approach would need to outweigh the increased cost. The proposal of a two-step detection procedure, unobtrusive measurement of vehicle control then a verbal secondary task (first suggested by Hardee, Dingus and Wierwille, 1985) may be simpler and cheaper than collecting eye closure or other driver variables in addition to steering wheel angle.

REFERENCES

Australian Bureau of Statistics. (1991). *Survey of Motor Vehicle Use Australia. 30 September 1991.* Canberra: ABS.

Chaput, D. and Planque, S. (1991). Traitement des signaux méchaniques obtenus sur route (Essai R25 du 20/12/90). Renault Internal Report.

Hardee, H.L., Dingus, T.A. and Wierwille, W.W. (1985). A comparison of three subsidiary tasks used as driver drowsiness countermeasures. (IEOR Department Report No.8505). Vehicle Simulation Laboratory, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Haworth, N.L. (1992). Systems for detection of driver fatigue. *Proceedings 16th ARRB Conference, Part 4,* 189-201.

Haworth, N.L. and Vulcan, A.P. (1995). Feasibility of development of impaired driver warning system. Preliminary results. Report to Federal Office of Road Safety.

Knipling, R.R. and Wierwille, W.W. (1993). U.S. IVHS research: vehicle-based drowsy driver detection. Paper presented at the Vigilance and Transport Conference, Lyon, December 9-10, 1993.

Petit, C., Chaput, D. and Tarrière, C. (1990). Détection des hypovigilances du conducteur et prevention de l'assoupissement au volant. Rapport final. Paris: Régie Nationale des Usines Renault.

Petit, C., Chaput, D., Tarrière, C., Le Coz, J-Y. and Planque, S. (1990). Research to prevent the driver from falling asleep at the wheel. In *34th Annual Proceedings. Association for the Advancement of Automotive Medicine.* October 1-3, 1990, Scottsdale, Arizona. (pp.505-522).

Ward, N. J. and Fairclough, S. H. (1994). A protocol for the assessment of subjective sleepiness. BRIMMI CED2 Deliverable No 1.3. Loughborough: HUSAT Research Institute, Loughborough University of Technology.

Williamson, A.M., Feyer, A-M., Friswell, R. and Leslie, D. (1994). *Strategies to combat fatigue in the long distance transport industry. Stage 2: Evaluation of*

alternative work practices (CR144). Canberra: Federal Office of Road Safety.

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HEAVY TRUCK CRASHWORTHINESS -- CASE STUDIES OF HEAVY TRUCK ACCIDENTS INVOLVING TRUCK OCCUPANT FATALITY

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ABSTRACT

The Society of Automotive Engineers (SAE) initiated a research program to evaluate heavy truck crashworthiness, with the goal of using that information to evaluate truck occupant protection. Phase I of this crashworthiness program entailed development of characteristic crash pulses and analysis of occupant dynamics for heavy truck accidents involving truck occupant fatalities. This paper is part of a series of reports documenting the Phase I results of the SAE heavy truck crashworthiness study. It presents the findings from an in-depth review of the case files for 182 fatal-to-the-driver heavy truck accidents from the National Transportation Safety Board (NTSB). Statistical analysis showed that this NTSB case study is representative of heavy truck accidents involving truck occupant fatalities. Five prominent accident scenarios were identified, containing combinations of three major accident events: 1) rollover, 2) collision with fixed object, and 3) collision with motor vehicle. Detailed analysis of these NTSB cases revealed trends in damage patterns and ranges of severity associated with these prominent accident scenarios.

INTRODUCTION

Over the past several years, considerable interest has been evidenced in the safety issues surrounding heavy trucks. Federal agencies of the United States, private groups, manufacturers, and safety researchers have voiced their concern for the need to address heavy truck crashworthiness. The Federal Motor Vehicle Safety Standards (FMVSS) involving full-scale dynamic crash test evaluations, such as FMVSS 208 -- Occupant Crash Protection, are not applicable to heavy trucks.

Echoing the concern for truck-occupant safety, the Society of Automotive Engineers (SAE) initiated a multi-phase research program to evaluate heavy truck crashworthiness. The goal of this program is to investigate means of evaluating truck occupant protection. Phase I (SAE Phase I) of this program develops: (1) deceleration time histories ("crash pulses") that best characterize heavy truck accidents producing occupant fatalities, and (2) the capability to simulate occupant dynamics in heavy truck crashes using these developed pulses. Future phases will use the composite crash pulses and findings from the occupant dynamics simulation to develop test procedures.

Background

Hundreds of heavy truck occupants are killed in crashes every year (Clarke and Leasure, 1986, Krall, 1993). Highway safety researchers have demonstrated that heavy truck accidents are complex. Various factors associated with the operating environment, vehicle, and driver contribute to truck accident performance.

The accident behavior of heavy trucks differs significantly from the accident behavior of passenger cars. A moving heavy truck possesses an enormous amount of kinetic energy. For most heavy truck crashes involving truck occupant fatality, dissipation of this large amount of energy results in a complex sequence of crash events such as skidding, minor and major impacts, jackknifing and rollover. A thorough understanding of the nature of heavy truck accidents resulting in truck occupant fatalities is therefore an essential first step in the evaluation of truck occupant protection.

Approach

This paper establishes a rational basis to develop deceleration time histories ("crash pulses") that best characterize heavy truck accidents producing occupant fatalities. In another part of the SAE Phase I study, sets of accident scenarios that characterize heavy truck accidents were developed through statistical analysis of Fatal Accident Reporting System (FARS), (FaAA, 1992). This study presents the findings from an in-depth review of the case files for 182 fatal-to-the-driver heavy truck accidents from the National Transportation Safety Board

(NTSB). Detailed analysis of these NTSB cases revealed trends in damage patterns and ranges of severity associated with these prominent accident scenarios.

In two companion studies, promising NTSB accident cases were selected for accident reconstruction (Cheng, *et al*, 1996a; Cheng, *et al*, 1996b). The two primary accident events, collisions and rollovers, were studied independently. Based on a combined methodology of statistical analysis, in-depth case review, and accident reconstruction, representative deceleration time histories were defined for the heavy truck collision and rollover accidents.

STATISTICAL ANALYSIS OF FARS DATA

The SAE Phase I study first analyzes heavy truck accidents by characterizing accident events leading to truck occupant fatalities. This step involved univariate and multivariate statistical analyses of the FARS data (FaAA, 1992). Fatal heavy truck accidents involving truck occupant fatality were clustered into categories sharing common characteristics such as first and most harmful events. This effort identified a number of distinct clusters, or accident scenarios (Table 1).

Table 1.
Cluster Distribution of FARS Data

Heavy Truck Fatal Accidents (FARS Data 1975-1989)

Cluster*	Tractor Fatal Vehicles		Event
	N	%	
A	1,741	18	Struck fixed object; rollover
B	1,895	20	Struck fixed object; no rollover
C	142	2	Rollover; struck fixed object
D	2,649	28	Rollover
E	685	7	Striking vehicle in transport; rollover
F	47	20	Struck by or striking vehicle in transport; no rollover
G	175	2	Struck and striking vehicle in transport
H	326	3	Struck non-fixed object
Total	9,460	100	

* Two clusters, "collision with railway train" and "fell from vehicle" were eliminated from the study due to their limited contribution to the development of crash pulse data to improve occupant safety.

Two primary observations can be made from Table 1. First, most fatal truck accidents are single-vehicle accidents (Clusters A through D; 68%). Second, three accident modes dominate fatal truck accidents:

Accident Mode	Cluster	%
Rollover	A, C, D, E	55
Collision with fixed objects	A, B, C	40
Collision with vehicle in transport	E, F, G	29

A significant portion (55%) of tractor fatal vehicles are associated with rollover accidents (Clusters A, C, D and E). Furthermore, when rollover appears as a single event or as one of a series of events, the rollover itself frequently is the most harmful event in the sequence. This principal finding demonstrates the need to focus attention on rollover accidents involving heavy trucks.

In the majority of collision accidents, the principal impact direction is frontal (FaAA, 1992). A significant population of collision accidents (40%) involves hitting fixed objects such as boulders, buildings, bridge piers, guardrails, traffic barriers, posts, culverts, and trees (Clusters A, B and C). Two types of "fixed object collisions" are identified. "Struck fixed objects" followed by "rollover" (Cluster A) is a highly-ranked accident cluster (18%). Review of the NTSB accident case files (discussed next) showed that the collision preceding a rollover is not necessarily severe, and most likely involves yielding structures such as a guardrail. "Struck fixed objects" occurring as a single harmful event (i.e., no rollover) constitutes 20% of the fatal tractor population (Cluster B). Review of the NTSB accident case files revealed (discussed next) that these are mostly frontal collisions with nonyielding structures such as boulders and bridge piers.

"Collisions with vehicle in transport" account for approximately 29% of the fatal tractor population (Clusters E, F, G). Some collisions with "non-fixed objects" also involve another stationary heavy truck (Cluster H; < 4%). Among these multiple-vehicle collisions, those occurring as a single harmful event (i.e., no rollover) are most common. Review of accident case files revealed (discussed next) that most of the multiple-vehicle collisions are head-on and rearend collisions involving another heavy truck.

NTSB ACCIDENT DATA

The fatal truck accident data files from NTSB were selected for the current in-depth investigation (NTSB, 1990). The original focus of the NTSB study was the influence of fatigue, alcohol, other drugs, and medical factors in fatal-to-the-driver heavy truck accidents. That

study conducted in-depth investigations for all fatal-to-truck-driver accidents in 8 states over a 1-year period from October 1, 1987 through September 30, 1988. For each accident case, the NTSB accident file contains detailed descriptions and photographic documentation of the accident, the truck(s), the driver(s) and the roadway.

This 182-case NTSB database was chosen here because 1) it is a relative large sample, 2) it is reasonably representative of fatal-to-driver heavy truck accidents, and most importantly, 3) it contains detailed documentation essential for accident reconstruction.

Characteristics of the 182 NTSB Study Cases

Campbell and Sullivan (1991), in their study of heavy truck cab safety, also performed an in-depth investigation of the NTSB study cases. They compared the NTSB data with the TIFA (Trucks Involved in Fatal Accidents) files, which reflects the national trend on truck accidents (Table 2). As shown, the NTSB study contains a much greater percentage of California cases, and a larger population of double-trailer combination units.

Table 2.
Comparisons of NTSB and TIFA Data

	NTSB (%)	TIFA (%)
California Cases	41.8	9.8
Doubles	12.9	6.6
Truck Age (pre-1982 model)	60.3	46.9
Cabovers	64.9	57.6
Carrier Type (interstate ICC)	46.5	65.4
Intrastate For-hire	11.4	5.0

(Campbell & Sullivan, 1991)

To further assess its statistical characteristics, the present study performed univariate and multivariate statistical analyses to develop the cluster distribution of the 182 NTSB case study. The resulting cluster distribution compares well with that for the FARS accident file in Table 1. One noted exception is that the NTSB file contains significantly fewer cases involving "striking fixed object without subsequent rollover" than the FARS accident file (Cluster B: 9% vs. 20%). In addition, the NTSB file has a slightly higher population of multiple-vehicle accidents (Clusters E, F and G) than FARS (39% vs. 29%).

Our in-depth review of the NTSB accident summaries provides an independent verification of the FARS coding. This comparison shows that FARS underestimates the frequency of impact following a rollover (2% vs. 11%). Since FARS captures crash events as being either the first or the most harmful, impact following rollover is not always coded when rollover itself is the most harmful event. Our study also shows that FARS occasionally miscodes post-rollover impacts as pre-rollover. As a result, the cluster distribution for NTSB has a larger population of Cluster C (rollover; struck fixed object), and a correspondingly smaller population of Clusters A (struck fixed object; rollover) and D (rollover).

Despite the differences observed above, the statistical analyses show that the 182 NTSB study cases are reasonably representative of the FARS database.

Characteristics of the 68 Selected NTSB Study Cases

Based on reviewing the NTSB case summary for the 182 cases, the present study employed an elimination process to reduce the scope of the in-depth investigation to 68 selected cases. For example, uncommon fatal heavy truck cases such as collision with train, fell from vehicle, and cases related to medical conditions (e.g., a heart attack) were excluded. Other cases eliminated included those involving unique accident modes such as falling over sharp drop-offs, and those with extreme vehicle damage either due to collision damage or post-impact fire. Cases involving straight trucks and tractors without trailers were also not considered.

Detailed information was gathered for 68 selected NTSB cases, including photographs and documentation concerning the motor carrier(s), the truck driver(s), the truck(s) and the roadway. These documentation allowed additional clarification of the event sequences which took place, such as whether a rollover occurred before or after an impact. The significance of the impact on occupant safety could also be addressed.

Univariate and multivariate analyses were performed to characterize the 68 selected NTSB cases. The univariate analysis shows that this subset closely approximates the statistical characteristics of FARS. The multivariate analysis shows that the cluster distribution for the 68 NTSB cases is similar to that for the 182 NTSB cases. Furthermore, the 68 NTSB cases exhibit similar differences to FARS as the 182 NTSB cases. Of most significance, FARS coding consistently underestimates the population for Cluster C (rollover; struck fixed object). Therefore, although the population of Cluster C is smaller than the four dominant accident clusters in Table 1 (Clusters A, B, D, F), this accident scenario should also be considered in crash pulse development.

Five Prominent Fatal Heavy Truck Accident Scenarios

The analyses of FARS and NTSB identified the following five prominent fatal heavy truck accident scenarios, comprising the two primary accident events, collisions and rollovers (Table 3):

Table 3.
Five Prominent Fatal Accident Scenarios

Cluster	Event
A	Struck fixed object; rollover
B	Struck fixed object; no rollover
C	Rollover; struck fixed object.
D	Rollover
F	Struck by or striking vehicle in transport; no rollover

IN-DEPTH REVIEW OF 68 NTSB CASES

This section summarizes the in-depth review of the reports and photographs for these 68 cases (referred to as the NTSB samples in this section). The objective of the review was to characterize damage patterns associated with collision and rollover accidents.

NTSB Trends in Tractor Damage Patterns

Review of reports and photographs for the 68 selected NTSB cases showed that heavy trucks have characteristic damage patterns unique to the following collision and rollover accidents:

1. Head-on collisions
2. Rearend collisions
3. Collisions with fixed objects
4. 90° rollover ($^1/_4$ turn) without a subsequent collision
5. 90° rollover ($^1/_4$ turn) with a subsequent collision
6. 180° rollover ($^1/_2$ turn)

1. Head-on Collisions. Of the multiple vehicle accidents in the 68-case NTSB set, 22% were head-on collisions between heavy trucks. No head-on collisions with full contact (i.e., minimal lateral offset) were observed in the 68-case NTSB sample. All of the head-on collisions involved a significant offset or even sideswipe, typically as a result of one heavy truck crossing over into the oncoming traffic lanes. Because these collisions often involved high closing speeds, the resulting damage consisted primarily of significant intrusion to the driver side of each tractor (Figure 1).

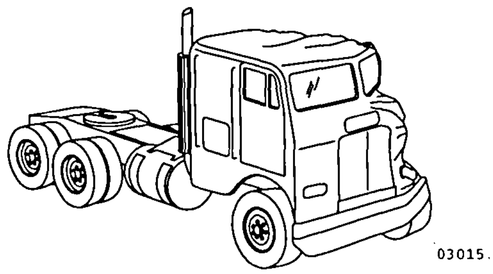

Figure 1. Typical Damage Pattern: Offset Head-on with Tractor.

2. Rearend Collisions. Of the multiple vehicle accidents in the NTSB set, 52% were rearend collisions between two heavy trucks. The striking tractor typically impacted the rear of another combination unit trailer with full contact. Most of these collisions did not involve subsequent rollover. Damage to the striking tractor was generally more severe than to the struck trailer.

Figure 2 illustrates the four characteristic damage patterns observed in rearend collisions with other combination units:

- Frontal cab intrusion,
- Rearward cab displacement,
- Forward cab rotation,
- Rear cab damage due to trailer impact or load shift.

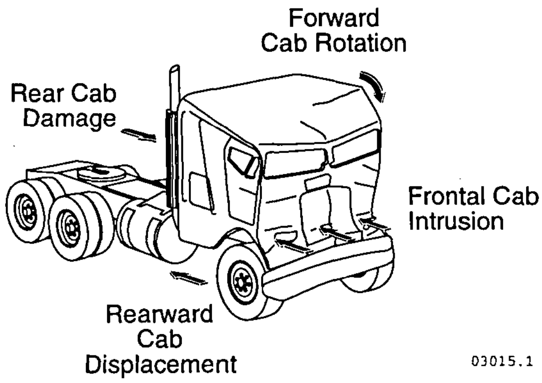

Figure 2. Typical Damage Pattern: Rearend Collision with Combination Unit.

In most rearend impacts, a height mismatch exists between the front bumper of the striking tractor and the bed of the struck trailer. The underride protective structures at the rear of the trailers cannot absorb the substantial amount of energy of a heavy truck impact. The impact therefore produces damage to the impacting tractor characteristic of underride collisions, in which cab

components above the bumper are crushed locally and sheared rearward.

Damage to the rear of the cab can occur in three ways:

- The cab is displaced rearward into the trailer;
- A failure of the kingpin/fifth wheel allowing the trailer to slide forward into the rear of the tractor;
- A failure of the load tie-downs resulting in load shift.

As the severity of the collision increases, the damage modes became less distinct. Total cab destruction was observed in many cases.

3. Collisions with Fixed Objects. Our statistical analysis grouped items such as boulders, buildings, bridge piers, guardrails, traffic barriers, posts, culverts and trees as fixed objects. In the NTSB set, all cases with "striking fixed object" as the first and most harmful event (Cluster B) involved collisions with massive fixed objects, such as bridge piers. Impact with massive fixed objects constituted approximately 12% of the 68 NTSB cases. These collisions tended to produce total destruction of the tractor.

Objects such as guardrails were typically moved or destroyed by the impact of a heavy truck. These objects should thus be considered semi-fixed. In the NTSB set, collisions with semi-fixed objects did not cause the same degree of tractor destruction as collisions with massive fixed objects. As illustrated schematically in Figure 3, significant intrusion into the occupant compartment was not observed in impacts with semi-fixed objects (unless the impacts followed rollovers). However, these collisions often resulted in loss of control and subsequent rollover.

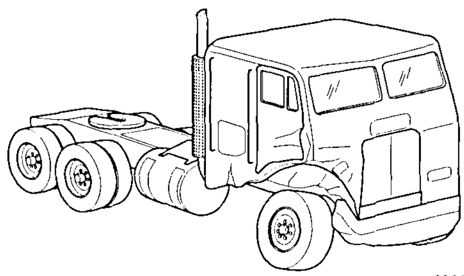

Figure 3. Typical Damage Pattern: Guardrail Impact.

4. 90° Rollover (1/4 Turn) Without a Subsequent Collision. A 90° rollover is defined here as a condition where the tractor/trailer unit came to rest substantially on its side. The characteristic damage pattern for a 90° rollover without a subsequent collision is illustrated in Figure 4.

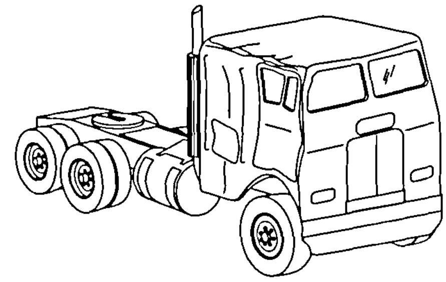

Figure 4. Typical Damage Pattern: 90° Rollover without Subsequent Collision.

Damage to the tractor in 90° rollovers without a subsequent collision was generally minor and confined to the near side of the cab. Cases involving uneven terrain (i.e., slope) or rollover past 90° produced greater intrusion at the roof level. In one case, the tractor was pulling a tank trailer and rolled slightly beyond 90°, extending the damage into the roof area.

5. 90° Rollover (1/4 Turn) with a Subsequent Collision. A collision following a 90° rollover typically produced greater damage to the tractor cab than the rollover itself. Figure 5 illustrates an impact following a 90° rollover. Damage to the roof and upper cab structure caused intrusion into the occupant space.

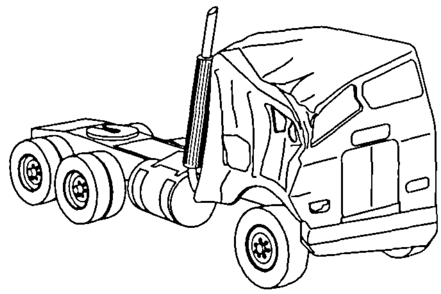

Figure 5. Typical Damage Pattern: 90° Rollover with Subsequent Collision.

The extent of the upper structure damage appears to depend upon the duration or aggressiveness of the post-rollover contact. In one case, the combination unit rolled over and slid into an embankment at relatively low velocity and came to rest. The resulting damage was minor to moderate. In contrast, the tractor in another case rolled over and slid along a concrete median barrier for 100 feet and then along the ground for 240 feet, ripping away much of the side and upper cab and trailer structure.

6. 180° Rollover (1/2 Turn). A 180° rollover is defined here as a condition where a tractor came to rest substantially on its roof, or rolled beyond 180°.

For rollovers of 180° or more, the occupant compartment was generally totally compromised by the rollover. As the sketch in Figure 6 illustrates, the cab roof was typically forced down to the level of the instrument panel. Subsequent impact in a 180° rollover generally led to destruction of the cab's upper structure exceeding that observed in the 90° rollover. The observed damage ranged from severe to extreme, with extreme damage reflecting total cab destruction.

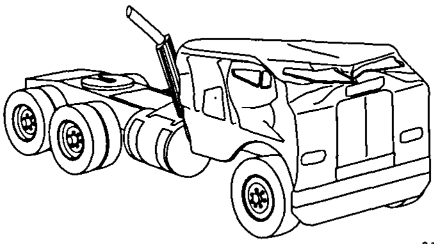

Figure 6. Typical Damage Pattern: ≥ 180° Roll.

SURVIVABILITY

The observed characteristic damage patterns confirm that objectives for occupant protection differ for heavy trucks and passenger cars (Clarke and Leasure, 1986). Accident reconstruction in a companion study demonstrates that many fatal truck collisions are low deceleration events (Cheng, *et al*, 1996a). In these heavy truck crashes, occupant ejection and excessive cab crush were observed to be among the primary causes of fatality. Therefore, restraint use and maintenance of survival space are the relevant measures for assessment of survivability. In the following discussion, an accident was subjectively judged to be survivable if enough space was available for a restrained occupant.

Using this subjective criteria for survivability, the reports and photographs from the 68 selected NTSB cases were reviewed. Figure 7 illustrates the distribution of survivable and nonsurvivable accidents (Right chart). Results show that approximately 16.2% of the accidents would be survivable with restraint use. In an additional 5.9% of the accidents, survivability was questionable but possible. Interestingly, approximately 80% of the survivable accidents involved rollover (Left chart, Fig. 7). The following discussions will address the survivability of each accident type.

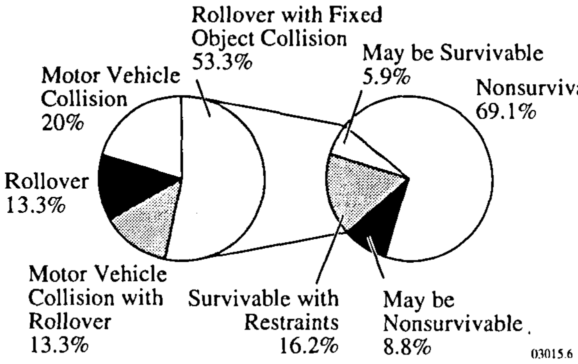

Figure 7. NTSB Accidents Survivable with Restraint Usage.

Collision

Collisions with another truck or with a fixed object, occurring as the most harmful event, were generally nonsurvivable. In the NTSB set, only two collision cases involved minor cab damage; these fatalities were caused by the driver jumping or falling out of the cab. The remaining cases involved substantial cab intrusion. Details of these cases are discussed below:

Head-on Collisions. Head-on full frontal contacts with other combination units were not observed in the NTSB sample. These collisions are expected to result in extreme amounts of tractor destruction, and are therefore considered nonsurvivable.

In head-on collisions involving an offset contact between two tractors, the assessment of survivability is less straightforward; survivability of offset and sideswipe collisions needs to be judged on a case-by-case basis.

Overall, cab damage for head-on collisions ranged from severe to complete destruction, generally resulting in a total loss of occupant survival space. For these cases, there appears to be no practical structural design changes to improve occupant protection.

Rearend Collisions. The majority of the rearend collisions in the NTSB sample involved full-width contact between the impacting tractor and impacted trailer. Generally, a tractor-trailer rearended a slower moving or stationary tractor-trailer. The simple impact geometry in these accidents produced similar damage characteristics for most rearend cases.

In the NTSB set, COE (cab-over-engine) tractors appeared especially susceptible to the underride condition. There is no significant structure above the frame of a COE tractor to resist the intrusion of the relatively rigid trailer

bed. Therefore, rearend accidents involving COE tractors typically displayed a large amount of intrusion into the occupant compartment. The accident reconstruction in a companion study showed that the deceleration associated with a rearend collision was very low (i.e., on the order of a few g's), even up to the point of total cab destruction (Cheng, *et al.* 1996a).

Unlike COE tractors, conventional tractors are more likely to maintain sufficient occupant survival space in rearend collisions. This is due in part to the engine placement in conventional cabs, and the separation between the front of the tractor and the occupant compartment. Accident reconstruction, performed in a companion study, indicated that the stiffer structures in conventional cabs resulted in buildup of the deceleration level, before the occupant compartment was threatened by intrusion from the front. While these higher deceleration levels remained tolerable for the restrained occupant, they created significant forces on the trailer and its load. This finding was confirmed by the more severe rearend collisions involving conventional tractors. In addition to a moderate amount of frontal cab damage, shifting of the trailer load or shearing of the kingpin or 5th wheel was observed. This failure allowed the trailer or load to move forward and impact the cab from behind.

Figure 8 illustrates the distribution of rearend accidents of the NTSB sample which involved failures associated with the trailers. Overall, cab damage for rearend collisions ranged from severe damage to complete cab destruction. In light of the above discussion, structural design changes to reduce frontal cab crush must be accompanied by proportional strength increase to structures such as the 5th wheel, kingpin and the load tie-downs.

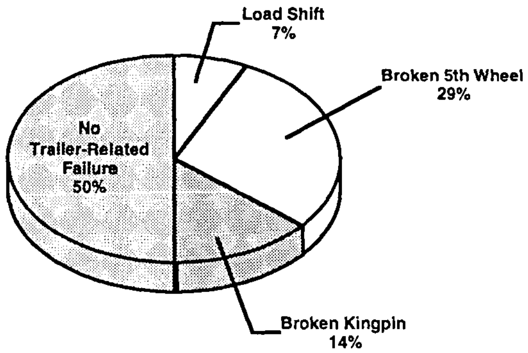

Figure 8. Trailer-Related Failures in Rearend Collisions (n = 14).

<u>Collisions with Fixed Objects.</u> In the NTSB sample, collisions with massive fixed objects such as bridge piers generally resulted in extreme amounts of cab crush to the point of total disintegration. Subsequent rollover was of little consequence. Therefore, collisions with fixed objects, when occurring as the only harmful event causing the fatality, are generally not survivable. There appears to be no practical structural design changes to improve occupant protection.

In collisions with semi-fixed objects such as guardrails, it was generally a subsequent rollover which posed the most significant threat to occupant survival. The potential for survivability in rollover is discussed below.

Rollover

Figure 9 illustrates for the NTSB sample the distribution of accidents involving rollover according to the direction of roll and degree of rollover. These results show a relatively even distribution both in direction of roll, and degree of rollover.

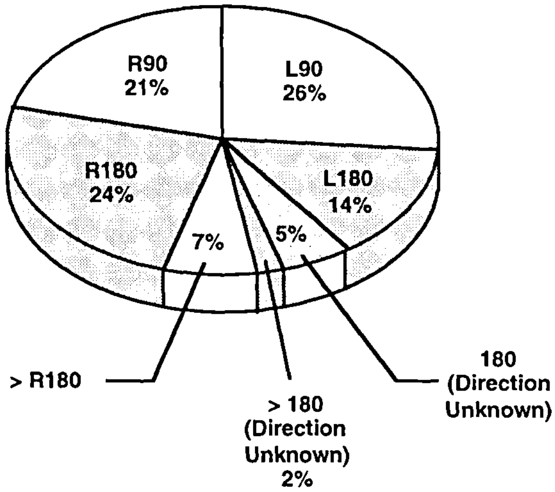

Figure 9. Direction/Degree of Roll (n = 42).

Among the rollover accidents, trailer type was observed to strongly influence the degree of rollover. Figure 10 illustrates the distribution of degree of rollover as a function of trailer type for the NTSB sample. Of the rollover accidents involving rolls of greater than 90°, 59% involved flatbed trailers. An additional 23% involved van trailers which had their upper structures substantially destroyed or removed during the rollover, essentially converting them into flatbeds. Undestroyed van trailers were involved in only about 5% of the rolls greater than 90°. In contrast, only 20% of the 90° rolls involved flatbed trailers (Figure 10).

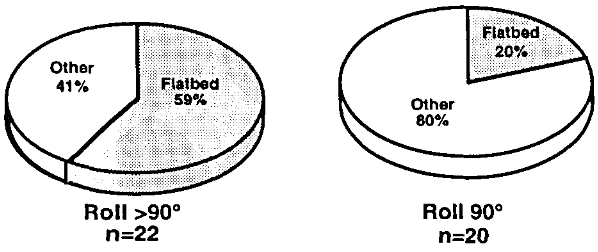

Figure 10. Degree of Rollover by Trailer Type (n = 42).

Figure 11 illustrates the breakdown of survivability among rollover accidents of the NTSB sample. In approximately 52% of the cases, the tractor rolled more than 90°. Only two of these accidents (9%) were considered survivable with restraint use. In the majority of the cases, the roof was crushed down to the instrument panel.

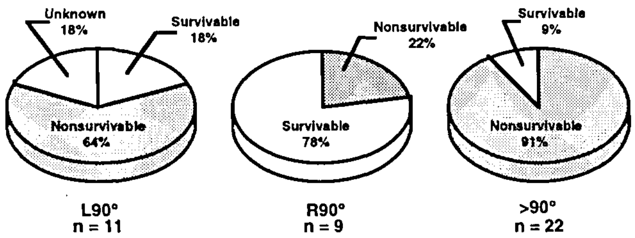

Figure 11. Rollover Survivability (n = 42).

The influence of trailer type was especially noteworthy given the high survivability potential for heavy truck rollovers which do not continue beyond 90°.

In the majority of the survivable rollover accidents, the direction of roll was toward the passenger or right side of the tractor (Figure 11). Clearly, a restrained far-side (driver or left) occupant would be kept from falling the width of the tractor during the rollover. The same restrained far-side occupant would also be minimally affected by the loss of space on the near side, if a post-rollover impact occurred.

Restraint use would be less effective in protecting a near-side occupant in a rollover involving subsequent collisions. This conclusion is confirmed by the NTSB sample, where rolls toward the near side were observed to have lower survival potential (Figure 11).

It should be noted that the assessment of survivability applies only to the driver. If the focus was expanded to include passenger survival, then the overall survivability for rollover accidents might decrease due to passenger side intrusion.

CONCLUSIONS

Based on the studies outlined above, the following observations were made :

General

- Heavy trucks have characteristic damage patterns unique to various rollover and collision events.

Collisions

- Fatal-to-truck-driver collisions are primarily frontal, and consist mainly of head-on and rearend collisions with another heavy truck, and head-on with fixed objects.
- Large amounts of crush and occupant compartment intrusion caused by high closing speeds are characteristic of fatal-to-truck-driver head-on collisions.
- Fatal-to-truck-driver rearend collisions occur over a range of closing speeds. Occupant compartment intrusion is partly caused by height mismatch between the striking tractor frame and the struck trailer frame.
- Maximum 5th wheel load, cargo tie-down strength, and trailer front end strength are among the factors that must be considered if the tractor front end is stiffened.

Rollover

- Of the 42 rollover cases in the 68 selected NTSB accidents, slightly more tractors rolled to the right than to the left. Nearly 50% of these 42 cases rolled 90°.
- One-quarter turn (90°) rollovers (without subsequent collision) do not compromise occupant space integrity.
- Tractors towing flatbed and tanker trailers have a greater propensity to roll onto the roof (180°) than van trailers.

Survivability

- An accident was subjectively judged to be survivable if enough space was available for a restrained occupant. Based on this criterion, the study revealed

that approximately 22% of 68 NTSB fatal-to-truck-driver accidents were at least possibly survivable.

- Of the survivable fatal-to-driver heavy truck accidents, 80% involved rollover. Rolling 90° to the right (far side) was observed to be more survivable than rolling 90° to the left (near side).

- Rollovers onto the roof are generally not survivable because the occupant compartment integrity is compromised.

ACKNOWLEDGMENTS

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REFERENCES

Campbell, K. L. & Sullivan, K. P. (1991). "Heavy Truck Cab Safety Study," Proceedings of the 35th Stapp Car Conference, San Diego, SAE 912903.

Cheng, L. Y., Werner, S. M., Girvan, D. S., Khatua, T. P. (1996a) "Heavy Truck Crashworthiness - Collision Accidents." 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Australia.

Cheng, L. Y., Girvan, D. S., Werner, S. M., Khatua, T. P. (1996b) "Heavy Truck Crashworthiness - 90° Rollover Accidents." 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Australia.

Clarke, R. M. and Leasure, Jr., W. A. (1986). "Truck Occupant Protection," U.S. DOT/NHTSA Report No. DOT-HS-807-081.

Failure Analysis Associates, Inc. (1992). "Heavy Truck Crashworthiness, Phase I, Task A1-2, Statistical Analysis," Prepared for SAE International.

Krall, F. L. (1993). "The Decade of Declining Heavy Truck Fatalities -- A Tribute to the Cooperative Process," SAE 933058.

National Transportation Safety Board (1990). "Fatigue, Alcohol, Other Drugs, and Medical Factors in Fatal-to-the-Driver Heavy Truck Crashes," (Volume 1 and 2), NTSB/SS-90/01 and NTSB/SS-90/02.

HEAVY TRUCK CRASHWORTHINESS -- COLLISION ACCIDENTS

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ABSTRACT

The Society of Automotive Engineers (SAE) initiated a research program to evaluate heavy truck crashworthiness, with the goal of using that information to evaluate truck occupant protection. Phase I of this crashworthiness program entailed development of characteristic crash pulses and analysis of occupant dynamics for heavy truck accidents involving truck occupant fatalities. This paper is part of a series of reports documenting the Phase I results of the SAE heavy truck crashworthiness study. A companion study identified three major accident events in these accidents: rollover, collision with a fixed object, and collision with motor vehicle. Rearend collision with another heavy truck was identified as a commonly occurring accident mode that was also amenable to accident reconstruction. Results indicated that the failure of fifth wheel/kingpin assembly occurs at approximately 5.5 g's for a loaded trailer. Therefore, design changes to reduce frontal cab crush must be accompanied by proportional strength increases to structures such as the fifth wheel, kingpin, and the load tie-downs. This study further develops the capability for simulating occupant dynamics in collision accidents. It is concluded that future studies in occupant protection should further investigate steering wheel geometry and stiffness, in addition to the design of ICP and suspension seat.

INTRODUCTION

Over the past several years, considerable interest has been evidenced in the safety issues surrounding heavy trucks. Federal agencies of the United States, private groups, manufacturers, and safety researchers have voiced their concern for the need to address heavy truck crashworthiness. The Federal Motor Vehicle Safety Standards (FMVSS) involving full-scale dynamic crash test evaluations, such as FMVSS 208 -- Occupant Crash Protection, are not applicable to heavy trucks.

Echoing the concern for truck-occupant safety, the Society of Automotive Engineers (SAE) initiated a multi-phase research program to evaluate heavy truck crashworthiness. The goal of this program is to investigate means of evaluating truck occupant protection. Phase I (SAE Phase I) of this program develops: (1) deceleration time histories ("crash pulses") that best characterize heavy truck accidents producing occupant fatalities, and (2) the capability to simulate occupant dynamics in heavy truck crashes using these developed pulses. Future phases will use the composite crash pulses and findings from the occupant dynamics simulation to develop test procedures.

Background

Hundreds of heavy truck occupants are killed in crashes every year (Clarke and Leasure, 1986, Krall, 1993). Highway safety researchers have demonstrated that heavy truck accidents are complex. Various factors associated with the operating environment, vehicle, and driver contribute to truck accident performance.

The accident behavior of heavy trucks differs significantly from the accident behavior of passenger cars. A moving heavy truck possesses an enormous amount of kinetic energy. For most heavy truck crashes involving truck occupant fatality, dissipation of this large amount of energy results in a complex sequence of crash events such as skidding, minor and major impacts, jackknifing and rollover. A thorough understanding of the nature of heavy truck accidents resulting in truck occupant fatalities is therefore an essential first step in the evaluation of truck occupant protection.

Approach

As described in a companion paper (Cheng, *et al.*, 1996a), sets of accident scenarios that characterize heavy truck accidents were developed through a statistical analysis of the Fatal Accident Reporting System (FARS). This analysis revealed that most of the accidents involve some combination of rollover, collision with fixed object, and collision with motor vehicle.

The files of the National Transportation Safety Board (NTSB) were reviewed because they contain detailed investigations into a subset of the FARS accidents. Sixty-eight of the 182 NTSB cases studied were selected for detailed review; outlying cases were not considered. This group of 68 NTSB cases forms the group upon which accident reconstructions were performed. Damage patterns unique to heavy truck collisions and rollovers were identified. This provided guidance for crash pulse development and occupant dynamics simulation.

In this paper, we discuss the reconstruction and simulation of frontal collision accidents. A companion paper (Cheng, *et al.*, 1996b) describes the same for rollover accidents.

ACCIDENT RECONSTRUCTION

The accident behavior of heavy trucks differs significantly from the accident behavior of passenger cars. Passenger car crashes typically involve relatively high decelerations (on the order of 30 g's for frontal impacts) over short time duration's (100 milliseconds). Heavy truck crashes, on the other hand, typically involve a complex sequence of events such as skidding, minor and major impacts, jackknifing and rollover, over a long period of time (more than 1 second). The deceleration associated with each of these crash events is comparatively small (less than 10 g's).

This difference in crash characteristics is mainly due to the weight difference between heavy trucks and passenger cars. A loaded heavy truck weighs on the order of 80,000 lb (approximately 36,000 kg), approximately 25 times the weight of a typical passenger car.

Because of the tremendous kinetic energy possessed by the moving truck, the energy lost in the most harmful event may be only a small portion of the initial truck kinetic energy; the energy lost to skidding and sliding may be many times greater than that lost to crush. Consequently, in accident reconstruction of heavy truck accidents, the calculated crush energies and decelerations are more sensitive to input variations than for passenger car accidents. A customized technique was necessarily devised to reconstruct heavy truck collision accidents.

Accident Selection

From the in-depth review of NTSB data, the principal impact direction for a majority of the collision accidents is frontal (Cheng *et al*, 1996a). In the present study, collisions in which a heavy truck impacted another parked or slow-moving heavy truck were selected as promising accidents for reconstruction. Of the 68 cases selected from the NTSB database, 21% were rearend collisions between a faster moving tractor-trailer and the trailer of a slower moving or stationary tractor-trailer unit, and these collisions were similar in nature with respect to extent of damage, speed, load, and collision geometry (FaAA, 1992b).

In these collisions, there is generally no pre-impact skidding. Also, the two tractor-trailer units generally stick together at impact and remain together until reaching their final rest positions. Therefore, the potential pitfalls of estimating the energy of pre- and post-impact events were avoided, and the estimation of pre-impact velocities was straightforward.

Reconstruction Methodology

Conservation of linear momentum was used to calculate the post-impact velocities of the two tractor-trailer units. Since the vehicles remained together after the initial impact, the contact condition was treated as nearly perfectly plastic. A small coefficient of restitution (0.05) was used in each case to account for minor deformation recovery.

Post-impact decelerations were computed based on post-impact velocities and distances traveled and were compared with observed post-impact braking or rolling. This step served as an independent validation of the computed velocities.

The amount of crush energy lost was estimated based on the difference between pre- and post-impact kinetic energies. Deformation in the trailer rear and the tractor front was determined from photographs and descriptions in the NTSB investigation reports. This energy and deformation were used to compute the average force exerted on each vehicle during the collision. The corresponding deceleration was then computed using

$$a = \frac{Force}{Mass_{V1}} = \frac{Energy_{crush}}{(Mass_{V1})\ \ (depth_{V1+V2})} \qquad (1.)$$

where a and $Mass_{v1}$ are the deceleration and the mass of the impacting vehicle, V_1, and $depth_{v1+v2}$ is the combined crush depth of both vehicles.

Results obtained as above require qualification in cases involving failure of either the fifth wheel, kingpin, or the load tie-downs of the impacting vehicle. In these cases, the observed damage is actually due to two separate impacts: the first with the other vehicle, and the second where the trailer or the load slides forward into the tractor cab. Therefore, the computed

impact force and deceleration are average values for the entire impact event. They generally represent a lower bound of the peak force and deceleration experienced during the portion of impact preceding the failure.

Benchmarking

Full-contact crash tests were studied in order to benchmark the collision methodology. These tests included barrier tests by Rice and Shoemaker (1981) and Franchini (1970) and rearend impact tests by Grandel and Berg (1989).

In the Rice and Shoemaker test, a cab-over-engine (COE) tractor and flatbed trailer, moving at 29.2 mph (13 m/s), impacted a rigid barrier fronted with a deep array of steel barrels. The average deformation of the barrels was 13.4 feet (4 m). There was essentially no measurable damage to the front of the tractor except at the cab corners above the bumper where the barrels wrapped around the bumper and pressed against the cab sheet metal. The authors reported a peak measured deceleration of 2.5 g's during impact. Using our methodology, we calculated the average deceleration to be approximately 2 g's.

In Franchini's tests, two COE straight trucks impacted a rigid barrier at speeds of 20.5 and 22.5 mph (9.2 and 10 m/s). Based on the reported speeds and deformations, the average decelerations calculated were 40.5 and 84 g's for the 22.5 and 20.5 mph impacts, respectively. No measured decelerations were available for comparison.

Grandel and Berg conducted two tests involving an impact of COE straight trucks into the rear of a stationary tank trailer at 13.7 and 22.4 mph (6.1 and 10 m/s). Decelerations for the striking vehicle were calculated to be 7.4 and 7.1 g's, respectively. These deceleration levels are consistent with expectations for rearend collisions involving underride.

Reconstruction of Rearend Collisions

There were 14 rearend collisions in the 68-case NTSB sample. Of these, seven were selected for reconstruction because of well defined initial conditions. In addition, one case from the Failure Analysis Associates, Inc. (FaAA) files was included.

As discussed earlier, the rearend collisions involved a tractor-trailer traveling at freeway speed and a slow moving or stationary tractor-trailer. Each accident was reconstructed using the energy and momentum procedures outlined above.

All of the impacting tractor-trailer units which did not experience a kingpin or fifth wheel failure were subjected to average decelerations of less than approximately 5 g's.

Clustered above approximately 5.5 g's are three cases in which the fifth wheel failed. The calculated load transferred to the kingpin in the impact was between 300,000 and 360,000 lb (1,300,000 and 1,600,000 N). Considering the fact that these reconstructions provide lower bounds for the force preceding kingpin failure, these calculated decelerations and loads are in very good agreement with the results of Labra (1982), who estimated kingpin failure at approximately 7.5 g's and 420,000 lb (1,900,000 N).

The findings from our in-depth review of NTSB accident cases and accident reconstruction allude to a dilemma in designing for occupant protection in all frontal heavy truck accidents. A typical rearend collision with underride produces easily manageable deceleration with a great deal of cab deformation. If intrusion is reduced, the deceleration and likelihood of load shift or kingpin/fifth wheel failure increases, allowing the load or trailer to impact the rear of the cab. Therefore, design changes to reduce frontal cab crush must be accompanied by proportional strength increases to structures such as the fifth wheel, kingpin, and the load tie-downs.

CRASH PULSE DEVELOPMENT

Based on the findings of the accident reconstructions, a representative crash pulse was developed for a heavy truck collision accident. A generic crash pulse shape was characterized by the magnitude of the deceleration and the pulse duration.

Crash Pulse Shape

The generic crash pulse profile takes the form of

$$a(t) = \frac{1}{2}A\left[1-\cos\left(\frac{2\pi t}{T}\right)\right] \qquad (2.)$$

where A is peak deceleration and T is pulse duration (Figure 1). The quantities A, T and a_{ave} completely characterize the crash pulse.

Parameters

Based on the results of the accident reconstructions, an average deceleration of 5.5 g's was predicted to be the threshold for fifth wheel/kingpin failure. For the three cases in which this failure occurred, the computed average pulse duration was 0.13 second. From this, a peak deceleration of 11 g's, average deceleration of 5.5

g's, and pulse duration of 130 ms were selected to characterize the crash pulse for heavy truck collision accidents (Figure 1). This crash pulse corresponds to a delta V of 15.7 mph.

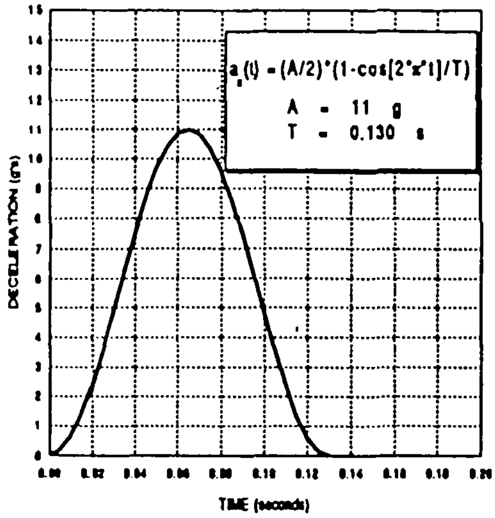

Figure 1. The longitudinal deceleration crash pulse for frontal collisions is based on accident reconstruction.

OCCUPANT DYNAMICS SIMULATIONS

Part of SAE Phase I was to develop the capability to simulate occupant dynamics in heavy truck crashes. These simulations can then be utilized to determine peak occupant excursions, identify occupant impact velocities and locations, demonstrate the differences in occupant response for different restraint configurations, provide information for the design of test procedures, and guide future investigations into truck occupant protection.

The MADYMO computer simulation package was chosen for the occupant dynamics simulations (Heinz *et al.*, 1991; Philippens *et al.*, 1991: Wismans and Hermans, 1988). The crash pulse defined above was used as input for these simulations of a frontal collision. Vehicle cab crush was not included in the current model.

In this study, the simulations were performed to model a truck driver who is either three-point belted, lap-belted, or unrestrained. Both the COE and the conventional designs were analyzed.

MADYMO Model

In constructing the MADYMO model, cab interior geometry, occupant properties (segment geometry, inertial properties, and joint properties), and occupant/vehicle contact interaction properties must be specified.

The program, MADYMO, has proven capability to analyze occupant response and evaluate occupant protection designs in passenger cars. The developer of the program, TNO of the Netherlands, has published numerous articles validating data sets for various dummy models (Heinz *et al.*, 1991; Philippens *et al.*, 1991: Wismans and Hermans, 1988). As part of the SAE Phase I, this heavy truck model was validated against frontal barrier crash tests by Rice and Shoemaker, 1981, and by Rice, 1981 (Girvan *et al.*, 1994). As an example, simulated driver head acceleration profiles are a very good match to experimental findings (Figure 2).

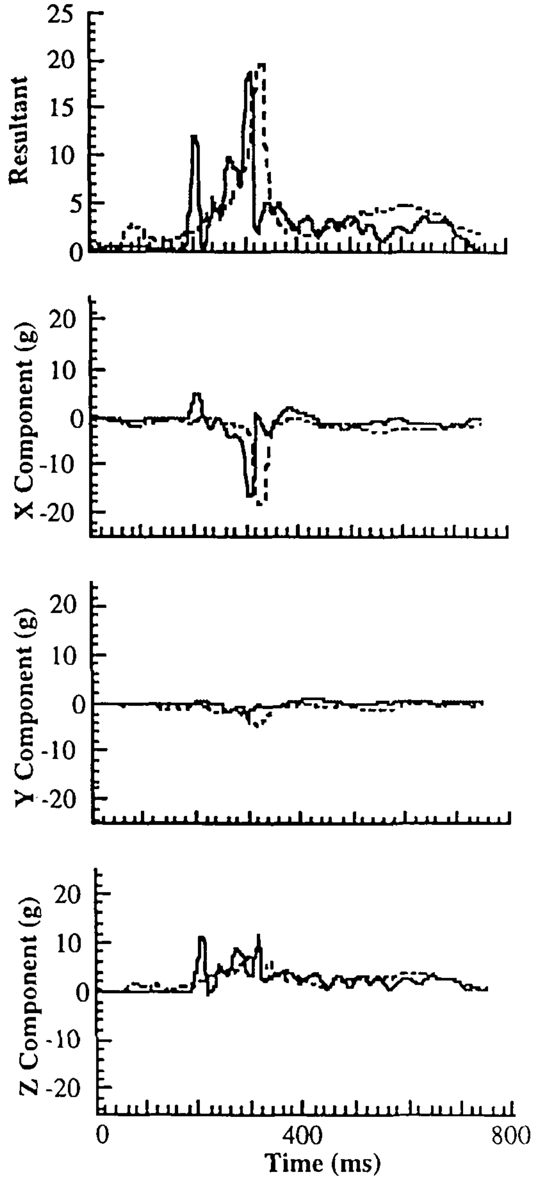

Figure 2. The simulation (solid) was validated against the experimental (dashed) driver's head acceleration in a frontal collision by Rice and Shoemaker (1981).

Cab Interior Geometry. A typical cab interior model was developed for both the COE and conventional tractor designs. This typical cab model was chosen based on the cab with the interior geometry closest to the computed average of key dimensions from several different cabs (three COE's and six conventionals). These dimensions were obtained from tractor manufacturers and independent vehicle inspections.

Occupant Model. The occupant properties were based on the Hybrid III anthropomorphic crash dummy (Figure 3, in the COE cab model). The MADYMO library contains a standard data set, "Advanced 50th Percentile Hybrid III Male Dummy Model", which characterizes the dynamic behavior of the Hybrid III dummy in a crash. Geometric, inertial, and joint properties were obtained from various measurement techniques, including static and pendulum tests (MADYMO, 1992; Heinz *et al.*, 1991; Philippens *et al.*, 1991; Wismans and Hermans, 1988).

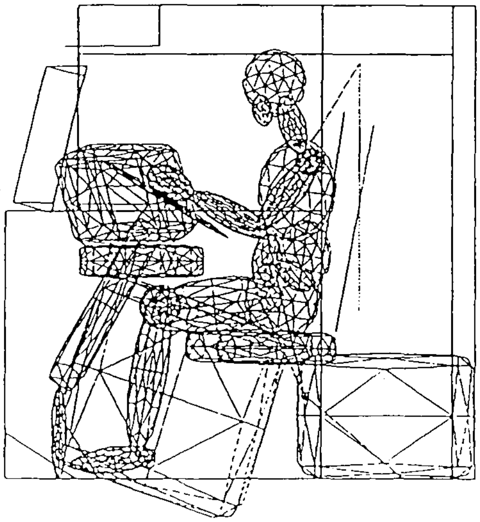

Figure 3. The occupant model is seated and three-point belted within the COE cab.

Seat Model. Most current production heavy trucks use an air suspension for the driver's seat. Lap and lower shoulder belt anchorages are then attached to the suspended portion of the seat (Figure 4). Because of the importance of the seat in providing the initial position of the occupant in a crash, and because the restraints are attached to the seat, a realistic model of the seat is necessary for the occupant dynamics simulations.

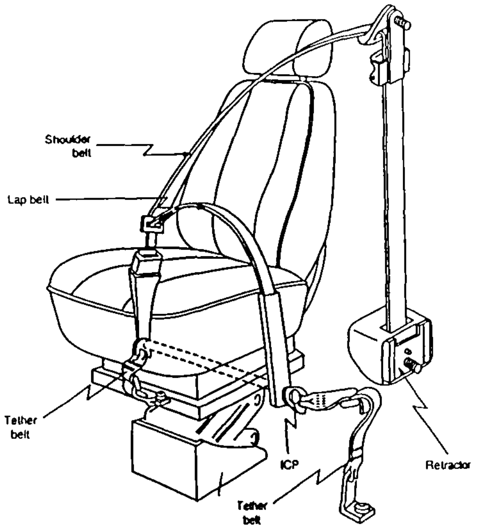

Figure 4. The tractor suspension seat features occupant seat-belt attachments to the seat bottom and tether belts continuing to the floor.

The model consists of the suspended portion of the seat attached to the cab by a translational joint which permits only vertical motion. The body that models the suspended portion captures the inertial properties of the seat bottom and back. Values for the stiffness, damping, and travel of the translational joint were chosen to be representative of values obtained from a seat manufacturer and various literature sources (Gouw *et al.*, 1990; Fairley, 1990; Palanichamy *et al.*, 1978). The accuracy of the model was verified using vibration test transmissibility data provided by a seat manufacturer.

Belt Model. The belt system used in heavy trucks is more complex than that used in automobiles because of attachments to the suspension seat, at the interconnecting points (ICP's). The ICP on each side is then connected to the floor by a tether belt. The tether belt is adjusted so that it does not restrict the movement of the seat and becomes taut when the seat is at the top of its travel. In a crash, the ICP's are designed to transfer the occupant belt load through the tether belts to the floor of the cab.

Each ICP was modeled as a separate system of negligible inertia connected to the seat by three mutually orthogonal springs. The spring characteristics were determined from a quasi-static pull test of an ICP. The model also included a wall-mounted retractor connected to one end of the shoulder harness.

The occupant and tether belt were modeled with eight segments; each segment has the force-elongation properties of a typical seat belt used in heavy truck

applications. For the lap belt, the belt properties were adjusted to account for abdominal compression.

All segments were included in the three-point belted case. For the lap belted case, the shoulder segments were removed. Only the tether belts were included in the unrestrained case.

<u>Occupant/Vehicle Interaction.</u> By representing body segments and vehicle interior components as ellipsoids and planes, the MADYMO algorithm models the interactions for ellipsoid-ellipsoid and plane-ellipsoid contacts according to the contact parameters specified by the user, which include stiffness, hysteresis, and friction.

The seat cushion force-deflection data was based on tests by Gouw and colleagues (1990); this data is similar to that provided by a seat manufacturer. Contact interaction data for the steering wheel and dashboard loading were obtained from the MADYMO data library and from published data (Nusholtz, *et al.*, 1988; Knapton, 1987). To ensure proper modeling of torso interaction with the steering wheel rim, a large contact plane was attached to the surface of the dummy abdomen so that the rim would not become trapped between two ellipsoids.

Results

A total of six frontal collision simulations were performed. These consisted of occupants in the driver's position for three different restraint conditions (three-point belt, lap belt only, and unrestrained) in two different truck cab designs (COE and conventional). All frontal collision simulations used the same crash pulse and were performed for 230 ms, 100 ms beyond the duration of the crash pulse. Tables 1 through 4 tabulate the predicted responses for the occupant and restraint system.

<u>Cab Style.</u> The differences in occupant response between the COE and conventional cab models were small. Therefore, only results for the COE model will be discussed.

<u>Three-Point Belted.</u> The crash pulse caused the driver to slide forward until his motion was arrested by a combination of interactions with the steering wheel and the dashboard and the tensioning of the lap and shoulder belts (Figure 5). The first contact made with the interior of the cab was between the abdomen and the steering wheel. This was followed by contacts between the knees and dash, and the chest and steering wheel.

The predicted contact force between the dummy abdomen and the steering wheel rim was 850 lb (3781 N) (Table 2). The maximum shoulder belt tension was 831 lb (3694 N) (Table 3). The tension on the lap and shoulder belts pulled the air seat up by the ICP's. The ICP's also deformed approximately 1 inch (2.54 cm) up and forward on the outboard side, and 2 inches (5.08 cm) up and 1 inch (2.54 cm) forward on the inboard side. The load on the inboard ICP was higher than the outboard because the lap and shoulder belts are anchored inboard, while only the lap belt is anchored outboard. The maximum tether belt load was 273 lb (1212 N) on the inboard side. The outboard tether belt experienced no loading because there was sufficient slack in the tether belt which allowed the ICP to resist the entire load.

The peak resultant acceleration and velocity data for the head, chest and pelvis are listed in Table 2. The corresponding HIC was 56 (Table 4). The computed 3-ms chest acceleration and the maximum femur load were 25 g's and 909 lb (4043 N), respectively.

<u>Lap-Belted.</u> Without the benefit of the shoulder belt, the lap-belted occupant contacted its head on the top of the steering wheel rim (Figure 5). This contact came after the abdomen and knee contacts and was primarily axial to the steering wheel. In addition, the steering-wheel-to-abdomen contact force was also increased for the lap-belt case.

The lap belt pulled on the ICP and raised the suspension seat, although the forces on the inboard ICP were less than that for the 3-point belt condition because of the absence of the shoulder belt (Table 3). The tether belts experienced no loading because the ICP's resisted the entire load without taking up all the slack available in these belts.

<u>Unrestrained.</u> With no restraint, the occupant motion is almost indiscernible from the lap-belted case up to 230 ms (Figure 5). This is because the lap belt did not develop tension to significantly affect the occupant forward excursion prior to interaction with the steering wheel rim. Beyond that, the unrestrained occupant may continue its motion forward, unlike in the lap-belted case. The abdominal force was highest for this case (Table 2).

CONCLUSIONS

Rearend collision with another heavy truck was identified as a commonly occurring accident mode that was also amenable to accident reconstruction. Through reconstruction and simulation of occupant dynamics, we have characterized the driver's response to inertial and contact loads during the collision event. These results will serve to guide design efforts to improve occupant protection in severe heavy truck accidents.

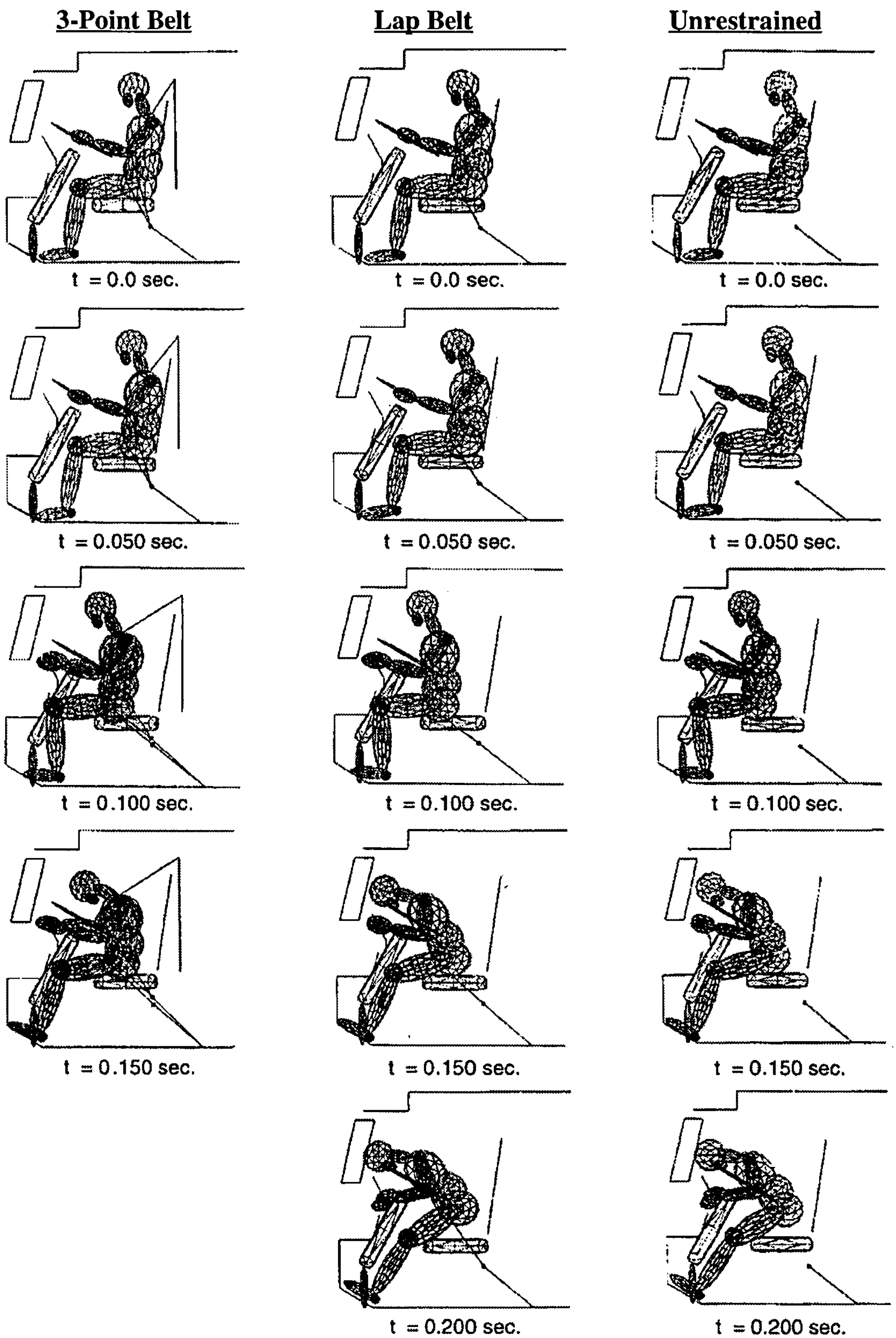

Figure 5. Occupant interaction with COE cab components varied with restraint configuration. With the use of a three-point belt, head/steering wheel contact was avoided.

Table 1.
Peak Velocity and Acceleration Results

Kinematic Response		3-Point		Lap		Unrestrained	
		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Resultant Velocity							
Pelvis	(mph)	8.4	91.0	8.8	88.7	10.9	91.4
	(m/s)	3.8		3.9		4.9	
Chest	(mph)	9.7	84.3	11.8	89.8	11.7	90.3
	(m/s)	4.3		5.3		5.2	
Head	(mph)	12.6	95.1	16.2	107.1	15.5	105.6
	(m/s)	5.6		7.2		6.9	
Resultant Acceleration							
Pelvis	(g's)	43.0	95.1	45.9	102.6	41.5	99.7
Chest	(g's)	27.7	108.2	24.3	106.0	22.3	104.5
Head	(g's)	23.2	114.1	23.3	161.4	20.5	114.1

Table 2.
Peak Resultant Contact Force Results

Resultant Contact Force		3-Point		Lap		Unrestrained	
		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Head-Steering Wheel	(lb)	No		290	161	231	182
	(N)			1290		1027	
Abdomen-Steering Wheel	(lb)	850	108	1263	119	1291	119
	(N)	3781		5618		5742	
Right Knee-Dash	(lb)	1172	103	1197	103	1378	100
	(N)	5213		5324		6129	
Left Knee-Dash	(lb)	1235	102	1162	107	1391	100
	(N)	5493		5169		6187	

Table 3.
Peak Resultant Belt and Interconnecting Point (ICP) Force Results

Resultant Belt / ICP Force		3-Point		Lap		Unrestrained	
		Peak	Time (m/s)	Peak	Time (ms)	Peak	Time (ms)
Shoulder Belt	(lb)	831	114				
	(N)	3696					
Lap Belt	(lb)	301	105	411	103		
	(N)	1339		1828			
Outboard Tether Belt	(lb)	0	0	0	0	0	0
	(N)	0		0		0	
Inboard Tether Belt	(lb)	273	108	0	0	0	0
	(N)	1214		0		0	
Outboard ICP	(lb)	305	105	393	103	0	0
	(N)	1357		1748		0	
Inboard ICP	(lb)	616	95	420	103	0	0
	(N)	2740		1868		0	

Table 4.
Peak Injury Criteria Response Results

Injury Criteria Response		3-Point		Lap		Unrestrained	
		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Left Femur Axial Load	(lb)	909	102	840	107	1080	100
	(N)	4043		3736		4804	
Right Femur Axial Load	(lb)	858	108	848	107	1065	100
	(N)	3816		3772		4737	
Chest Acceleration	(g's)	25		22		21	
Head Injury Criteria (HIC)		56		48		34	

Accident Reconstruction and Crash Pulse Development

Because of the tremendous amount of kinetic energy possessed by a moving heavy truck, an accident reconstruction technique was customized and used to characterize collision accidents. The reconstruction revealed that failure of the fifth wheel/kingpin assembly occurs at approximately 300,000 - 360,000 lb (approximately 5.5 g's for a loaded trailer). Therefore, maximum fifth wheel load, cargo tie-down strength, and trailer front end strength are among the factors that must be considered if the tractor front end is stiffened.

Model Development

The goal of SAE Phase I was in part to develop the capability for simulating occupant dynamics. This study developed and validated two truck cab computer models (COE and conventional) for simulating occupant dynamics in collision accidents. These models feature a mathematical model of an air suspension seat and three-point belt attached to the moving seat bottom and tether belts. A 22 segment occupant model was also developed to simulate occupant interaction with the truck cab and occupant responses to applied forces and accelerations.

With this model, frontal collisions in both COE and conventional cabs were simulated with the driver three-point belted, lap belted only, or unrestrained.

Cab Style

The difference in the simulation results between the COE and conventional cabs were very subtle in frontal collisions.

Restraint Effectiveness

Shoulder belt use was shown to be effective in limiting forward excursion of the upper body and preventing head impact with the steering wheel. Use of only a lap belt was less effective. Up to 230 ms, the occupant dynamics simulation predicted very little difference in occupant motion between the lap belt only and unrestrained configurations. The abdomen of the dummy struck the steering wheel independent of the restraint configuration, although, abdomen force was lowest for the three-point belt case and highest for the unrestrained case. Therefore, future studies in occupant protection should further investigate steering wheel geometry and stiffness, in addition to the design of ICP and suspension seat.

Occupant Response

For the three COE simulations, the maximum HIC, 3-ms chest acceleration, and femur load were 56 (3-point belt), 25 g's (3-point belt), and 1080 lb (4804 N) (unrestrained).

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REFERENCES

Cheng, L. Y., Werner, S. M., Khatua, T.P., Ray, R., Lau, E. (1996a) "Heavy Truck Crashworthiness – Case Studies of Heavy Truck Accidents Involving Truck Occupant Fatality." 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Australia.

Cheng, L. Y., Girvan, D. S., Werner, S. M., Khatua, T.P. (1996b) "Heavy Truck Crashworthiness -- 90° Rollover Accidents." 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Australia.

Failure Analysis Associates, Inc. (1992a) "Heavy Truck Crashworthiness, Statistical Analysis." Task A1-2 Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-92-02-11.

Failure Analysis Associates, Inc. (1992b) "Heavy Truck Crashworthiness, Accident Reconstruction." Task B Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-92-09-09.

Failure Analysis Associates, Inc. (1994) "Heavy Truck Crashworthiness, Occupant Dynamics Simulation." Task C Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-94-12-01.

Fairly, T. E. (1990) "Predicting the Transmissibility of a Suspension Seat," Ergonomics, Vol. 33, No. 2, February, 1990, pp. 121-135.

Franchini, E. (1970) "Truck Crash Testing," SAE 700411.

Girvan, D. S., Khatua, T. P., and Cheng, L. Y. (1994) "Application of the MADYMO Program in Heavy

Truck Crashworthiness" 5th International MADYMO Users' Meeting, Fort Lauderdale, Florida.

Gouw, G. J., Rakheja, S., *et al.* (1990) "Increased Comfort and Safety of Drivers of Off-Highway Vehicles Using Optimal Seat Suspension," SAE 901646, International Off-Highway & Powerplant Congress and Exposition, Sept. 10-13, 1990.

Grandel, J. and Berg, A. (1989) "Accident Tests with a View to the Analysis of and Further Development in the Safety of Road Transport Tankers," Twelfth International Technical Conference on Experimental Safety Vehicles.

Heinz M. *et al.* (1991) "An Advanced 50th Percentile Hybrid III Dummy Database", *SAE* Paper #910658.

Knapton D.A. (1987) "Static Force-Deflection Properties of Automobile Steering Components", Report DOT-TSC-NHTSA.

Krall, F. L. (1993) "The Decade of Declining Heavy Truck Fatalities -- A Tribute to the cooperative Process," SAE 933058.

Labra, J. (1960) "Impact Attenuators for Motor Vehicles - A Feasibility Study," U.S. DOT/FHWA Report No. FHWA RD-82/160.

MADYMO (1992) MADYMO databases, TNO Road-Vehicles Research Institute, The Netherlands.

Nahum A.M. and Melvin J.W. (1993) Accidental Injury, Biomechanics and Prevention, Springer-Verlag, New York.

Nusholtz G.S., Kuiker P.S. and Lehmon R.J. (1988) "Steering Wheel System Abdominal Impact Trauma." UMTRE Report No. 88-19, MVMA.

Palanichamy, M. S., *et al.* (1978) "Minimization of the Vertical Vibrations Sustained by a Tractor Operator, by Provision of a Standard-Type Tractor Seat Suspension," Annals of Biomedical Engineering, 1978, pp. 138-153.

Philippens M. *et al.* (1991) "An Advance Database of the 50th Percentile Hybrid III Dummy", *SAE* Paper # 910813.

Rice, R. S. (1981) "Heavy Truck Pilot Crash Test Rollover," DOT-HS-805-978, July, 1981.

Rice, R. S. and Shoemaker, N. E. (1981) "Heavy Truck Pilot Crash Test: Frontal Impact," U.S. DOT/NHTSA Report No. DOT-HS-805-935.

Wismans J. and Hermans J.H.A. (1988) "MADYMO 3D Simulations of Hybrid III Dummy Sled Tests", *SAE* Paper # 880645.

HEAVY TRUCK CRASHWORTHINESS -- 90° ROLLOVER ACCIDENTS

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ABSTRACT

The Society of Automotive Engineers (SAE) initiated a research program to evaluate heavy truck crashworthiness, with the goal of using that information to evaluate truck occupant protection. Phase I of this crashworthiness program entailed development of characteristic crash pulses and analysis of occupant dynamics for heavy truck accidents involving truck occupant fatalities. This paper is part of a series of reports documenting the Phase I results of the SAE heavy truck crashworthiness study. A companion study identified three major accident events in these accidents: rollover, collision with a fixed object, and collision with motor vehicle. Ninety-degree rollover accidents with and without subsequent collision were reconstructed in order to develop a representative crash pulse, which in turn was input into a dynamic model of the cab interior and occupant. Occupant dynamics analyses demonstrated the effectiveness of restraint use in occupant protection. Shoulder belt use was shown to be effective in limiting forward and lateral excursion of the upper body, but less effective in limiting vertical occupant excursions. Head impacts with the roof, roof header, and side roof rail were the most common and significant occupant impacts in the 90° rollover simulations.

INTRODUCTION

Over the past several years, considerable interest has been evidenced in the safety issues surrounding heavy trucks. Federal agencies of the United States, private groups, manufacturers, and safety researchers have voiced their concern for the need to address heavy truck crashworthiness. The Federal Motor Vehicle Safety Standards (FMVSS) involving full-scale dynamic crash test evaluations, such as FMVSS 208 -- Occupant Crash Protection, are not applicable to heavy trucks.

Echoing the concern for truck-occupant safety, the Society of Automotive Engineers (SAE) initiated a multi-phase research program to evaluate heavy truck crashworthiness.' The goal of this program is to investigate means of evaluating truck occupant protection. Phase I (SAE Phase I) of this program develops: (1) deceleration time histories ("crash pulses") that best characterize heavy truck accidents producing occupant fatalities, and (2) the capability to simulate occupant dynamics in heavy truck crashes using these developed pulses. Future phases will use the composite crash pulses and findings from the occupant dynamics simulation to develop test procedures.

Background

Hundreds of heavy truck occupants are killed in crashes every year (Clarke and Leasure, 1986, Krall, 1993). Highway safety researchers have demonstrated that heavy truck accidents are complex. Various factors associated with the operating environment, vehicle, and driver contribute to truck accident performance.

The accident behavior of heavy trucks differs significantly from the accident behavior of passenger cars. A moving heavy truck possesses an enormous amount of kinetic energy. For most heavy truck crashes involving truck occupant fatality, dissipation of this large amount of energy results in a complex sequence of crash events such as skidding, minor and major impacts, jackknifing and rollover. A thorough understanding of the nature of heavy truck accidents resulting in truck occupant fatalities is therefore an essential first step in the evaluation of truck occupant protection.

Approach

As described in a companion paper (Cheng, *et al.*, 1996a), sets of accident scenarios that characterize heavy truck accidents were developed through a statistical analysis of the Fatal Accident Reporting System (FARS), (FaAA, 1992a). This analysis revealed that most of the accidents involve some combination of rollover, collision with fixed object, and collision with motor vehicle.

The files of the National Transportation Safety Board (NTSB) were reviewed because they contain detailed investigations into a sub-set of the FARS accidents. Sixty-eight of the 182 NTSB cases studied were selected for detailed review; outlying cases were not considered. This group of 68 NTSB cases forms the group upon which accident reconstructions were performed. Damage patterns unique to heavy truck collisions and rollovers were identified. This provided guidance for crash pulse development and dynamic simulation.

In this paper, we discuss the reconstruction and occupant dynamics simulation of rollover accidents. The current study focuses on 90° rollover with and without subsequent collisions. Work involving trucks rolling 180° onto their roofs is in progress.

A companion paper (Cheng, *et al.*, 1996b) describes the reconstruction and occupant dynamics simulation for frontal collision accidents.

ACCIDENT RECONSTRUCTION

The accident behavior of heavy trucks differs significantly from that of passenger cars. The crucial distinction between automobile and truck rollovers is the vehicles' different stability characteristics. A typical passenger car has a lateral stability coefficient of about 1.3 (Garrot, *et al.*, 1988). A tripping mechanism such as a curb or soil is generally necessary to induce automobile rollover. Heavy trucks, on the other hand, have stability ratios ranging from 0.38 for a fully loaded van trailer to 1.10 for a tractor without a trailer (FaAA, 1992b). For these trucks, tripping is not necessary to initiate rollovers.

Because passenger car rollovers are generally initiated by a tripping mechanism, it is not uncommon for passenger cars to roll more than one full rotation. Of the heavy trucks involved in the rollovers from the 68-case NTSB sample, only 9% rolled more than 180°, and 47% rolled only 90°; the remainder rolled 180°.

The wide variety of rollover conditions and vehicle configurations complicates the analysis of heavy truck rollovers. The observations of NTSB accident trends proved quite valuable in understanding this complex problem (FaAA, 1992b). First, that study revealed that the type of trailer strongly influences whether a vehicle will roll more than 90°. The similarity in damage between all 90° rollovers without subsequent collisions suggests that the rollover crash pulse is not sensitive to accident conditions such as the vehicle speed. These observations suggest that vehicle mass and geometric properties are the more important parameters influencing the ground impact during a 90° rollover.

Ground Impact Velocity at 90° Rollover

A reconstruction technique based on conservation of energy was developed to analyze the ground impact velocity at 90° rollover.

Review of literature and crash test footage showed that the trailer is less stable than the tractor and typically pulls the tractor over. Based on this observation, the trailer rollover rate at impact was determined by work-energy techniques. The impact velocity of the tractor was then computed from the trailer roll rate.

The tractor and trailer were treated as one rigid body in the analysis. This rigid body assumption can underestimate the tractor impact velocity for flatbed trailers, which are inherently more flexible than van or tank trailers and can twist during the rollover. A separate analysis indicates that trailer flexibility ("wind-up") can cause an increase in impact velocity by a maximum of 50% over that predicted using this method (FaAA, 1994).

In the analysis, a lateral overturning acceleration equal to the rollover stability coefficient, $T/2h$, was applied to the vehicle to induce rollover, where T is track width and h is center-of-gravity (CG) height. Work is done by this overturning acceleration as long as the truck tires maintain contact with the ground.* Since it is unknown when the tires leave the ground, three different acceleration profiles were examined, allowing upper, middle, and lower bounds on the ground impact velocity (Figure 1).

This methodology was applied to various vehicle configurations:

Tractor,
Empty Van Trailer,
Van, Full Gross, Medium Density,
Van, LTL Freight,
Van, Full Gross, Full Cube,
Empty Tanker,
Full Tanker,
Empty Flat Bed, and
Full Flat Bed.

* FaAA performed a rollover test involving a straight truck traveling at an initial velocity of 50 mph (22.4 m/s). When subjected to full steering to the left, the vehicle rolled, became airborne at approximately 60° of roll, and rolled 90° when it came to a stop. Although the truck initial velocity was 50 mph (22.4 m/s), the vehicle damage was minimal.

Tractor dimensional and inertial properties found in the literature were used to compute lateral impact velocities (NHTSA, 1986; Francher and Mathew, 1987). For each lateral acceleration profile in Figure 1, the work done by the lateral overturning force and the change in potential energy were equated to the increase in kinetic energy of the trailer going from 0° to 90° roll angle. The computed tractor CG impact velocities (v), range from 3 to 6 mph (for the loaded configurations) depending upon the trailer configuration and the lateral acceleration profile considered. The relatively low magnitude and small range of these impact velocities are consistent with the minimal amount of damage observed in the NTSB files.

Ground Impact Deceleration at 90° Rollover

The energy method was used to reconstruct three 90° rollover accidents without subsequent collision selected from the 68-case NTSB cases. Review of the case files showed that all three of the vehicles rolled over due to instability. The vehicles sustained the characteristic 90° rollover crash pattern, with crush increasing linearly from the bottom of the tractor to the cab roof (Cheng, *et al*, 1996a).

Tractor crush distance, d, was estimated from photographs of each accident, and was used as a measure of stopping distance to compute average tractor CG acceleration, a:

$$a = \frac{v^2}{2d} \qquad (1.)$$

Average CG deceleration for the three cases ranged from 3 to 6 g's, and average pulse duration ranged from 0.04 to 0.06 seconds. It should be noted that these decelerations may be overestimated and durations underestimated because of the approximation in estimating crush and the fact that ground deformation was ignored. Nevertheless, these results agree with data gathered from instrumented wall testing by Mak and Beason (1988). One instrumented wall test produced a damage pattern to a COE tractor similar to that observed in an NTSB 90° rollover accident without a subsequent collision. Based on the measured impact force data, the peak tractor deceleration was estimated to be approximately 4.4 g's.

Subsequent Collision

Data on cab structural stiffness and strength for heavy trucks are not available in the open literature. This makes analysis of subsequent collision difficult. The case selected for reconstruction here was a right-side rollover with subsequent collision with on oncoming passenger car. The car struck the right top corner of the cab above the windshield producing significant roof crush typically seen in rollover accidents with a subsequent collision. Because the energy to crush the front end of the passenger car was quantifiable from crash test data, the impact force, F, was estimated from the crush energy, E_{crush}, and the crush distance, d, as follows:

$$F = \frac{E_{crush}}{d} \qquad (2.)$$

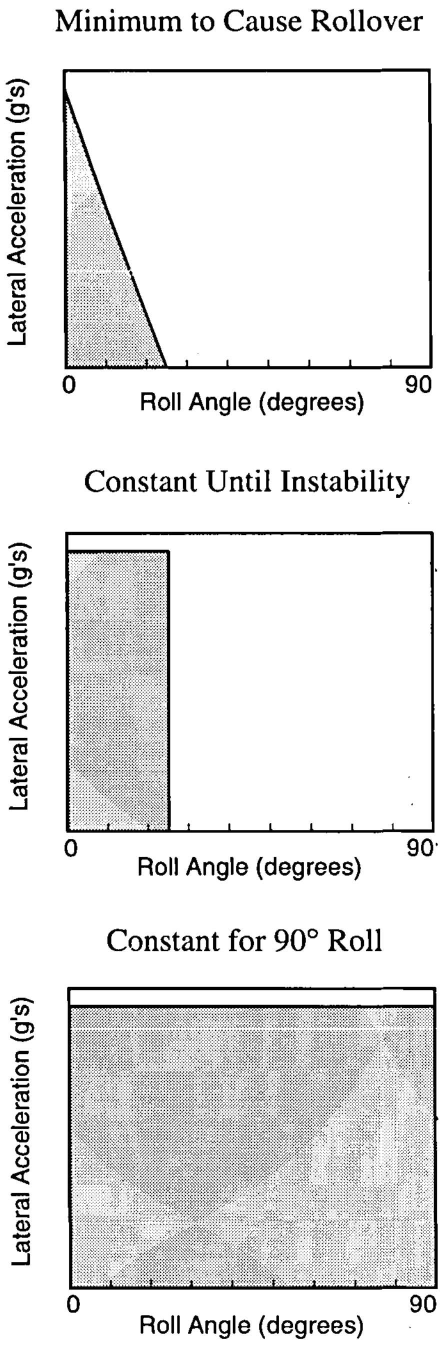

Figure 1. The applied acceleration profiles provide an upper, middle, and lower bound on the calculated impact velocity.

A cab deceleration of 2.5 g's was computed by dividing the impact force by the cab mass. Note that this analysis of the cab deceleration for a subsequent impact is based on simplifying assumptions and on accident reconstruction of a single case.

CRASH PULSE DEVELOPMENT

Based on the findings of the accident reconstructions, a representative crash pulse was developed for both the rollover portion and subsequent collision accident events. A generic crash pulse shape was characterized by the magnitude of the deceleration and the pulse duration.

Crash Pulse Shape

The generic crash pulse profile takes the form of

$$a(t) = \frac{1}{2} A \left[1 - \cos\left(\frac{2\pi\, t}{T} \right) \right] \qquad (3.)$$

where A is peak acceleration and T is pulse duration. The quantities A and T completely characterize the crash pulse. A similar pulse shape defines the angular counterpart:

$$\alpha(t) = \frac{1}{2} \alpha_{max} \left[1 - \cos\left(\frac{2\pi\, t}{T} \right) \right] \qquad (4.)$$

where α_{max} is the maximum angular deceleration. Note that the average decelerations, a_{ave} = $A/2$, and $\alpha_{ave} = \alpha_{max}/2$.

Rollover Motion

To perform the occupant dynamics simulations of rollover accidents, a full description of the rollover motion of the tractor is necessary. For this purpose, a single degree of freedom (SDOF) rollover model of a typical trailer (full gross, medium density) was developed. This analysis assumes that the axis of rotation (pivot) for the trailer during a roll is at the tire-ground interface of the outside tires. The forces acting on the trailer are gravity and the lateral overturning force. The resulting trailer rollover behavior was then used to approximate that of the tractor.

In this model, the lateral acceleration that initiates the roll was assumed to act throughout the rollover motion (upper bound curve in Figure 1). The magnitude of the lateral acceleration was set at 0.54 g, which is greater than the 0.47 g necessary to initiate rolling of the typical trailer (FaAA, 1992b). This 0.54 g value was chosen because it causes the 90° rollover to occur in approximately two seconds, a duration which approximates that observed in several real truck rollover tests.

The resulting roll angle time history, as shown in Figure 2, is consistent with observed motion of a truck rollover. At 90° roll, the analysis yielded a tractor roll rate of 172 deg/s and a lateral velocity of 6 mph (2.7 m/s), at the CG of the tractor, in agreement with the accident reconstruction results discussed previously.

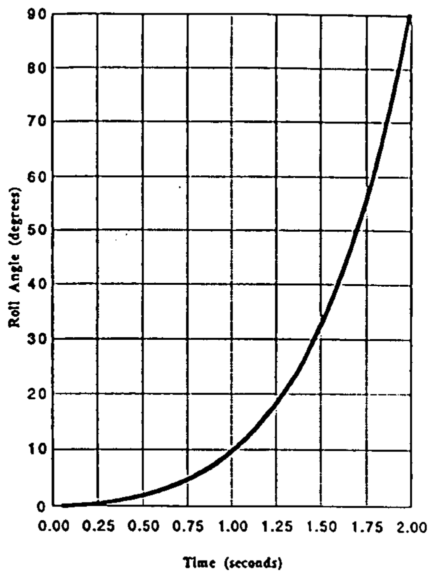

Figure 2. Rollover Phase -- Roll Angle Time History.

A more complex computer model of a truck rollover was developed to assess the accuracy of the SDOF model (FaAA, 1994). This three-degree-of-freedom (TDOF) rollover model allowed vertical and lateral truck motion in addition to the rotational motion. Results showed that the less complex SDOF model provides reasonable predictions of the truck rollover motion, and was therefore chosen to serve as the basis for occupant dynamics simulations of rollover accidents.

Ground Impact at 90° Roll

The crash pulse at ground impact was evaluated using the computed tractor roll rate of 172 deg/s from the SDOF rollover model, and an impact duration of 50 ms from reconstruction of the three NTSB cases discussed above. The parameters for the resulting roll angular deceleration profile (Equation 4) are:

α_{max} = 120 rad/s^2
α_{ave} = 60 rad/s^2
T = 50 ms

This crash pulse completely characterizes the motion of the tractor during ground impact at 90° rollover

(Figure 3). This profile depicts the tractor motion about the pivot, which is the location to which motion is specified in the occupant dynamics model. The deceleration generated by friction, of the order of 0.5 to 1.0 g, was not included in the occupant dynamics simulation. Also, the simulations did not incorporate any crushing to the side of the cab; it is general small in 90° rollover accidents (Cheng, *et al*, 1996a).

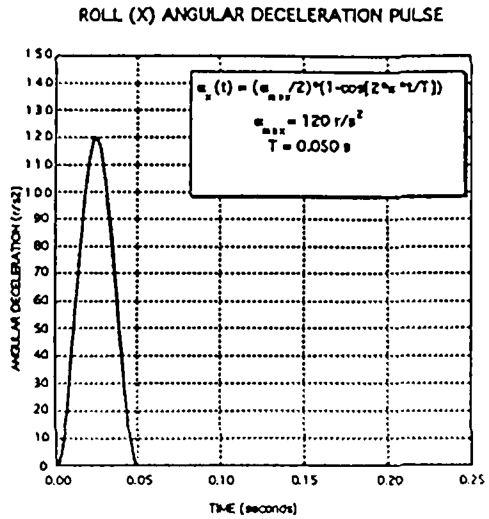

Figure 3. Crash Pulse -- 90° Rollover without Subsequent Collision.

90° Rollover with Subsequent Collision

As a conservative measure, the subsequent collision was modeled using both the longitudinal and the vertical decelerations. For the occupant dynamics simulations, both deceleration components begin immediately after the completion of the truck rollover crash pulse.

<u>Longitudinal Component.</u> The longitudinal component was assumed to be no greater than that determined for frontal collisions (about 5.5 g's average; Cheng, *et al*, 1996b). This is a reasonable deceleration limit since this impact geometry is subject to the same kingpin/fifth wheel limitations as frontal collisions. The parameters for the resulting longitudinal deceleration profile (Equation 3, Figure 4) are:

A = 11 g's,
a_{ave} = 5.5 g's, and
T = 130 ms.

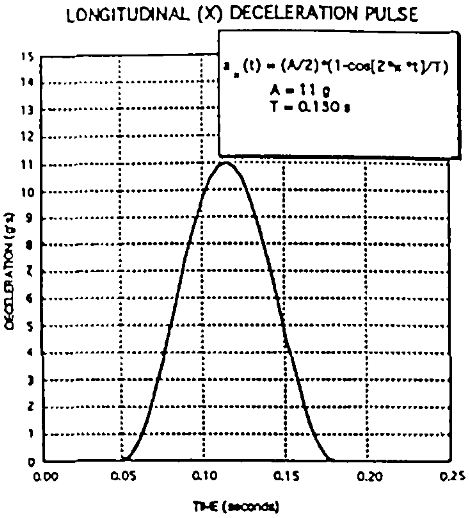

Figure 4. Longitudinal Crash Pulse -- 90° Rollover with Subsequent Collision.

<u>Vertical Component.</u> The vertical component of this crash pulse was estimated above in the accident reconstruction section. The parameters for the resulting vertical deceleration profile (Equation 3, Figure 5) are:

A = 5 g's,
a_{ave} = 2.5 g's, and
T = 190 ms.

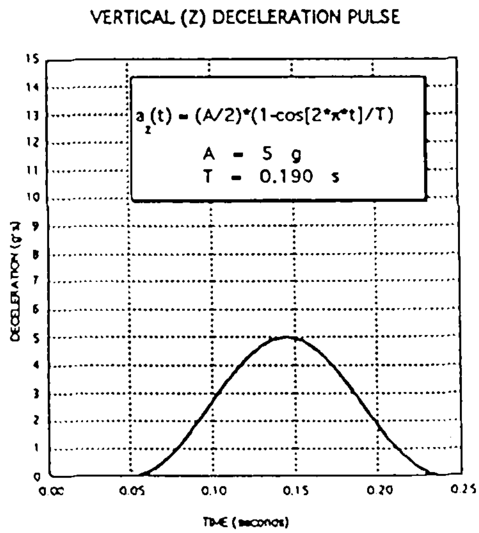

Figure 5. Vertical Crash Pulse -- 90° Rollover with Subsequent Collision.

OCCUPANT DYNAMICS SIMULATIONS

Part of SAE Phase I was to develop the capability to simulate occupant dynamics in heavy truck crashes. These simulations can then be utilized to determine peak occupant excursions, identify occupant impact velocities and locations, demonstrate the differences in occupant response for different restraint configurations,

provide information for the design of test procedures, and guide future investigations into truck occupant protection.

The MADYMO computer simulation package was chosen for the occupant dynamics simulations (Heinz, *et al.*, 1991; Philippens, *et al.*, 1991; Wismans and Hermans, 1988). The crash pulses defined above were used as input for the occupant dynamic in rollover accidents. Vehicle cab crush was not included in the current model.

Simulation Matrix

Review of the NTSB case files revealed a relatively even distribution in direction of rollover for accidents involving fatal truck occupants. Simulations were performed to analyze both near-side and far-side rollovers.

Table 1.
Scenarios and Restraint Configurations for Truck Rollover Simulation

Restraint	90° Rollover	90° + Collision
3-Point	Near-side	Near-side
Lap Only	Near-side	Far-side
Unrestrained	Far-side	Near-side

MADYMO Model

In constructing the MADYMO model, cab interior geometry, occupant properties (segment geometry, inertial properties, and joint properties), and occupant/vehicle contact interaction properties must be specified. The model development is outlined below and a more detailed description is found in the companion paper (Cheng, *et al.*, 1996b).

MADYMO has performed validation of data sets for various dummy models (Heinz, *et al.*, 1991; Philippens, *et al.*, 1991; Wismans and Hermans, 1988). FaAA specifically performed validation of the model for simulating heavy truck rollover accidents (Girvan, *et al.*, 1994).

<u>Cab Interior Geometry.</u> A typical cab interior model was developed for both the COE and conventional tractor designs. This typical cab model was chosen based on the cab with the interior geometry closest to the computed average of key dimensions from several different cabs.

<u>Occupant Model.</u> The occupant properties were based on the Hybrid III anthropomorphic crash dummy from the MADYMO data library (MADYMO, 1992; Heinz, *et al.*, 1991; Philippens, *et al.*, 1991; Wismans and Hermans, 1988).

<u>Seat Model.</u> Most current heavy trucks use an air suspension for the driver's seat. Lap and lower shoulder belt anchorages are then attached to the suspended portion of the seat. Because of the importance of the seat in providing the initial position of the occupant in a crash, and because the restraints are attached to the seat, a realistic model of the seat is necessary for the crash simulations.

<u>Belt Model.</u> The belt system used in heavy trucks is more complex than that used in automobiles because of attachments to the suspension seat, the interconnecting points (ICP). The ICP on each side is then connected to the floor by a tether belt. The tether belt is adjusted so that it does not restrict the movement of the seat and becomes taut when the seat is at the top of its travel. Each ICP was modeled as a separate system of negligible inertia connected to the seat by three mutually orthogonal springs. The occupant and tether belts were modeled with eight segments; each segment has the force-elongation properties of a typical seat belt used in heavy truck applications.

<u>Occupant/Vehicle Interaction.</u> By representing body segments and vehicle interior components as ellipsoids and planes, the MADYMO algorithm models the interactions for ellipsoid-ellipsoid and plane-ellipsoid contacts according to the contact parameters specified by the user, which include stiffness, hysteresis, and friction.

Results

A total of twelve rollover simulations were performed with varying restraint configurations, cab designs, direction of roll, and presence or absence of subsequent collision. All simulations used the same rollover motion with a superimposed lateral acceleration of 0.54 g acting over the entire duration of the rollover prior to ground impact (2 seconds). They also used the same ground impact crash pulse (50 ms). In cases of subsequent collision, the longitudinal and vertical collision crash pulse was applied immediately following the cessation of the ground impact.

<u>Cab Style.</u> For near-side rollover cases, the results for the conventional cabs were similar to those for the COE's. The far-side cases exhibited differences, especially for the unrestrained occupant. This difference occurs because the COE has an engine tunnel, while the conventional cab is open between the driver and passenger sides. In this paper, results for only the COE cab style will be reported; the interested

reader is referred to the full report for results for the conventional cab (FaAA, 1994).

Three-point Belted Occupant in a Near-Side 90° Rollover without Subsequent Collision. During the initial stages of the rollover, the occupant leaned to the left under the influence of the applied lateral acceleration (Figure 6). The occupant leaned against the door and side window and contacted the side window with the head at approximately 340 ms. Near the end of the rollover phase, the occupant lagged slightly behind the vehicle. At ground impact, the occupant moved laterally within the cab, impacting the door and side window at approximately 15 mph (6.7 m/s).

Maximum occupant and restraint responses for this and all other simulations are listed in Tables 2 through 5.

Lap-Belted Occupant in a Near-Side 90° Rollover without Subsequent Collision. The results of the lap-belt case were very similar to the three-point belt case. This result could be expected given the extensive occupant interaction with the door, leading to low shoulder belt loads in the 3-point restraint case.

Unrestrained Occupant in a Far-Side 90° Rollover without Subsequent Collision. In this accident scenario, the driver began by leaning to the right and continued until the occupant was lying sideways on the engine tunnel (Figure 6). At ground impact, the occupant was projected outward and impacted the roof. The occupant then fell head first into the bottom of the cab, impacting the passenger side roof rail with its head. Although some of the predicted injury parameters were low, the benefits of restraints were clearly demonstrated in this simulation.

Three-Point Belted Occupant in a Near-Side 90° Rollover with Subsequent Collision. The occupant motion during the rollover phase has already been described. The collision subsequent to the rollover caused the occupant to move forward and up relative to the vehicle. The three-point belt was effective in limiting the occupant excursion, and prevented any significant impacts during the subsequent collision. As a result, the peak occupant responses for this simulation were essentially the same as for the 90° roll without subsequent collision simulation.

Lap-Belted Occupant in a Far-Side 90° Rollover with Subsequent Collision. During the rollover phase, the occupant leaned to the right against the engine tunnel (Figure 6). As the roll angle increased past approximately 45°, the occupant started to lag behind the rolling truck. By 90° roll, the occupant was nearly upright within the truck in the seated position. The ground impact caused the occupant to move vertically and laterally within the cab, with the head impacting the roof. During the subsequent collision, the occupant moved forward and struck the roof header with its head near the vehicle centerline. Although the HIC was only 281, the head-roof peak contact force was 1,929 lbs (8,580 N), and the peak neck loading was over 1,300 lbs (5,782 N). Comparison of this simulation with the unrestrained case demonstrates that the lap belt was effective in reducing the lateral excursion of the occupant in a far-side rollover.

Unrestrained Occupant in a Near-Side 90° Rollover with Subsequent Collision. The unrestrained occupant's motion during the rollover phase was similar to that exhibited by the three-point belt counterpart. During the subsequent collision, the occupant moved forward and upward within the cab, striking its head on the roof and roof header. The peak impact force between the head and the roof header was 1,673 lbs (7,440 N) as compared to 18 lbs (80 N) for the three-point belt case.

CONCLUSIONS

Rollover accidents with and without subsequent collision were identified as commonly occurring accident modes that were also amenable to accident reconstruction. Through reconstruction and simulation of occupant dynamics, we have characterized the driver's response to inertial and contact loads during the 90° rollover with and without subsequent collision events. These results will serve to guide design efforts to improve occupant protection in severe heavy truck accidents.

Accident Reconstruction

The analytical method developed in this study was used to reconstruct three NTSB cases involving 90° rollovers without subsequent collision. Results from the reconstruction and crash tests indicate that average deceleration levels of 3-6 g's in the lateral direction can be expected. Lateral impact velocities are approximately 3-6 mph on flat terrain.

<u>3-Point Belted in Near-Side Rollover without Subsequent Collision</u> | <u>Unrestrained in Far-Side Roll without Subsequent Collision</u> | <u>Lap-Belted in Far-Side Roll with Subsequent Collision</u>

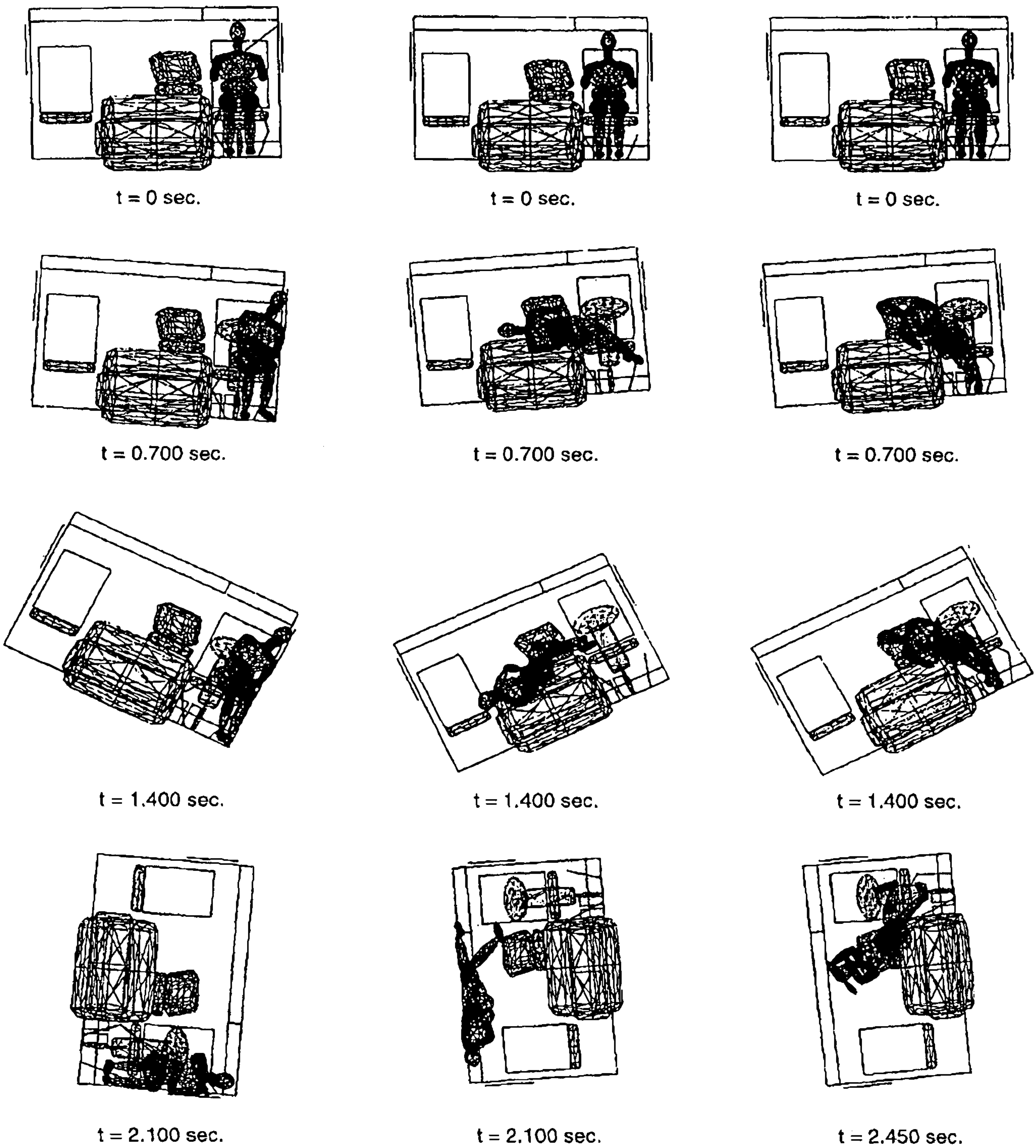

Figure 6. Occupant Dynamics Simulation Results for Three Different Accident Sequences.

Table 2.
Peak Velocity and Acceleration Results

		Without Subsequent Collision						With Subsequent Collision					
Restraint Direction of Roll		3-Point Near		Lap Near		Unrestrained Far		3-Point Near		Lap Far		Unrestrained Near	
Kinematic Response		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Resultant Velocity													
Pelvis	(mph)	13.5	1997	13.5	1998	16.6	2065	13.5	1997	15.2	1995	14.7	2015
	(m/s)	6.0		6.0		7.4		6.0		6.8		6.6	
Chest	(mph)	15.4	2024	15.4	2024	15.7	2069	15.4	2024	15.0	1989	16.7	2011
	(m/s)	6.9		6.9		7.0		6.9		6.7		7.5	
Head	(mph)	17.3	1997	17.4	1995	15.8	2065	17.3	1997	14.5	1974	18.4	1991
	(m/s)	7.7		7.8		7.1		7.7		6.5		8.2	
Resultant Acceleration													
Pelvis	(g's)	51.2	2047	51.1	2047	28.4	2107	50.1	2047	23.2	2029	50.3	2034
Chest	(g's)	54.0	2042	54.8	2042	30.4	2107	54.3	2042	22.3	2028	58.9	2032
Head	(g's)	181.3	2038	195.5	2039	77.6	2076	181.1	2038	75.7	2026	144.0	2030

Table 3.
Peak Resultant Contact Force Results

		Without Subsequent Collision						With Subsequent Collision					
Restraint Direction of Roll		3-Point Near		Lap Near		Unrestrained Far		3-Point Near		Lap Far		Unrestrained Near	
Resultant Contact Force		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Side Window-Chest	(lb)	258	2045	262	2045			262	2045			241	2037
	(N)	1148		1165				1165				1072	
Side Window-Head	(lb)	385	344	763	333			385	344			819	329
	(N)	1712		3394				1712				3643	
Roof-Head	(lb)	171	2019	177	2021	1699	2076	171	2019	1929	2030	998	2208
	(N)	761		787		7557		761		8580		4439	
Side Roof Rail-Head	(lb)	1991	2042	2135	2042	851	2157	2085	2042			2091	2485
	(N)	8856		9496		3785		9274				9301	
Header-Head	(lb)							18	2143	1223	2124	1673	2134
	(N)							80		5440		7442	

Table 4.
Peak Resultant Belt/ICP Force Results

		Without Subsequent Collision						With Subsequent Collision					
Restraint Direction of Roll		3-Point Near		Lap Near		Unrestrained Far		3-Point Near		Lap Far		Unrestrained Near	
Resultant Belt/ICP Force		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Shoulder Belt	(lb)	150	2199					1113	2140				
	(N)	667						4951					
Lap Belt	(lb)	407	2046	407	2046			687	2130	903	2160		
	(N)	1810		1810				3056		4017			
Outboard Tether Belt	(lb)	346	2046	343	2046	178	2026	633	2127	633	2034	26	2141
	(N)	1539		1526		792		2816		2816		116	
Inboard Tether Belt	(lb)	131	2032	129	2033	86	2026	927	2133	803	2148	0	0
	(N)	583		574		383		4123		3572		0	
Outboard ICP	(lb)	193	2046	194	2046	175	2026	192	2046	537	2166	63	1991
	(N)	858		863		778		854		2389		280	
Inboard ICP	(lb)	363	2039	361	2040	82	2027	665	2130	290	2036	63	1991
	(N)	1615		1606		365		2958		1290		280	

Table 5.
Peak Injury Criteria Response Results

		Without Subsequent Collision						With Subsequent Collision					
Restraint Direction of Roll		3-Point Near		Lap Near		Unrestrained Far		3-Point Near		Lap Far		Unrestrained Near	
Injury Criteria Response		Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)	Peak	Time (ms)
Left Femur Axial Force	(lb)	84	2044	144	2043	1387	2059	339	2316	421	2138	386	2136
	(N)	374		641		6169		1508		1873		1717	
Right Femur Axial Force	(lb)	118	2111	130	2058	476	2079	167	2109	181	2073	951	2137
	(N)	525		578		2117		743		805		4230	
Chest-Neck Resultant Force	(lb)	761	2042	864	2042	954	2076	846	2042	1319	2028	1371	2134
	(N)	3385		3843		4243		3763		5867		6098	
Neck-Head Resultant Force	(lb)	858	2042	969	2042	1042	2076	949	2042	1402	2028	1475	2134
	(N)	3816		4310		4635		4221		6236		6561	
Chest Acceleration	(g's)	44.8		43.6		28.6		45.2		22.1		47.8	
Head Injury Criteria (HIC)		1172		1181		231		1141		281		677	

Restraint Effectiveness

Occupant dynamics analyses demonstrated the effectiveness of restraint use in occupant protection. For example, in far-side rollovers, the simulations demonstrated that lap belt use alone would control occupant excursion and prevent ejection.

Shoulder belt use was shown to be effective in limiting forward excursion of the upper body. In the collision subsequent to a rollover accident, use of the shoulder belt significantly reduced forward excursions, preventing potentially injurious head impact with the roof header. The use of lap belt alone was less effective.

Restraint use also dramatically reduced occupant lateral excursion in far-side rollovers. It was less effective in limiting vertical occupant excursions, due to the direction of movement relative to the belt, the compliance of the occupant lap, and the vertical movement allowed by the suspension seat.

In near-side rollovers without subsequent collision, shoulder belt use was shown to have little to no effect on the occupant response. In these cases, extensive occupant interaction with the driver door took place. As a results, the shoulder belt experienced very low loads.

The collision subsequent to rollovers produced higher shoulder, lap, and tether belt loads than the other cases (of the order of 1,000 lb, or 4,500 N). The ICP load was also increased to 665 lb (3,000 N).

Cab Style

The COE and conventional cabs exhibited similar responses for near-side rollovers. The engine tunnel in the COE cab altered the occupant dynamics in the far-side rollover, especially for the unrestrained case.

Occupant Response

Head impacts with the roof, roof header, and side roof rail were the most common and significant occupant impacts in the rollover simulations. The most significant of these occurred in far-side rollover when the occupant was projected upward and to the right into the roof. Head impacts with the side roof rail occurred during ground impact at 90° for near-side rollovers, independent of the restraint configuration.

In several rollover cases, HIC value of around 1,000 resulted when the dummy head impacted the roof, roof header or side roof rail. Of all rollover simulations, the peak 3-ms chest acceleration was 48 g's. The maximum femur loads were generally low in 90° rollovers (less than 1,000 lbs, or 4,500 N per leg). The only femur load over 1,000 lbs occurred in a far-side unrestrained simulation during which the occupant impacted the roof with its knee.

High neck loads occurred in several of the scenarios, particularly for the unrestrained occupant in all scenarios and for the lap-belted occupant in the far-side rollover with subsequent collision.

For all these rollover simulations (including conventional cabs), peak chest impact velocities were approximately 13 - 18 mph (5.8 - 8.0 m/s), while peak head velocities were 13 - 20 mph (5.8 - 8.9 m/s).

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REFERENCES

Cheng, L. Y., Werner, S. M., Khatua, T.P., Ray, R., Lau, E. (1996a) "Heavy Truck Crashworthiness – Case Studies of Heavy Truck Accidents Involving Truck Occupant Fatality." 15th International Technical Conference on the Enhanced Safety of Vehicles, Melbourne, Australia.

Cheng, L. Y., Werner, S. M., Girvan, D.S., Khatua, T. P. (1996b) "Heavy Truck Crashworthiness -- Collision Accidents." 15th International Technical Conferences on the Enhanced Safety of Vehicles, Melbourne, Australia.

Failure Analysis Associates, Inc. (1992a) "Heavy Truck Crashworthiness, Statistical Analysis." Task A1-2 Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-92-02-11.

Failure Analysis Associates, Inc. (1992b) "Heavy Truck Crashworthiness, Accident Reconstruction." Task B Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-92-09-09.

Failure Analysis Associates, Inc. (1994) "Heavy Truck Crashworthiness, Occupant Dynamics Simulation." Task C Report for Phase I Study on Heavy Truck Crashworthiness, FaAA Report No. SF-R-94-12-01.

Fancher, P. S. and Mathew, A. (1987) "A Vehicle Dynamics Handbook for Single-Unit and Articulated

Heavy Trucks," U.S. DOT/NHTSA Report No. DOT-HS-807-185.

Garrott, W. R., Monk, M. W. & Chrstos, J. P. (1988) "Vehicle Inertial Parameters - Measured Values and Approximations," SAE Publication No. 881767.

Girvan, D.S., Cheng, L.Y. and Khatua, T.P. (1994) "Application of the MADYMO Program in Heavy Truck Crashworthiness" 5th International MADYMO Users' Meeting, Fort Lauderdale, Florida.

Heinz M. *et al.* (1991) "An Advanced 50th Percentile Hybrid III Dummy Database", *SAE* Paper #910658.

MADYMO (1992) MADYMO databases, TNO Road-Vehicles Research Institute, The Netherlands.

Mak, K. K., Beason, W. L., Hirsch, T. J. and Campise, W. L. (1988) "Oblique Angle Crash Tests of Loaded Heavy Trucks into an Instrumented Wall," U.S. DOT/NHTSA Report No. DOT-HS-807-256.

Nahum A.M. and Melvin J.W. (1993) Accidental Injury, Biomechanics and Prevention, Springer-Verlag, New York.

National Highway Traffic Safety Administration (1986) "A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks," U. S. DOT/NHTSA Report No. DOT-HS-807-125.

Philippens M. *et al.* (1991) "An Advance Database of the 50th Percentile Hybrid III Dummy", *SAE* Paper # 910813.

Rice, R. S. (1981) "Heavy Truck Pilot Crash Test Rollover," DOT-HS-805-978, July, 1981.

Wismans J. and Hermans J.H.A. (1988) "MADYMO 3D Simulations of Hybrid III Dummy Sled Tests", *SAE* Paper # 880645.

VEHICLE ROLLOVER AND OCCUPANT RETENTION

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ABSTRACT

Research on real-world coach accidents reveals a high level of tipover and rollover accidents. It also shows that the main occupant injury mechanism is due to the insufficient protection offered by the roof structures in this type of accident.
The aim of this paper is to shed some light on these questions, using information gathered from two separate sources:
. A series of three experimental crash tests using road ready vehicles.
. Accident research on 16 real-world accidents.
Comparing and correlating the results of these two studies provides a mine of information which is essential for designing the countermeasures necessary to enhance occupant protection.

INTRODUCTION

This paper sets out the results of work performed on a particular accident typology for passenger transport vehicles: ROLLOVER.

Statistical analysis of coach and bus accidents shows that the proportion of fatalities each year in France in this type of vehicles remains very small relative to the total number of deaths on the road, with 0.3% of fatalities at 6 days. However, somewhat paradoxically the occurrence of this type of accident always results in a very strong media outcry.

Among the most frequent types of coach accidents are rollovers, that will be analysed in this study on the one hand through 16 cases of real-world accidents of this type and on the other hand through three cases of experimental impacts of the "static rollover of coach in operating condition" type.

Finally, this paper should make it possible to define all the countermeasures needed to improve the safety and protection of passengers in this type of accident.

STUDY OF 16 CASES OF REAL-WORLD ACCIDENTS

The "engineer-doctor" multi-disciplinary survey carried out since 1980 covers, to date, 62 public transport vehicles involved in severe road accidents throughout France. Of these cases, 16 are of the "rollover, landing on right or left side" type.

The study performed in the days following the accident consists of:

. Analysis of the accident circumstances, with a study of the site of the accident, the infrastructure, traffic and weather conditions. A precise plan is drawn up for the pre-collision, collision and post-collision phases.

. Technical examination of the vehicle, covering all matters relating to passive safety.

. Measurements and photographs taken of both exterior and interior deformation. Very special care is taken in inspecting the seats and their direct environment. The characteristics, deformation and any occupant impacts are systematically inventoried.

. Acquisition of a knowledge of the position occupied by each passenger, determined from hearings carried out by the police force, interviews performed by accident research workers and the questionnaires sent out to those involved in accidents.

. Medical report on each occupant, requested of the hospitals.

In coach rollover occurrences, the studies performed show that four particular circumstances will determine the extent of severity of the final medical consequences. These four circumstances are as follows:

. the fact that rollover occurs against a fixed barrier or not;

. the fact that the coach is single- or double-decker;

. the presence or absence of sliding over the ground after rollover, depending on the energy remaining to be dissipated;

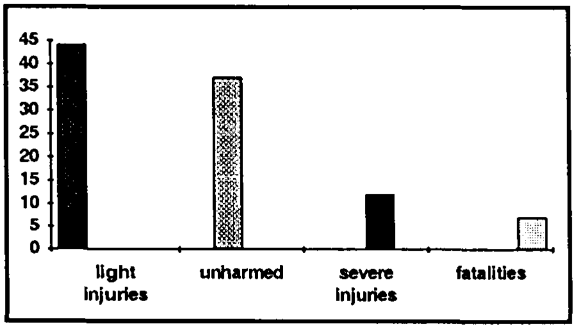
. the presence or absence of structural deformation of the vehicle, which will influence the effects on humans.

The analysis of these 16 real-world coach and bus accidents will therefore be performed as a function of these four circumstances which will lead to highly variable levels of severity from one case to another.

Sample:
15 coaches;
1 bus;
accidents causing bodily harm with victims on board;
rollover with final immobilization of the vehicle on one side;
direction of rollover: 9 right side, 7 left side.

Within the 16 accidented vehicles was a population of 727 occupants (passengers and drivers). The diagram below shows the severity of injuries.

Figure 1.
Breakdown of the 727 occupants according to injury severity



The overall severity index for this impact configuration is:

- 19% of fatalities and severe injuries;
- 81% of light injuries and unharmed.

This severity index is in every way similar to that known to us for all coach accidents, considering all impact configurations together.

The severity index adopted as a reference for this study is therefore as follows:
Severity index = Number of fatalities + number of severe injuries / number of occupants.

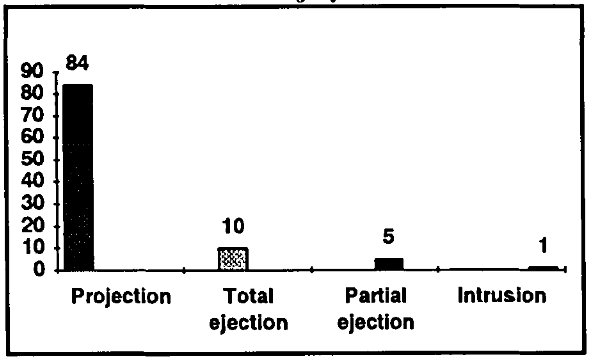
Study of the injury mechanisms for the 727 occupants, of which there are six

When a passenger is involved in a severe coach accident, irrespective of his or her position in the vehicle, there are six main potential injury mechanisms.

It may occur that on a given occupant several mechanisms are involved simultaneously. In this case it is up to the accident research worker to determine the main injury mechanism responsible for the injuries to said occupant.

1. *Projection*: persons injured inside the vehicle due to movement of their body during the accident.
2. *Intrusion*: injured occupants inside the coach, due to structural deformation of the vehicle.
3. *Total ejection:* users injured outside the coach by being completely thrown outside during the accident.
4. *Partial ejection:* occupants for whom part of their body is thrown out of the passenger compartment, due to a deformation of the vehicle.
5. *Asphyxia* in fires.
6. *Drowning* in the event of total submersion of the vehicle.

Figure 2.
Breakdown of injury mechanisms



It appears that projection is by far the most frequent injury mechanism. On the other hand, passenger fatalities and severe injuries are mainly caused by total and partial ejection and intrusion.
Now that the sample is known, we shall perform the analysis as a function of the four aggravating circumstances selected initially.

I. ROLLOVER WITH OR WITHOUT FIXED BARRIER

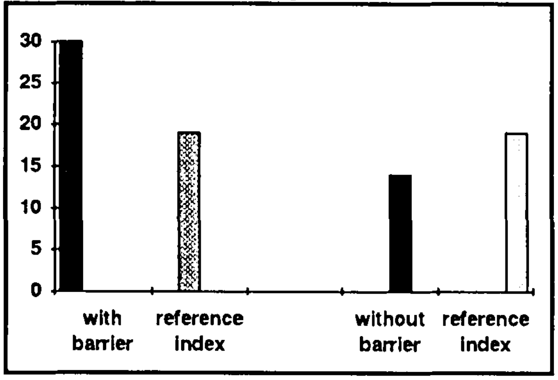
In these accidents either the vehicle rolls over on a fixed barrier (e.g. safety crash barrier, tree stumps, etc.), in which case intrusion in the passenger compartment plays an important role, or else the vehicle rolls over on a smooth surface (e.g. pavement, fields, roadside, etc.), in which case there is never any intrusion.

Table 1.
Number of cases with or without fixed barrier

Fixed barrier	Number of cases	Number of occupants
WITH	5	236
WITHOUT	11	491

The following diagram shows the comparative severity index for accidents with or without fixed barrier and the mean reference index for all accident victims.

Figure 3.
Severity depending on presence of barrier or not



This result shows, on the one hand, that the passengers are less safe in a rollover on a fixed barrier, with a very high rate of fatalities + severe injuries: 30%.

Conversely, there is a sharp reduction in the number of fatalities and severe injuries in accidents without fixed barrier, with a severity rate of 14%.

Rollover of a single- or double-decker coach.

In a coach rollover, our studies have shown that the type of vehicle involved influences the human effects. There is a great difference between a single-decker vehicle and a double-decker vehicle.

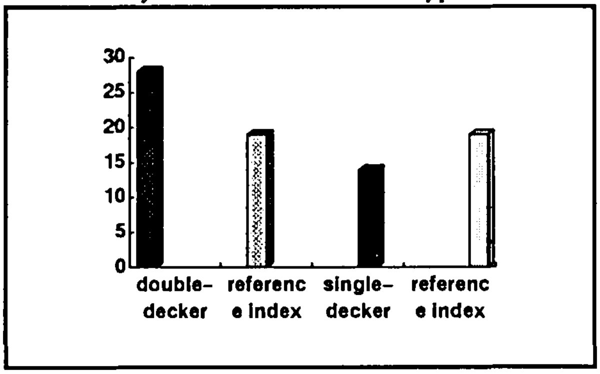
Table 2.
Breakdown of cases by type of vehicle

COACH	Number of cases	Number of occupants
Single-decker	12	464
Double-decker	4	263

We then compare the specific severity index for double-decker vehicles with the reference index.

The diagram below gives the severity indices for single-decker vehicles and for double-decker vehicles relative to the reference index for the 16 accidents.

Figure 4.
Severity index as a function of the type of coach



It appears that the involvement of a double-decker vehicle in rollover considerably aggravates the overall medical consequences for the occupants. More than 80% of the fatalities and severe injuries are located in the upper section of double-decker coaches in rollovers.

Rollover with or without sliding over the ground after rollover

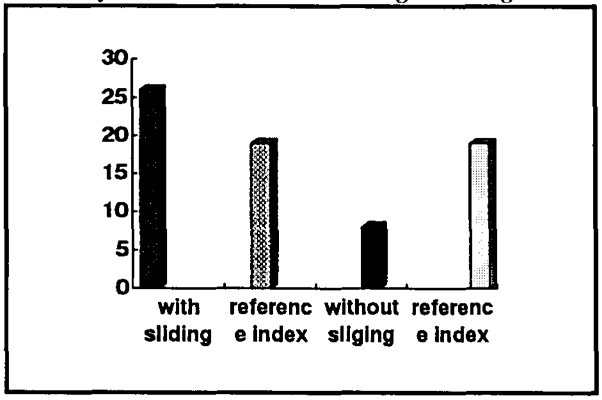
In an accident, rollover occurs when the vehicle is travelling at a certain speed. After landing on one of its sides the coach will slide over the ground until the kinetic energy corresponding to the speed at rollover has been completely dissipated. Our work has shown that it is during this sliding phase that the most severe injuries occur to passengers.

Table 3.
Number of cases with or without sliding

SLIDING	No. of cases	No. of occupants
WITH	10	476
WITHOUT	4	156
UNKNOWN	2	95

Using the same method we investigate the severity of accidents with or without sliding over the ground, which we compare with the reference severity index for all 16 accidents.

Figure 5.
Severity index with or without sliding over the ground



When sliding over the ground occurs after rollover of the coach, the human consequences are greatly aggravated, especially compared with what happens when there is no sliding after rollover.
During sliding over the ground (on average: 45 metres), the human consequences due to partial or total ejection are greatly aggravated.

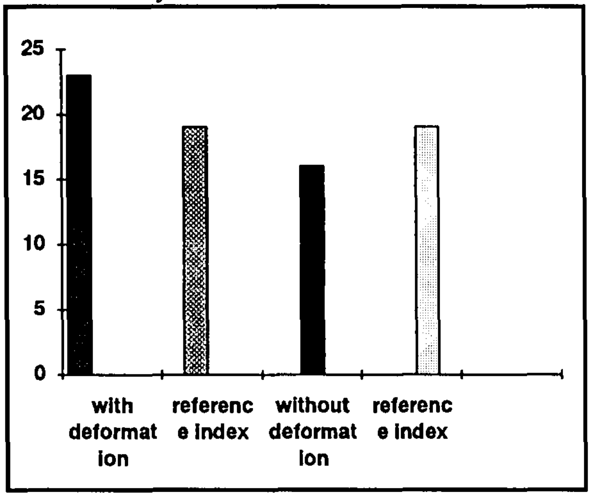
Rollover with or without structural deformation of the vehicle
In coach or bus rollovers it is common to find a vehicle with no structural deformation. Either the speed was very slow at the time of rollover, or the ground was very soft and not aggressive for the vehicle. It is therefore important to know what happens to the passengers when the structure of the vehicle is entirely undamaged.

Table 4.
Number of cases with or without structural deformation

Deformation	No. of cases	No. of occupants
WITHOUT	10	406
WITH	6	321

As for the previous circumstances we determine the severity index for the passengers with and without structural deformation, which we compare with the reference index for all 16 accidents. This information is given in the diagram below.

Figure 6.
Severity index for the vehicle after rollover



As can be seen, the injury results are aggravated when the vehicle undergoes structural deformation. In rollovers, such deformation is usually due to the sideways movement of the entire roof panel. This movement results in a large number of partial ejections for the passengers, which is a very severe injury mechanism for the persons concerned. When there is no structural deformation, most of the fatalities and severe injuries are due to passengers being completely ejected from the vehicle through the side windows. In conclusion to this first section we observe that during rollover of a coach involved in a real-world accident the aggravating factors for the passengers are, in order:

Table 5.
Aggravating factors for passengers in a rollover

Aggravating Factors	Severity Index
fixed barrier	30 %
double-decker vehicle	28 %
sliding over the ground	26 %
structural deformation	23 %
sample reference mean	19 %

Accordingly, the most severe coach rollover accident is: a double-decker vehicle, rolling over on a fixed barrier, with sliding over more than 45 metres after rollover, and with structural deformation.

EJECTION, total or partial, is the main cause of the most severe injuries, with 92% of fatalities and 35% of severe injuries.
The priority is therefore to counter all these forms of ejection in cases of coach rollover.

Examples:

1. A real-world coach accident which occurred in France in 1995. A double-decker coach rolled over on a fixed barrier - a safety crash barrier - and slid over a distance of 83 metres. Post-impact structural deformation was relatively slight. Medical consequences of this accident: 22 fatalities, 8 severe injuries, 22 light injuries, 7 unharmed. In other words, very severe consequences, but very rare.
2. A real-world coach accident which occurred in France in 1994. A standard single-decker coach rolled over on the side of a country road on a flat, soft surface while travelling at very low speed. It came to a stop on its right side, without sliding over the ground, and showed no structural deformation. Medical consequences: 6 light injuries, 20 unharmed.

In order to adopt countermeasures to provide better protection for public transport passengers in accidents, it is essential not only to know the injury mechanisms but also to define the injury severity related to each mechanism so as to determine the most effective future measures in terms of real safety.

The following table gives an indication of the injury severity related to each injury mechanism in rollovers.

Table 6.
Breakdown of accident victims according to injury mechanisms and severity

Severity	total ejection	partial ejection	projection	intrusion	total
all severity n = 727	10%	5%	84%	1%	100%
fatalities n = 53	77%	15%	8%	0%	100%
severe injuries n = 86	13%	22%	54%	11%	100%
light injuries	5%	3%	91%	1%	100%

This table provides essential information for an understanding of how passengers are injured or killed in rollovers:

PROJECTION inside the vehicle is the cause of 91% of light injuries, but also 54% of severe injuries. Here again, the present situation must be improved.

PART II
This second part of our study will highlight the main results, again solely in terms of safety, provided by three experimental rollovers of coaches in perfect operating condition. This work was carried out through close cooperation between RENAULT V.I. and CEESAR.

Description of the experimental impact chosen:
The test is a test of static ROLLOVER of a large-capacity public transport vehicle. This static rollover test was carried out in accordance with the stipulations of Appendix 3 of ECE Regulation R66. Three coaches were tested by this method.
These three experimental impacts were performed to:

- define and comply with the deceleration space necessary for survival of the passengers, hence for structural integrity as defined by Regulation R66;
- study and analyse the behaviour of the occupants inside the vehicles during rollover;
- test new interior trims and various solutions for glazing of the side windows;
- measure structural deformation to acquire data for a computing model;
- perform preliminary preparation of a photo library as a reference for accident research studies.

Test method:
A vehicle of the large-capacity coach type undergoes static rollover from a tilting platform. The vehicle rolls over onto a flat surface plane from a height of 800 mm above the ground. In the vehicle are templates by which it can be verified after impact that the integrity of the passenger deceleration space is preserved, with six instrumented HYBRID III type dummies, some of which are restrained and others not. The vehicle and its occupants are of course instrumented with numerous sensors, and with several interior and exterior cameras.

Analysis of results:

It is of course impossible to present results for all the three tests performed, since the results depend strictly on each type of vehicle experimented. We have therefore selected here only the information common to the three tests and only the information corresponding to occupant protection.

- In the three experimental impacts, all the glazed side windows broke during the rollover. In every case, the windows were of tempered glass or in single glazing. This situation will of course tend to result in total ejection of the occupants.

- During the tests some unrestrained dummies were completely ejected and were found stretched out on the ground.

- On the films taken inside the coach, it is possible to view the projection inside the passenger compartment of certain unrestrained dummies. For the dummies seated on the far side relative to rollover, along the side windows, the head of the HYBRID III will impact the roof panel on the impact side with an average acceleration of 3.5 J, with peak accelerations of up to 85 J. In spite of this the HIC remains very low, at 167.

- The restrained dummies all stayed in their position and did not slip out of their restraint system. The seat belt forces remained very low, and always less than 200 DaN.

- In the three tests the behaviour of the seats, all certified as per Regulation 80, was excellent, since no seat or bench seat with or without dummies moved from its initial position. There was no problem of defective fastening or anchorage to the structure.

PART III

In this final section we compare the results for real-world accident cases and the experimental impacts.

- The problem of total ejection of passengers through the glazed side windows is exactly identical in real-world accidents and in the tests. In both situations the tempered-glass side windows break upon rollover and the passengers are ejected.

- The problem of projection of passengers inside the vehicle is identical in real-world accident cases and in rollovers on test platform. It is very significant that we find in real-world accident research passenger head impacts identical to those that can be observed on films taken during the tests. This of course applies only to unrestrained passengers.

- In both cases, whether for accidents on the road or during experimental tests, all the seats of the vehicles remain exactly in position. There is no total or partial breakage of the bench seats during these two types of rollover.

- Both in real-world accidents and in the tests, all the glazed side windows break at initial impact, and this fact tends to lead to ejection of the occupants.

CONCLUSION.

From all the knowledge acquired either through accident research on real-world cases or through the three tests performed, we can consider a number of countermeasures to improve the real safety of coach passengers in rollovers.

The basic principle for protection of the occupants is to maintain all the accident victims inside the structures of the vehicle. The first priority therefore is to try and prevent any form of total or partial ejection.

The first countermeasure which seems necessary based on the results of this study is that compulsory wearing of seat belts should be recommended in all positions in the vehicle. The belts would of course be three-point seat belts with a reel system.

This first measure will be effective in countering total ejection but also projection inside the vehicle. However, the presence of seat belts worn correctly will have no effect on problems of partial ejection.

The second countermeasure should make it possible to limit structural deformation, and especially to reduce side movement of the roof panel during rollovers landing on roof and rollovers landing on wheels.

This countermeasure would concern the structures of the vehicle and especially the strength of the uprights between the side windows.

The third countermeasure should make it possible to counter partial ejection through side windows which, due to their specific structure, could remain in position during impacts by complying with and accepting some deformation of the vehicle's structures. In this case these windows should be able to play a role as a safety net to maintain passengers within the structure of the coach and especially to prevent occupant contact with the ground during the sliding phase.

The other countermeasure concerns all emergency exits during rollovers, to enable the passengers to be removed rapidly in case of accident if necessary. It appears that the two main exits in this type of impact are the front windscreen and the rear window of the vehicle. These

two natural exits when a coach is lying on its side should therefore always be available for use if need be. If the rear window is covered up by advertising panels an essential exit is lost in case of accident, and this can become dramatic in the case of a fire or submersion.

Finally, the roof hatches are very effective and practical means of evacuation during rollovers.
A final countermeasure will involve a definition of the nature of the various materials used as interior trim in the vehicle. It is essential that all the materials selected for interior trim on the side walls, the roof panel and even the seats should not be traumatizing in the event of passenger projection inside the coach's passenger compartment. The same applies to the nature of the separating panels in public transport vehicles.

As this paper shows, there are still many possibilities for improving passenger safety in the event of coach and bus rollovers. The seat belt, which is required in all seating positions in cars and aircraft, should soon naturally find its place in public transport vehicles. This countermeasure will further enhance the safety of this mode of transport, which is already very efficient in terms of safety.

<u>**BIBLIOGRAPHY**</u>

1. **K. LANGWIEDER M. DANNAR and T. KUMMEL**
« Collision types and characteristics of bus accidents. Their consequences for the passengers and the accident opponent ».
Proceedings of the 10th E.S.V. Conference, Oxford, England, July 1-4 1985.

2. **RICKEY L., STANIFER and Robert A. ROMBERG**
« An analysis of accidents involving buses and an assessment of the need for safety belt requirements in such vehicles ».

3. **Klaus ROMPE and Hans J. FRUGER**
« Improvements for bus safety »
Proceedings of the 10th E.S.V. Conference
Oxford, England, July 1-4 1985

4. **MERRIT M. Davis**
« A study of some school bus crashes »
Proceeding of 21st A.A.A.M. Conference
Vancouver, British Columbia
September 15-17 1977

5. **André ST LAURENT and Dan ROLPE**
« School bus seat backs and their relation to facial injuries »
Proceedings of the Canadian Multidisciplinary Road Safety Conference
Montreal, Quebec, May 26-28 1985

6. **P. BOTTO, C. THOMAS, C. TARRIERE**
« Accidents mortels d'autocars »
June 1984

7. **C. THOMAS, F. HARTEMANN, C. TARRIERE, P. BOTTO**
« Severe coach accident survey »
Proceedings of the 10th E.S.V. Conference
Oxford, England, July 1-4 1985

8. **P. BOTTO, C. THOMAS, C. TARRIERE, C. GOT and A. PATEL**
« Lésions imputables aux sièges dans les accidents d'autocars »
International Conference on Road Safety in Europe
Goteborg, Sweden, 12-14 October 1988

9. **American Association for Automotive Medicine**
« The abbreviated injury scale »
Meeting of November 1994

10. **P. BOTTO, C. THOMAS, C. TARRIERE, C. GOT and A. PATEL**
« Injuries caused by coach crashes in France »
ELMIA ERGONOMICS
Jonkoping, Sweden, 1989

11. **P. BOTTO, MC CAILLIERET, C. TARRIERE, C. GOT and A. PATEL**
« Evaluation of restraint system for coach passengers »
Proceedings of the 14th E.S.V. Conference
Munich, Germany, May 23-26 1994

12. **P. BOTTO, MC CAILLIERET, C. GOT, A. PATEL and C. TARRIERE**
« Passenger protection in single and double decker coaches in tipping over »
Proceeding of the 13th E.S.V.Conference
Paris, France, November 4-7 1991

13. **P. BOTTO**
« Bilan accidentologique de 40 accidents d'autocars »
January 1994

BOARD FRAME,
A possible contribution to improve passive safety

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Paper Number 96-S11-W-16

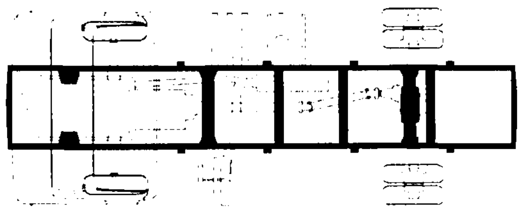

Fig 1 Conventional Truck Frame

ABSTRACT

The board frame is a fully supporting board concept for commercial vehicles. The essential amount of structural strength is being provided by a surrounding main member. This surrounding member has the outside dimensions of the vehicle. Its height ranges from lower edge of the rim up to upper edge of the tire. The smooth surface and external finish of this member lead to an acoustic capsulation of rolling noise, lessen any spray problems and provide a gliding surface to reduce the degree of collision impact. An application out of extruded aluminum profiles will clearly reduce the dead weight in spite of optimized passive safety

CONVENTIAL TRUCK FRAME

Since the days of carriages and first tracks conventional truck frame is state of art for designing of commercial vehicles.
This concept is dated back to the times, when there was only small traffic, when is was economical to design vehicles individually, when noise and pollution control were still foreign words, and when road damages were not yet any subject of dicussions due to unpaved roads. The times have changed, but the concept did not.
It is a logical consequence that on the basis of conventional truck frames commercial vehicles cannot fulfil the requirements of modern road traffic anymore. They are too noisy, the ratio of payload to total weight and its emmission behaviour do not reach an opitmum level. In a mixed road traffic crash behaviour of these vehicles is incompatible with their collision partners. However, because commercial vehicle with its rigid structure and its high weight is superior to other road users, incompatibility in case of a collision ist not being noticed by manufacturers and users of commercial vehicles.

Commercial vehicles are generally accepted to transport goods from A to B. Meanwhile there are only few breakdowns. Truck components are highly reliable, technically (nearly) perfect, and are constantly being improved. This is valid for the engine up to ABS-devices.
To improve the depth of manufacturing commercial vehicles are put together on a component basis according to the customer's requirements. In this context conventional truck frame is accepted and has proven to be good. New frame concepts, e.g. the box frame of DAF, have not gone beyond project phase.

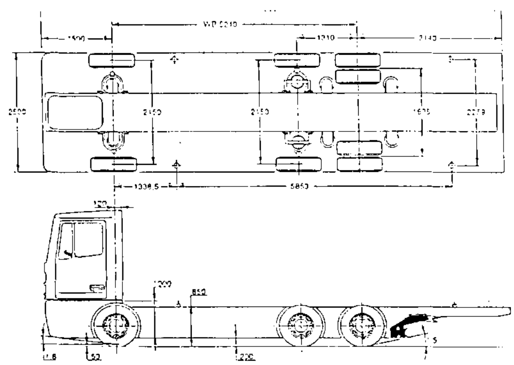

Fig. 2 Box frame DAF

As long as the basic idea is being maintained, that commercial vehicles have to be assigned to road works as well as to city distribution, conventional truck frame will have to be considered.

INCREASING DEMANDS

Times of commercial vehicle on a lonely country street have gone. Continued trend of motorization, mixed traffic, and the cost pressures raise the question, wether the basic concept for commercial vehicles does not have to reconsidered.

Following items have to be resolved:
- weight reduction,
- better aerodynamics (reduction of fuel consumption),
- reduction of noise level,
- protection against splashing water,
- improvement of passive safety,
- better protection of the operator's seat area,
- clear and unique visual signal effect during night times,
- turning to the right without danger,
-utilization of modern material,
-image improvements,
-sales improvements.

Except for weight reduction nearly all items mentioned above have been achieved by adding parts to the existing conventional truck frame.

The noise level is achieved by capsulation, better aerodynamics by covers, improved safety by safety bar devices, etc. An increase in weight by all the add-on-parts, however, leads to a conflict in aims.

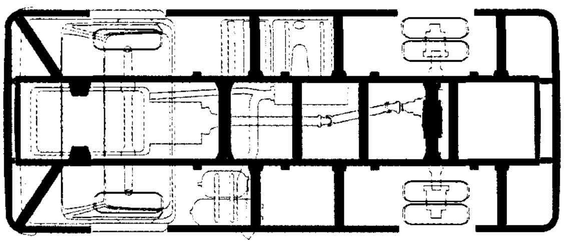

Fig. 3 Conventional truck frame with attachments

BORD FRAME

If all necessaries are being combined and designed as supporting elements, the conventional truck frame will not be necessary anymore. This will lead to an outside frame called board frame.

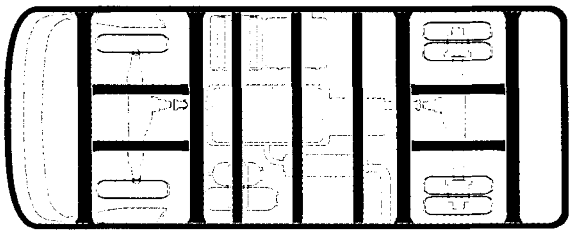

Fig. 4 Board frame

With the board frame all requirements to modern vehicles can be integrated into one concept.

The board frame provides a fully supporting frame concept for commercial vehicles.The main portion of structural strength will be achieved by a surrounding main member, which has outside dimensions of the vehicle, viewed from the top. Its height ranges from lower edge of the rim to upper edge of the tire. Smooth surface and external finish of this member provide an acoustic capsulation of rolling noise and any spray problems will be eliminated. Furthermore, this new concept provides a gliding surface to reduce the degree of collision impact. An application of extruded aluminum profiles will clearly reduce dead weight in spite of optimized passive safety.

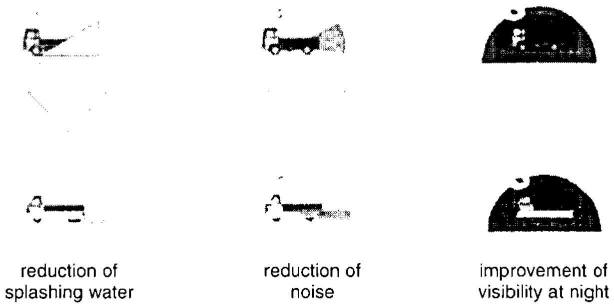

Fig. 5 Advantages of the board frame concept

With the board frame aggressiveness of commercial vehicles will be reduced to a minimum. Compatibility in mixed and also for commercial vehicles under each other will be achieved.

Fig. 6. Incompatibility: Truck and Motorcar

The board frame represents the outside shape of the vehicle. By itself it provides already a good aerodynamic design and styling. Outside surrounding main members serve as a noice capsulation of drive train and tires. By application of high and flat profiles the board frame is predestined to provide a lightweight construction. The board frame makes a fully aluminum truck come reality for the first time.

The board frame consists of an extruded press profile out of 100% recycled secondary aluminum. In a first step it makes sense to adapt the board frame to commercial vehicles up to a gross weight of 10 tons, which means for so-called city distribution vehicles.

WEIGHT COMPARISON

The maximum of permissible weight of a 7.5 ton vehicle is composed equally by payload and dead weight. That means that transportation of a 1 ton payload requires moving a total weight of 2 tons. This ratio surely cannot be regarded as ideal. Weight savings with conventional truck frames can hardly be achieved anywhere else but in context with a reduction of structural strength. In view of weight it has already reached on optimum today.

For the same reasons no significant weight reductions can be achieved on the essential attachments e.g. supporting members or back safety bar.

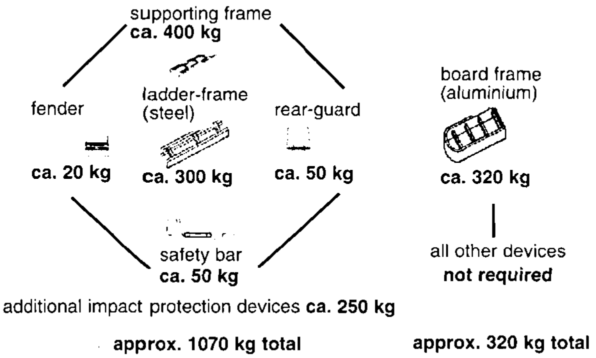

Fig. 7 Comparison of frame weights of trucks with 7.5 tons gross weight.

It becomes evident that it is possible to realize a weight reduction of 750 kg with board frame concept, that is one tenth of the gross weight. This weight advantage for trucks with board frame can be converted into additional payload. Excellent aerodynamic shape with closed outside skin results in reducing fuel consumption. Resulting cost savings can be calculated in relative easy way.

More difficult, but clearly noticeable, are cost advantages for commercial vehicles with board frame, it looks at indirect vehicle costs. In this context costs for road construction (fewer commercial vehicles transport more payload, resulting in less dense traffic), costs for victims (seriousness of injuries and amount of damages are clearly being reduced by a safety concept with the board frame), up to cost reductions for noise reduction measures have to be considered. These factors of cost are directly created by commercial vehicles, however, so not only manufacturers and users, but also political economics and citizens benefit from economical advantages of the board frame concept.

SAFETY COMPARISON

To illustrate the gains in safety a typical urban accident has been simulated.

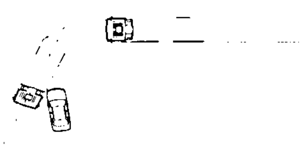

Fig. 8. Accident car/truck within a town

For first tests out-of-production vehicles have been used. Both vehicles were totally damaged. A repair even in case of new vehicles would hardly be worth to do. Average deceleration of passenger compartment was 25 g. This means that occupants would be stressed up to their load limits. Furthermore, there was intrusion into passenger compartment, that means, it was an accident with most severe consequences.

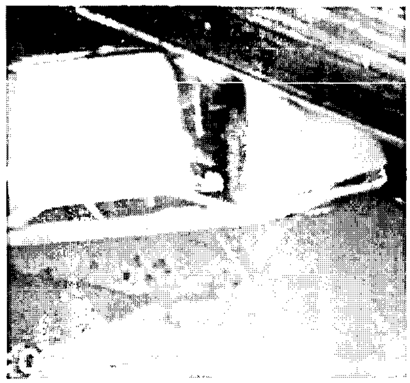

Fig. 9 Vehicles after collision (production)

In a second test a board frame out of aluminum was simulated at a truck. All other test parameters were identical.

Fig. 10 Vehicles after collision (board frame)

With an average deceleration of compartment by about 5 g and less vehicle damage now you find a petty accident. By using a board frame compatibility is not only achieved for vehicles under each other but also between commercial trucks and pedestrians resp. bike riders.

Fig 11 Real accident involving truck and bicycle

In right turn accidents the high and smooth outside frame pushes pedestrians and bike riders aside and thus prevents them from being run over by the rear axle.

Fig. 12 Real accident involving two trucks

The board frame also provides the possibility to design operator's seat in a safe surrounding in view of truck to truck collisions.

Due to the height of the frame reaching from lower edge of the rim to upper edge of the tire, frames of most different commercial vehicles will crash against each other. An intrusion into operator's compartment will be prevented.

Fig 13 No intrusion into the operator's compartment with a board frame concept

When naming the barrier (board) frame the term "crash barrier" had been considered. Like a crash barrier the main member surrounds the commercial vehicle. The purpose of a crash barrier is to guide a vehicle away from obstacles. For example, if a vehicle collides with a tree, the total kinetic energy of the vehicle is being transformed into energy of deformation. The vehicle is totally being damaged. High deceleration of compartment and partial intrusion into take place. This leads to severe injuries.
If the tree is shielded by a crash barrier, the vehicle collides against the barrier and its kinetic energy will only be transformed into energy of deformation to an certain portion. The bigger portion remains as kinetic energy. Only the direction is changed. Within the run-out phase speed can be reduced after collision by crash barriers. The board frame is based on this principle,too.
Colliding vehicles do not reduce their kinetic energy by deformation anymore, the gliding zone of board frame however provides a gliding-off an re-direction of kinetic energy.
The gliding-off effect applies to all road users. Thus a compatibility is being achieved.
Commercial vehicles can be driven in mixed traffic without endangering other road user too much.

DESIGN CHANGES

A change from conventional truck frame to board frame requires a redesign of the axles.
First of all wheel changes have to be mentioned. If an air suspension is being used, axles can remain as they are. At axles with conventional suspension fixation of wheels to wheel hubs must be redesigned in a way that wheels can be pulled away to the bottom.

Fig. 14 Wheel change

To retain front axle track as large as possible in a view of stability an extension of the frame can be considered in this area. Because of changes a new steering geometry has to be considered.

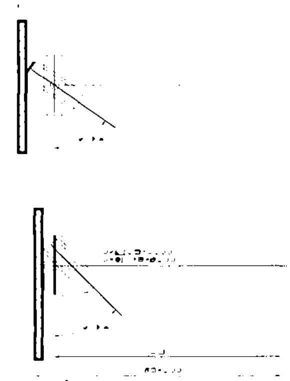

Fig 15 Steering axle

Out a design point of view many changes are necessary. This, however, is a change to leave custom thinking and to find better solutions in the view of reduced production depth.

FRAME CONCEPT

A frame designed for extruded aluminum will be most suitable. Of course out of design purposes even steel can be considered. Being independent of basic material the board frame concept allows a simple module concept for front and rear portions. These components can be produced out of plastics and houselights for example can be integrated. This allows to realize a very simple design for commercial vehicles.

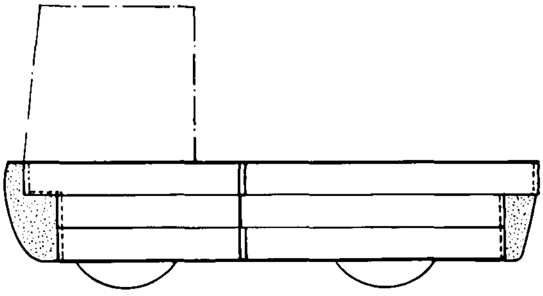

Fig 16

If a city distribution vehicle is being designed on basis of a board frame the following design concept could be an example.

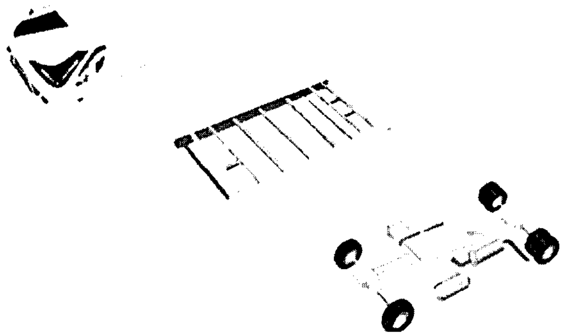

Fig 17a. Design concept for a city distribution vehicle

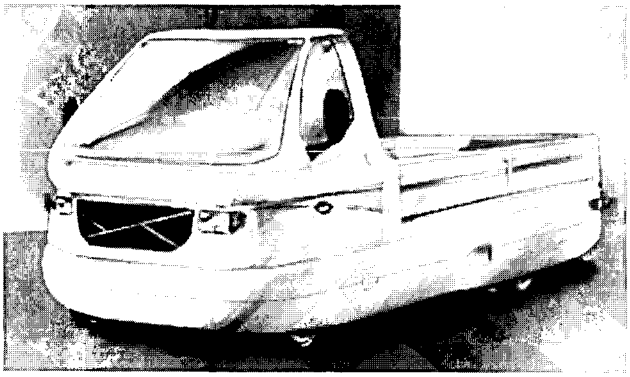

Fig 17b. Design concept for a city distribution vehicle

Conclusions below list the advantages for manufacturers, users, and citizens, if the board frame concept is being applied .

ADVANTAGES FOR PRODUCERS

- simple construction
- smaller deadweight
- lower assembling efforts
- cheaper production
- simple process chart
- integration of all passive safety elements without additional costs and material expenses
- no problems to satisfy the requirements of law concerning noise reduction and passive safety
- lower center of gravity
- better aerodynamics
- a truck only made out of aluminum does not remain an illusion
- reduction of measures for rust protection
- easy to recycle (e.g. reusing the frame material)
- installation traverse motor and front wheel drive are possible
- enough space for exhaust gas filter
- image improvement
- rising of advertising potentials «Vorsprung durch Technik»
- excellent design

Disadvantage:
- a new thought has to be given to the traditional way of thinking in truck-construction

ADVANTAGES FOR ECONOMY AND POPULATION

- less noise
- less energy consumption
- less damage of streets (lighter trucks)
- traffic improvement (higher truck speed)
- better visibility in case of rain
- reduction of consequences in case of accidents concerning personal and property damage recovery costs, pensions
- reduction of costs after accidents regarding loss of wages, loss of taxes, claiming compensation
- less young pensioners
- less fear of trucks
- less insurance premium
- rising of sales figures
- better chances in export by innovative technology
- creation of jobs
- better relationship between trucks and other participants in traffic
- better acceptance of trucks by population through image improvement

ADVANTAGES FOR USERS

- higher payload
- higher capacity of transportation
- faster loading and unloading (no steps)
- by compatibility: possibility of rising speed
- less running-time
- less fuel consumption
- less insurance premium (lower risk)
- less routine maintenance
- not sensitive to corrosion (aluminum)
- larger advertising space
- lower deficits during repair after an accident
- lower costs of repair after an accident
- job improvement
- noise reduction
- less damages in case of accidents
- no leaking of fuel in case of accidents
- better acceptance by population
- image improvement

Another reference to this subject:
The Gliding Zone, K.-H- Schimmelpfennig, Münster Germany, Paper No. 96-S4-0-06, 1996

TRUCK SEAT BELTS

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ABSTRACT

This paper addresses why seat belt wearing rates remain low among truck drivers, despite revisions to Australian Design Rules aimed at making truck seat belts more comfortable. These changes allow for anchorage of the seat belt to the seat and reduced retractor sensitivity. Drivers of articulated and rigid trucks were interviewed regarding seat belt use and reasons for nonuse. Responses are analysed as a function of type of belt and anchorage, type of truck and driver characteristics.

INTRODUCTION

AUSTROADS and the National Road Transport Commission (NRTC) commissioned this study of seat belt wearing (or more specifically, non-wearing) by truck drivers. The study arises from the view that wearing rates remain low, despite revisions to design rules aimed at making truck seat belts more comfortable. These changes allow for anchorage of the seat belt to the seat and reduced retractor sensitivity.

This paper discusses:

1. how many and what groups of heavy vehicle drivers do not wear belts
2. why truck drivers do not wear belts
3. what effect if any the changed Australian Design Rule has had on wearing rates and whether further belt design improvements are required
4. what is necessary to achieve greater wearing rates
5. guidelines for the development and conduct of a communications strategy to improve seat belt wearing.

REGULATIONS REGARDING FITTING OF SEAT BELTS IN HEAVY TRUCKS

Fitting of lap seat belts for the driver and outboard passenger in heavy trucks (trucks over 4.5 tonnes Gross Vehicle Mass) was provided for in the second edition of Australian Design Rule 32 (ADR 32) for vehicles manufactured on or after 1 July 1977. The ADR requires seat belt anchorages to withstand a force of 9kN applied to the body block.

The same strength requirements for lap anchorages applicable to the above vehicle categories were subsequently mandated under the Motor Vehicle Standards Act 1989 by ADR 5/00 as amended by ADR 5/01. ADR 5/01 was subsequently amended by ADR 5/02 which required lap sash belts with retractors for certain seating positions instead of lap belts for vehicles manufactured on or after 1 July 1992. ADR 5/02 has been subsequently amended by ADR 5/03 without affecting type or strength of anchorage requirements for heavy vehicles.

Also, to make seat belts more user friendly, a modified retractor was required to be fitted (effective July 1992) where a lap/sash belt was fitted to the driver's seat and this modified retractor was also required where lap belts were fitted to the driver's or front outboard seating position. The modified retractor has reduced sensitivity to acceleration and therefore is not as prone to cycling in and out of lock due to the occupant bouncing in the seat as do normal retractors. This retractor does not subject the occupant to unnecessary locking forces due to rough suspension/terrain and leads to less wear and tear on the locking mechanism.

The effect of the Package 20 amendments effective from July 1993, in respect of lap/sash belts, is that these modified retractors are only required if fitted to a suspension seat and only if all of the anchorages are not mounted on the moving part of the seat. The modified retractors were only intended to be fitted in situations where there would be relative movement between the occupant and the anchorages, as would occur when the retractor or any of the other anchorages were fitted to the vehicle body.

The Package 20 amendments also dispensed with the need for modified retractors for lap belts because ADR

5/02 currently requires the anchorages to be fitted to the moving part of a suspension seat which makes modified retractors redundant for lap belts.

Details of type of seat belt required for seating positions are shown in Appendix 1.

REGULATIONS REGARDING WEARING OF SEAT BELTS

While Australian Design Rules are a Federal matter, the regulations regarding wearing of seat belts come under State and Territory jurisdiction.

In many States, seat belts are required to be worn if they are fitted, unless the vehicle is continually operating at low speed. In Victoria, for example, Section 1506 (1) of the Road Safety (Traffic Regulations) 1988 states that "A person must not be seated in a motor vehicle that is in motion in a seat for which a seat belt is provided unless- (a) that person is wearing the seat belt; and (b) the seat belt is properly adjusted and securely fastened." The only exemption that could apply to heavy vehicle drivers is found in paragraph 2(d) which states that subregulation (1) does not apply to a person engaged in delivering bread, milk or other similar commodities.

In New South Wales, drivers of vehicles of over 2 tonne gvm are exempt from wearing seat belts.

The section of the proposed Australian Road Rules (Part 16) regarding wearing seat belts does not contain any direct exemptions for heavy vehicle drivers. However, certain clauses allow the relevant Authority to issue exemption certificates for persons or classes of persons. In addition, the occupants of a vehicle are exempt from the regulation if frequent deliveries are being made and the vehicle is not travelling over 25 km/h (16.2(2)(e)).

Even in States and Territories where seat belts are required to be worn in trucks, there is not a high level of enforcement of this legislation because of the difficulty of observing whether drivers are wearing a seat belt when the truck is in motion.

STUDY DESIGN

Because of the similar ADRs applying to the two categories of vehicle, the study focussed on heavier medium commercial vehicles (GVM>4.5 but <=12.0 tonnes) and heavy commercial vehicles (GVM>12.0 tonnes).

The sample of drivers was classified in two ways:

- those who drive articulated vehicles versus rigid trucks
- those who drive trucks which comply with ADR 5/01 or 5/02 or 4/01 Appendix A ("new trucks") versus older trucks.

Drivers of articulated vehicles were interviewed in Melbourne and Western NSW. In Western NSW, it was thought that there would be relatively few rigid trucks. For this reason, our aim was to interview 40 drivers of "new" articulated trucks and 40 drivers of older articulated trucks.

In both Melbourne and Western NSW, difficulties were experienced in interviewing sufficient drivers of "new" trucks. According to the Australian Bureau of Statistics 1991 Survey of Motor Vehicle Usage, trucks less than two years old comprise less than 10% of trucks registered in Victoria. It was not possible to interview equal numbers of drivers of "new" and older trucks and so the samples comprised a larger proportion of rigid trucks. However, this meant that the samples more truly reflect the real ratios of the kinds of trucks in operation. Given that wearing rates were so low, it was considered not worth the significant cost and time penalties needed to attempt to balance the numbers of new and old trucks.

<u>New and old trucks</u> - In the original design, "new" trucks are those which comply with ADR 5/01 or 5/02 or 4/01 Appendix A. Since it was not possible to easily gauge compliance from the interviews, trucks were classified according to the date of manufacture. In piloting we looked at a range of indicators on the trucks, including compliance plates and registration labels but found that it was difficult to find out which year and month a vehicle was manufactured.

The approach finally taken was to ask the driver the age of the truck. Trucks aged less than three years old were classed as "new". If the driver said that the truck was three years old, it was classed as "new" if the seat belt was fitted to the seat or "old" if the seat belt was fitted to the vehicle body.

One drawback with this approach was that in some cases the driver mentioned that either the seat or the seat belt had been replaced (or fitted) some years after manufacture. These examples of "retrofitting" tend to weaken the relationship between age of the truck and the Design Rules to which it actually complies.

INTERVIEW METHOD

Face-to-face individual interviews were conducted to ask drivers about their frequency of wearing seat belts and the factors which influence whether or not they wear seat belts. This method was chosen because an earlier attempt to obtain observational information on seat belt wearing showed that it was possible to see whether truck drivers were wearing a lap belt from an overhead

position. The interviews were conducted at depots and road houses in Melbourne and western NSW between November 1994 and January 1995.

SAMPLE CHARACTERISTICS

Truck characteristics

A total of 184 interviews were conducted, 106 in Melbourne and 78 in Western New South Wales. The numbers of drivers of new and old articulated and rigid trucks interviewed in each location are summarised in Table 1.

Table 1.
Numbers Of Drivers Of New And Old Articulated And Rigid Trucks Interviewed In Melbourne And Western New South Wales

Type of truck	Melbourne	Western New South Wales	All trucks
Articulated	62	78	140
New	23	17	40
Old	39	61	100
Rigid	44		44
New	18		18
Old	26		26
Total	106	78	184

More than 90% of the rigid trucks in the sample were of the cabover design. The majority of articulated trucks were of the conventional bonneted design (66%), and the proportion of conventional designs was greater in Western NSW (76%) than in Melbourne (55%).

The most common make of rigid truck was Hino (32% of rigid trucks in the survey). The most common make of articulated truck was Kenworth (25% of articulated trucks in the survey). The distributions of makes of articulated trucks differed somewhat between the two samples with Western Star/White being more common and Volvo less common in Western NSW.

Seat and seat belt characteristics

No drivers interviewed drove a truck with a bench seat. Most trucks had bucket seats with suspension (47%) or suspension and oscillator (42%). This applied for both rigid and articulated trucks.

Lap-sash retractor seat belts were the most common form of seat belt fitted in both rigid and articulated trucks. However, in more than a third of the articulated trucks in Western NSW there was no seat belt in the truck (none fitted or removed) or the driver did not know what type of seat belt was fitted. Old trucks were more likely to have lap-only static seat belts and were also more likely to have no belt or for type of belt to be unknown. New trucks were more likely to have a retractor belt, most commonly a lap-sash style.

Overall, the seat belt was most commonly connected to the vehicle. Fitting to the seat was most common for the Melbourne articulated trucks. Table 2 summarises where the seat belts connected for new and old trucks. While it was expected that old trucks would have vehicle-mounted seat belts and new trucks have seat-mounted seat belts, there were exceptions to this generalisation. These exceptions could have arisen from any of the following circumstances:

- inaccuracies in judgement of the age of the truck by the driver. He may not have known when the vehicle was manufactured or made a mistake in calculating its age.
- the driver saying that the seat belt was mounted to the seat when it was actually mounted to the vehicle
- most of the old trucks with seat mounted seat belts were four to six years old. It is possible that some of these trucks would have been manufactured after 1 July 1990 and thus complied with ADR 5/01 which allowed for mounting the belts directly to the seats.

Table 2.
Where Seat Belt Connects In New And Old Articulated And Rigid Trucks

Type of truck	Seat	Vehicle body	Not applicable	Unknown
Articulated - Melb.				
New	48%	52%		
Old	31%	56%	10%	3%
Articulated - NSW				
New	53%	29%		18%
Old	15%	34%	43%	8%
Rigid				
New	33%	67%		
Old	12%	73%	8%	8%

Trip characteristics

In Western New South Wales, 74 of 78 trucks were engaged in long-distance transport. In Melbourne, 45 of 62 articulated trucks and 22 of 44 rigid trucks were engaged in long-distance transport. The percentages of new and old trucks engaged in long-distance transport did not differ (new: 62%, old: 71%).

HOW MANY AND WHAT GROUPS OF HEAVY VEHICLE DRIVERS DO NOT WEAR SEAT BELTS

Overall, 72% of drivers said that they had never used the seat belt in the truck they were driving. As Table 3 shows, frequency of belt use was coded as Not applicable for an additional 16% who had stated that there was no seat belt fitted in their truck or it had been removed. Given this, it is more accurate to say that 88% of drivers never used the seat belt in the truck they were driving. Only 4% of drivers stated that they used their seat belt all the time. An additional 6% wore it between 10% and 50% of the time.

Table 3.
Frequency Of Seat Belt Use By Drivers Of New And Old Articulated And Rigid Trucks (%)

Type of truck	Never	Less than 10% of the time	10-50% of the time	All the time	Not applicable
All articulated	**74**	**4**	**3**	**0**	**20**
All new articulated	**90**	**3**	**8**	**0**	**0**
All old articulated	**68**	**4**	**0**	**0**	**28**
Articulated - Melb.	**82**	**7**	**3**	**0**	**8**
New	87	4	9	0	0
Old	80	8	0	0	13
Articulated - NSW	**68**	**1**	**1**	**0**	**30**
New	94	0	6	0	0
Old	61	2	0	0	38
Rigid	**64**	**14**	**2**	**16**	**5**
New	61	11	0	28	0
Old	65	15	4	8	8
Total	**72**	**6**	**2**	**4**	**16**

Truck characteristics

New versus old trucks - While no articulated truck drivers reported wearing a seat belt all the time, drivers of new articulated trucks were more likely than drivers of old articulated trucks to report wearing a seat belt some of the time (Melb: 13% vs 8%, Western NSW: 6% vs 2%). Among rigid truck drivers, those driving new trucks were significantly more likely to wear their seat belt all the time than were those drivers driving old trucks (28% versus 8%, z=1.78, p<.05).

Overall, 26% of older trucks but no new trucks had no seat belt fitted or the seat belt removed.

Rigid versus articulated trucks - Drivers of rigid trucks were more likely to report wearing their seat belt all of the time than were drivers of articulated trucks (16% versus 0).

Conventional versus cab-over trucks - It was not possible to compare wearing rates in cab-over and conventional rigid trucks because there were too few conventional rigid trucks. However the data suggest that drivers of cab-over articulated trucks were somewhat more likely to wear a seat belt some of the time than drivers of conventional articulated trucks (9% vs 4%).

Type of seat and seat belt

Five of the 20 drivers who stated that their truck had a bucket seat without a suspension system (25%) reported wearing a seat belt at least some of the time. This compares with 10% of those with bucket seats with suspension only and 8% of those with bucket seats with both suspension and oscillation. Examination of the proportions of rigid and articulated trucks with each type of seat showed that this finding was not due to types of seats being related to types of trucks.

Drivers with lap static belts appeared somewhat more likely to wear the seat belt some of the time than those with other designs of seat belts (see Table 4). It should be noted, however, that it was drivers with lap-sash retractors that were most likely to wear a seat belt all of the time. This latter finding may have been due to the greater prevalence of lap-sash retractor seat belts among rigid trucks than articulated trucks.

Table 4.
Frequency Of Seat Belt Use As A Function Of Type Of Seat Belt Fitted

Type of seat belt fitted	Never	Less than 10% of the time	10-50% of the time	All the time	Not applicable (not fitted)
Lap static *(n=23)*	70%	22%	4%	0%	4%
Lap retractor *(n=28)*	89%	0%	7%	4%	0%
Lap-sash static *(n=6)*	83%	0%	0%	17%	0%
Lap-sash retractor *(n=86)*	86%	7%	1%	6%	0%
Unknown/no belt *(n=41)*	29%	0%	0%	0%	71%
Total	**72%**	**6%**	**2%**	**4%**	**16%**

Whether the seat belt was connected to the seat or vehicle body had little effect on frequency of use: seat belts connected to the seat were worn at least some of the time by 14% of drivers, whereas seat belts connected

to the vehicle body were worn at least some of the time by 16% of drivers.

Driver characteristics

Drivers aged 40 or over were somewhat more likely to wear a seat belt at least some of the time than younger drivers. However, this pattern reflects that of the Melbourne rigid truck sample in which most of the seat belt wearing was reported. This relationship with age was not found in either of the articulated truck samples. In the Melbourne articulated truck sample, drivers aged 40 or over were more likely than younger drivers to have had no seat belt fitted or the seat belt removed (17% vs. 0%). In the NSW articulated truck sample, this was not the case and the only drivers who reported sometimes wearing a seat belt were in 30-39 age group.

Owner-drivers of articulated trucks were more likely than employees to have no seat belt fitted or the seat belt removed (Melbourne: 31% vs 2%, Western NSW: 39% vs. 21%). Further analysis has shown that this reflects the larger proportion of older trucks driven by owner-drivers.

Among the Melbourne rigid trucks, there were very few seat belts not fitted or removed so no differences were seen in the degree to which this occurred for owner-drivers and employees (there were also very few owner-drivers in that sample - 9%).

Trip characteristics

Drivers of articulated trucks in Melbourne and Western NSW were no different in their rate of seat belt wearing. However, in Western NSW it was more common that a seat belt was not fitted or had been removed.

The frequency of seat belt use was highest for those drivers who usually made local trips. This group comprised largely drivers of rigid trucks.

WHY TRUCK DRIVERS DO NOT WEAR SEAT BELTS

This section discusses drivers' views on a range of factors which could contribute to not wearing a seat belt. They include:

- general views on seat belts
- specific reasons for not wearing
- discomfort
- inconvenience
- fear of fire or load shift
- perceived safety value of seat belts
- perceived danger of seat belts
- driver physical characteristics.

General views on seat belts

Drivers were asked to indicate, on a scale from 1=disagree very strongly to 7=agree very strongly whether they agreed that "seat belts in trucks are a good idea and should be worn". Almost half of the drivers disagreed very strongly with this statement (46%) and only 13% agreed very strongly. Overall, 57% disagreed (ratings 1 to 3) and 27% agreed (ratings 5 to 7).

Not surprisingly, drivers who wear seat belts are more likely to agree that they are a good idea and should be worn. However, it is interesting to note that 9% of those who report that they never wear a seat belt agreed very strongly that they are a good idea and should be worn.

Drivers were asked for the main reason why they wear or do not wear a seat belt. The most common reason given for not wearing a seat belt was that it was uncomfortable (35%), 10% of drivers said a seat belt had no safety value and 17% of drivers gave reasons related to seat belts being dangerous. Reasons for wearing a seat belt were equally divided between enforcement and safety consequences.

Discomfort

Drivers were asked to indicate, on a scale from 1=disagree very strongly to 7=agree very strongly whether they agreed that "seat belts are uncomfortable because they rub" and "seat belts tend to tighten or lock up". In 10 to 15% of cases, the driver answered "don't know" because he did not wear a seat belt. However, most drivers answered these questions despite having indicated that they had never worn the seat belt in the truck that they were driving. Of those drivers who responded to the question, 69% agreed that seat belts are uncomfortable because they rub (ratings 5 to 7), with almost half of the drivers indicating that they agreed very strongly with this statement. However, responses were affected by the frequency of use of the seat belt. Those drivers who wore a seat belt more often were less likely to agree that it rubbed and more likely to disagree.

Of the drivers who responded to the question, 76% agreed that seat belts tend to tighten or lock up. About 60% of drivers indicated that they agreed very strongly with this statement. The level of agreement decreased with increased frequency of wearing.

Inconvenience

Drivers were asked whether they agreed with the statement that "having to buckle up all the time is too much of a bother". Most drivers felt that this was not an important issue, with comments such as "well, you do it in your car anyway" or "that is not the problem". Overall, only 38% of drivers agreed that it was a bother, with only 23% agreeing very strongly. In contrast, 26% of drivers disagreed very strongly and a total of 47% disagreed that it was a bother.

Drivers who stop frequently - It was hypothesised that those drivers who had to get out the truck more often each day, would be less likely to wear a seat belt. This is not true in general, it was those drivers who had to get out of the truck most times per day who were more likely to wear seat belts (the reverse was also true). This was because the drivers who got out of their trucks most often were the drivers of rigid trucks.

Having to get out of the truck often does not seem to lower the frequency of wearing seat belts among rigid truck drivers: the highest wearing rates are among those drivers who estimate that they have to get out of the truck more than 20 times per day. While the number of times the driver has to get out of the truck each day does not seem to affect seat belt wearing behaviour, analyses showed that it does affect the driver's attitude. Mean ratings of how strongly drivers feel that seat belts are "a bother" increased with number of times they got out of the truck each day.

Fear of fire or load shift

While it was expected that frequency of seat belt use might be lower for those carrying dangerous goods or loads that were likely to shift, this was not found.

Safety value of seat belts

A number of questions were asked which addressed drivers' attitudes about the safety value of seat belts.

Drivers were asked to indicate, on a scale from 1=disagree very strongly to 7=agree very strongly whether they agreed that "you feel safer when you are using a seat belt". Most drivers disagreed very strongly with this statement (58%) and a total of 78% of drivers disagreed at some level. Only 13% of drivers agreed with this statement. Ratings of safety were related to frequency of seat belt use. Only 8% of those who never wore a seat belt or did not have one available in their truck said that they would feel safer wearing a seat belt. However, 50% of those who wore a seat belt at least some of the time said they felt safer.

Drivers were asked whether they agreed that wearing a seat belt would reduce their chance of being injured in a head-on crash with another truck or a rollover. More than half (59%) of the drivers who responded disagreed very strongly that a seat belt would reduce their chance of injury in a head-on crash with another truck. In total, 70% of drivers felt that wearing a seat belt would **not** reduce their chance of injury in a head-on crash with another truck and only 23% thought a seat belt would reduce their chance of injury. Of those drivers who wore a seat belt at least sometimes, 41% thought that wearing a seat belt would reduce their chance of injury in a head-on with another truck.

More drivers thought that seat belts had the potential to reduce injury in a rollover, than in a head-on crash with another truck. While 43% disagreed very strongly with this and a total of 55% disagreed at some level, 35% agreed that seat belts would reduce their chance of injury in a rollover. In contrast, 77% of drivers who wore a seat belt at least some of the time agreed that this would reduce their chance of injury in a rollover.

Drivers were asked whether they had been involved in a crash in which the truck was severely damaged, whether they were wearing a seat belt at the time and whether they thought that wearing a seat belt had (or would have) protected them from injury. Overall, 30% of drivers had been involved in such a crash and only 3% were wearing a seat belt at the time. Only 4% of drivers felt that wearing a seat belt had or would have provided protection from injury.

More than 70% of drivers knew of other drivers who had had crashes in which they were injured. Only 5% of drivers thought that seat belts would have protected them.

Perceived danger of seat belts

In addition to questions about the safety benefit of seat belts, drivers were also asked a series of questions which probed views about the possible dangers associated with wearing seat belts.

Most drivers agreed that wearing a seat belt would make it harder to get out quickly if a crash occurred (60% very strongly, total 79% agreed). Only 13% of drivers disagreed with this statement. Among drivers who wore a seat belt at least some of the time, 27% of drivers disagreed with the statement.

When asked what they would do to avoid injury in a rollover, 42% of drivers gave responses which were incompatible with wearing a seat belt. The most common of these were "get down low" (22%) and "jump out" (12%).

Driver physical characteristics

The effects of the driver physical characteristics of height, weight and Body Mass Index (a measure of obesity) on wearing rates and reasons for not wearing seat belts were investigated. The hypothesis investigated was that seat belts might be less comfortable for very short, very tall or overweight or obese drivers. However, there is no evidence that shorter drivers or taller drivers wear seat belts less frequently than drivers of normal height.

Half of the drivers were classified as overweight or obese according to their Body Mass Index. There is a trend for seat belt wearing to become less frequent as Body Mass Index increases. Underweight drivers were somewhat more likely than normal drivers who were somewhat more likely than overweight drivers to wear a seat belt at some time. All of the obese drivers reported never wearing a seat belt or not having one fitted or having the seat belt removed.

Three drivers reported having exemptions from wearing seat belts because of medical problems (back, shoulder problems, hiatus hernia).

WHAT IS NECESSARY TO ACHIEVE BETTER WEARING RATES

Drivers who had a seat belt fitted were asked whether there were any circumstances under which they would be more likely to use a seat belt in a truck. Two-thirds of these drivers could not report any such circumstances. The most common circumstances reported were enforcement situations (44%) and situations of high perceived crash risk (hazardous locations, poor road conditions, city driving, bad weather, when tired - total 29%). Few drivers nominated improvements to seat belt design as making them more likely to wear a seat belt in a truck.

Quite a few drivers who said that they never wore the seat belt in their truck answered this question. Their responses related to hazardous locations (7), poor road conditions (2) and enforcement situations (18), as well as other circumstances such as on longer trips (4).

Education and promotion

Drivers in Victoria, but not New South Wales, are required by law to wear a seat belt if one is fitted. Overall, about 90% of rigid truck drivers in Melbourne thought that they were legally required to wear a seat belt "all the time" or "all the time except in vehicles having to stop all the time such as milk delivery trucks and mail vans". Only 64% of articulated truck drivers interviewed in Melbourne believed this to be the case. In Western NSW, 46% of the drivers (who were not legally required to wear a seat belt) thought that it was required by law.

While all of the drivers who used a seat belt (at least some of the time) said that they were legally required to wear it, more than 60% of those who never wore a seat belt also said that they were legally required to wear it. Half of those who had no seat belt (not fitted or removed) said that they were legally required to wear a seat belt.

Only 9% of employees had ever been told by their employer that they should wear the seat belt in their truck. Almost all employee drivers said that they would have to pay the fine if they were booked by the police or enforcement officers for not wearing a seat belt.

Enforcement

There is a perceived low level of enforcement of the requirement to wear seat belts. Only 15% of drivers had been fined or cautioned by the police or enforcement officers for not wearing a seat belt in a truck. Almost half of the truck drivers interviewed did not know of any other truck drivers who had been fined or cautioned. About 30% of drivers knew of one or two drivers who had been fined or cautioned.

Improvement of cabin strength

Many drivers, particularly those of articulated trucks, felt that the cabin afforded very little protection in the case of rollover. It was for this reason that they wished to be able to "get down low" or "jump out" in order to minimise the chance of being injured in a rollover. To be held in place by a seat belt was considered to be "a death warrant".

Additional questions were asked to collect more information about drivers' views on occupant protection and cabin strength. Almost a third of the drivers interviewed considered that the cabins of trucks built in the last five years offer less protection than those built about 20 years ago. The overall pattern reflects that found in Western NSW but a larger proportion of drivers of rigid trucks in Melbourne felt the newer trucks offered less protection, as did a smaller proportion of articulated truck drivers in Melbourne.

The existence of rollover standards and better rollover performance of Swedish trucks was noted by a number of drivers of articulated trucks. This was the basis of many of the responses that "some models are better". However, many of those driving non-Swedish trucks said that modern cabins provide less protection

because they are built of weaker materials. Many drivers reported having seen crushed cabins and doubted whether a driver held in a seat could have survived.

INJURIES TO TRUCK DRIVERS

The truck driver interviews showed that many truck drivers feel that not wearing a seat belt enables them to fling themselves across the cabin or jump out in the event of a crash and, as a result, reduce the likelihood or severity of injury. This is partly an outcome of their concern that truck cabins will not maintain a survivable space in severe crashes (rollovers and collisions with other trucks and large objects). This section examines the magnitude of the problem of injuries to truck drivers and the safety benefits of seat belts in trucks.

Magnitude of the problem

Relatively little information is available about the problem of truck driver trauma, compared to considerable information about truck crashes and their overall consequences. This reflects the general emphasis on the large amount of injuries to other road users, rather than truck drivers, in truck crashes. In 1988, 59 truck drivers (and 294 other road users) were killed in the 289 fatal crashes involving articulated trucks in Australia (Attewell and Dowse, 1992). Articulated truck occupants comprised 3% of all road fatalities. No information was available about rigid truck drivers.

If the risk of death to the driver of a car and an articulated truck are compared, the pattern changes quite markedly. In 1990 there was one articulated truck driver death per 84 million km travelled by articulated trucks (calculated from 1990 FORS Fatality File and 1991 Survey of Motor Vehicle Use). In comparison there was one car (or light truck) driver death per 160 million km travelled. Thus, the risk of death per km for articulated truck drivers was almost double that for car (or light truck) drivers. Per 10,000 vehicles registered, the difference was even greater. There were 9.0 articulated vehicle driver deaths and only 0.9 car (or light truck) driver deaths per 10,000 vehicles registered. The figures for rigid trucks are similar to those for cars and light trucks.

Thus while the severe cost of articulated truck crashes to other road users should not be ignored, there is clearly a need to attempt to improve safety for drivers of articulated trucks. Wearing seat belts is one method which aims to reduce driver fatalities and injuries.

Safety benefits of seat belts in trucks

While little testing of the occupant protection ability of truck cabins has occurred outside of Sweden, studies of truck crashes have not supported the drivers' view that they are safer without seat belts. The NSW Heavy Vehicle Crash Study found that in 19 cases (23 percent of the fatal truck crashes studied) the driver was ejected and so injury severity would have been likely to have been less severe if seat belts were worn (Sweatman et al., 1990). It is likely that in the additional cases in which the driver was not ejected, seat belts (particularly lap/sash models) would have helped restrain the occupant inside the truck and reduced injury.

In a United States study, Clarke and Leasure (1987, cited in Sweatman, 1991) found that rollover, ejection and contact with interior surfaces were among the main mechanisms responsible for truck driver fatalities. They concluded that wearing a seat belt could have avoided many of these fatalities. Another US study estimated that seat belt use would have reduced injury severity for 64 out of 77 heavy vehicle drivers involved in fatal and non-fatal crashes (Ranney, 1982; cited by NTSB, 1992, p. 2). Rossow (1987, cited in Sweatman, 1991) found that unbelted truck drivers tended to have severe impacts with the steering wheel, partly due to the relatively upright seating posture of a truck driver and the near horizontal orientation of the steering wheel.

The National Transportation Safety Board (NTSB) in the US investigated 182 heavy truck crashes in which the driver died (NTSB, 1990; cited by NTSB, 1992. p.1-2). Although the majority of the heavy trucks had lap belts installed (82.4%), only 6.7% of the drivers of these vehicles were restrained at the time of the crash.

It is important to note that only two of the 10 restrained drivers died of injuries to which wearing the lap belt probably contributed. The deaths of the remaining eight drivers were attributed to *extreme* crash severity (6 drivers), fire (1 driver) and pre-crash heart attack (1 driver).

The same data were re-examined by Campbell and Sullivan (1991; cited by NTSB, 1992, p.2) with a view to assessing cabin crush. Of the 121 cases which could be assessed, they found survivable space remained after the impact in 42 cabins and estimated that 32 of the 42 drivers would not have died if restrained by a seat belt. Extrapolations to national US data led the authors to conclude that 26% (155) of the drivers killed in heavy vehicles during the study period (1st October 1987 to 30th September 1988) would not have died if seat belts had been worn.

Our analyses of the 1990 Fatality File (which includes data on all fatal crashes in Australia in that

year) showed that unbelted drivers were twice as likely to be killed as belted drivers. However, there is a possible alternative explanation of the data. If the driver had left the cabin before the Police arrived, they could code seat belt status as unknown or ask the driver, who would probably state that he was wearing the belt (if one was fitted). Thus, for ambulatory drivers, the quality of seat belt data is likely to be very poor. In crashes in which the driver was killed, the quality of data should be much better. If the driver was retained within the cab, Police or rescue personnel could see if a seat belt was worn. If the driver was ejected, it would be clear that the seat belt was not worn.

Given the strength of truck drivers' beliefs in the danger of remaining in their seat in a crash, there is a need for the safety benefits of seat belts to be clearly established and,assuming they are found, for them to be communicated to drivers. It is possible that only crash testing or other demonstrations in Australia would convince Australian truck drivers.

CONCLUSIONS AND RECOMMENDATIONS

Seat belt wearing rates

Both the pilot study of direct observation and the truck driver interviews showed that the perception that few truck drivers wear seat belts is correct. The interview data suggests that very few drivers of articulated trucks wear seat belts and that seat belts are worn "all the time" by only about 16% of rigid truck drivers.

Why drivers do not wear seat belts

Many truck drivers said that they did not wear seat belts because they were uncomfortable. Others believed that seat belts had no safety benefits or could be dangerous.

Effects of Australian Design Rule changes

The finding that wearing rates were higher in new trucks than old trucks suggests that the changed ADR has improved wearing rates. However, when wearing rates were analysed by where the seat belt connected, drivers with seat-mounted seat belts were no more likely to wear the seat belt than those with vehicle-mounted seat belts.

Achieving greater wearing rates

The finding that drivers of newer trucks had higher wearing rates suggests that overall wearing rates may improve over time as these trucks become a larger proportion of the truck fleet. Yet the turnover of the truck fleet is quite slow and this improvement would take many years.

In most road safety issues, driver behaviour can be changed by increasing the perceived risk of detection or by convincing the driver that the change will reduce the risk of crash or injury. The introduction and promotion of seat belt wearing in cars combined these methods.

The interviews showed that most truck drivers do not believe that wearing a seat belt will reduce their chance of injury in a crash and many believe that seat belts increase the chance of injury. The limited number of investigations that have been undertaken in this area have not settled the issue. Therefore the underlying question to be answered before going ahead with any campaign aimed at improving seat belt wearing rates among truck drivers is whether they do have a net safety benefit. Examination of real-world crashes and crash testing of trucks are two possible methods of examining this issue.

Guidelines for a communications strategy to improve seat belt wearing

If it is established that seat belts do have a net safety benefit, then a campaign encouraging greater wearing rates would be appropriate. In this case campaigns promoting seat belt wearing among truck drivers are more likely to achieve success if drivers of rigid trucks, drivers of articulated trucks and employers are targeted separately. Some possible communication paths to reach these target groups are:

- *enforcement:* one approach is to convince truck drivers that wearing seat belts is compulsory and that police are targeting truck drivers. This approach could be quite effective with rigid, but not articulated, truck drivers and would have most relevance for owner drivers and employees. If this strategy is used, enforcement must occur in reality and would need to await adoption of more uniform laws.
- *employee safety:* truck drivers' behaviours could be indirectly targeted through a communication program aimed at employer organisations. This program should use a variety of media to reach employer organisations.
- *driver safety:* there is a need to convince drivers that a seat belt offers a greater level of driver safety in

trucks. One suggested communication path is the notion of *vehicle control.* It may be possible to convince drivers of rigid, and hopefully articulated, trucks that loss of control is the main danger *and* that loss of control is exacerbated when drivers are not restrained. Employers also represent a useful group to be targeted with this message.

REFERENCES

Administrator of Vehicle Standards. (1989). *Australian Design Rule 4/01. Seatbelts.* Canberra: Federal Department of Transport and Communications.

Administrator of Vehicle Standards. (1988). *Australian Design Rule 5/01. Anchorages for seatbelts and child restraints.* Canberra: Federal Department of Transport and Communications.

Administrator of Vehicle Standards. (1992). *Australian Design Rule 5/02. Anchorages for seatbelts and child restraints.* Canberra: Federal Department of Transport and Communications.

Allison, P. and Tarkir, R (1982). *Heavy truck occupant restraint use.* DOT Technical Report prepared under contract No DTNH-22-81-C-07075. Washington, DC: National Highway Traffic Safety Administration. Cited by National Transportation Safety Board (1992).

Attewell, R. G. and Dowse, M. J. (1992). *Fatal crash types. Analysis of 1988 Fatality File* (CR105). Canberra: Federal Office of Road Safety.

Australian Bureau of Statistics. (1993). *Motor vehicle registrations.* Catalogue No.9303.0.

Campbell, K. L. and Sullivan, K. P. (1991). *Heavy truck cab safety study.* UMTRI-91-28. Ann Arbor, MI: The University of Michigan Transportation Research Institute. Cited by National Transportation Safety Board, 1992.

Copenhaver, M. and Wilkinson, T. (1991). *Heavy truck occupant restraint use.* DOT-HS-807-752. Washington, DC: National Highway Traffic Safety Administration. Cited by National Transportation Safety Board (1992).

Haworth, N., Vulcan, P. and Foong, C. W. (1991). *Analysis of Australian data on truck accidents and assessment of data sources: Australian Truck Safety Study. Task 5* (ARR205). Vermont South: Australian Road Research Board.

Haworth, N. L., Vulcan, P., Schulze, M. T. and Foddy, B. (1991). *Truck driver behaviour and perceptions study. Final report* (No.18). Melbourne: Monash University Accident Research Centre.

National Transportation Safety Board (1992). *Safety Recommendation (H-92-26).* Washington, DC.

National Transportation Safety Board (1990). *Fatigue, alcohol, other drugs, and medical factors in fatal-to-the-driver heavy truck crashes.* Volumes I and II. Safety Study NTSB/SS-90/01 and -90/02. Washington, DC. Cited by National Transportation Safety Board (1992).

Ogden, K. W. (1992). Heavy vehicle safety issues. Paper prepared for National Road Transport Commission.

Ranney, T. (1982). *Injury causation and heavy truck occupant crash protection.* In: Proceedings, 26th annual conference of the American Association for Automotive Medicine. Arlington Heights, Illinois. Cited by National Transportation Safety Board, 1992.

Sweatman, P. (1991). *Review of vehicle factors in truck crashes: Australian Truck Safety Study. Task 2* (ARR202). Vermont South: Australian Road Research Board.

Sweatman, P. F., Ogden, K. W., Haworth, N., Vulcan, A. P. and Pearson, R. A. (1990). *New South Wales Heavy Vehicle Crash Study. Final Technical Report* (CR92, CR5/90). Federal Office of Road Safety and Roads and Traffic Authority of NSW.

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APPENDIX 1. TYPES OF SEATBELTS AND RETRACTORS REQUIRED FOR HEAVY VEHICLES MANUFACTURED ON OR AFTER 1 JULY 1992

Seat belt required	Modified Retractor (July 92 - June 93)	Modified Retractor (Package 20 - June 93 onwards)
Trucks (G.V.M 4.5 to 12 tonnes) **Buses (G.V.M 3.5 to 5 tonnes)**		
Driver - lap/sash with retractors Front outboard passenger - lap/sash with retractors Other passengers - lap belts	Driver - yes Front outboard passenger - No Other passengers - No	Driver- yes if suspension seat and only if anchorages are not part of moving seat. Front outboard passenger - No Other passengers - No
Trucks (G.V.M. over 12 tonnes)		
Driver - lap belts with retractors Front outboard passenger - lap belts with retractors Other passengers - lap belts	Driver - yes Front outboard passenger - No Other passengers - No	Driver, Front outboard passenger, Other passengers -No

HEAVY VEHICLE IN SERVICE BRAKE REQUIREMENTS

Bruce Dowdell
Harry Vertsonis
Roads and Traffic Authority of NSW
Stephen Smith
Air Brake Engineering and Design Pty. Ltd.
Australia
Paper Number 96-S11-W-19

ABSTRACT

Brake testing using roller brake testers is conducted to ensure that brakes are properly maintained. The pass criteria for a roller brake test is currently a minimum of 4kN/wheel and no more than a 30% difference in brake force between wheels on an axle.

There are concerns that:-

1. the minimum brake force requirement is inadequate for heavily laden vehicles and too stringent for lightly laden vehicles;

2. the brake balance requirement across axles is unecessary;

3. the in-service roller brake tester standards do not have any relationship with the braking system standards of Australian Design Rules (ADR's) with which vehicles were originally designed to comply.

As a consequence of the above concerns and following a review of brake test standards in use in other countries a series of tests was conducted with the aim of:

1. determining the relationship between the brake forces measured by the VIT and actual braking performance of a heavy vehicle;

2. determining the relationship between brake force balance as measured by the VIT and actual truck behaviour during braking;

3. establishing a relationship between roller brake testing and standards compliance testing.

A strong relationship has been found to exist between the weight on a wheel and the brake force that wheel is capable of generating. On the basis of this relationship it is proposed to adopt a new minimum braking requirement expressed in kN/tonne.

A relationship between brake imbalance and vehicle performance was also established.

The practicality of the proposed brake test standards has been assessed by evaluating it against the roller brake test data obtained in two statewide heavy vehicle roadworthiness surveys.

1.0 INTRODUCTION

The New South Wales Roads and Traffic Authority (RTA) operates a number of roller brake testers. These are either fixed machines installed at inspection stations or mobile testers incorporated in Vehicle Inspection Trailers (VIT) which are used in roadside testing.

Routine brake testing is conducted to ensure that brakes are properly maintained and are still operating effectively. A vehicle is currently considered to have effective brakes if each brake can generate a specified minimum braking force and if the brakes on each axle are in balance.

The minimum force specified for roller brake testing in NSW is 4 kiloNewtons (kN) per wheel. The maximum imbalance allowed between brakes on one axle is 70 percent (i.e. the brake force on one wheel on an axle must be no less than 70% of the force on the other axle).

The RTA uses VIT's for roadside inspection of heavy vehicles. This requires a means of assessing brake performance with respect to the load the vehicle is carrying as a heavily loaded vehicle needs more braking force than 4 kN/wheel. Alternately a lightly loaded axle may not be able to generate sufficient braking force on the VIT because of the limited amount of friction available.

The minimum braking performance specified in Australia's National Heavy Vehicle Standards is a deceleration rate of 2.8m/s^2. The Australian Design Rules (ADR's) for heavy vehicles also contain specifications for braking performance in terms of deceleration rates or stopping distance from a specified speed. The relationship between brake force as measured by roller brake testers and the actual braking performance of a vehicle is not well documented . This lack of documentation has caused the heavy vehicle industry to question the relevance of roller brake testing and has led to a requirement to justify the roller brake test standard.

This paper describes research conducted with the aims of:

1. Determining the relationship between brake force measured in kN/tonne and actual braking performance (ie. braking distance) of heavy vehicles.

2. Determining the relationship between brake force imbalance and actual truck behaviour during braking.

3. Establishing a standard for roller brake testing.

This research was done by the Roads and Traffic Authority in co-operation with the Commercial Vehicle Industry Association of NSW and the Road Freight Advisory Council, an industry body established to provide advice to the government on transport matters.

2.0 METHODOLGY

The test vehicle and brake testing and data acquisition equipment are described in Appendix A.

2.1 Determination of Minimum Brake Force

To determine the relationship between VIT readings in kN/t and stopping distance the brake forces were varied by adjusting the available air pressure to the brakes while holding the mass of the vehicle and its load constant. For each air pressure setting the vehicle brake forces were measured on the VIT and then braking tests were conducted from a nominal speed of 60/km/hr

The test procedure was as follows:-

a) Remove all load from vehicle

b) Measure weight at each wheel;

c) Calculate necessary brake force to develop 2 kN/t brake force.

d) Adjust maximum air pressure available to each wheel until the required maximum braking force is obtained. Record air pressure.

e) Conduct eight VIT tests on each axle to establish consistency of brake performance.

f) Conduct 10 braking tests from 60km/hr to establish stopping distance.

g) Repeat Steps b) to e) for 3, 4, 5 kN/t braking force.

h) Repeat Steps a) to f) for vehicle masses of 9t and 12 t.

2.2 Determination of Brake Balance Requirement

This series of tests were carried out to determine the effect of brake imbalance on vehicle control.

A brake imbalance was induced in the steer axle by varying the air pressure from side to side on the steer axle. One wheel was maintained at full air pressure and the pressure on the other wheel was reduced to provide 70% and then 30% of the braking effort on the other wheel. It was intended to conduct ten braking tests at each setting.

3.0 RESULTS

3.1 Minimum Brake Force

The results of the testing are contained in the Appendix. Appendix B contains the data on roller brake (VIT) test measurements and Appendix C contains the data on stopping distance/ deceleration rates for each brake force. Table 1 shows the average stopping distance and average brake force for the three load conditions of the truck. It should be noted that the standard deviations from the average were small for both the braking test decelerations and the brake roller test forces.

Table 1

Brake Force vs Stopping Distance (vehicle mass 12.3 tonnes)

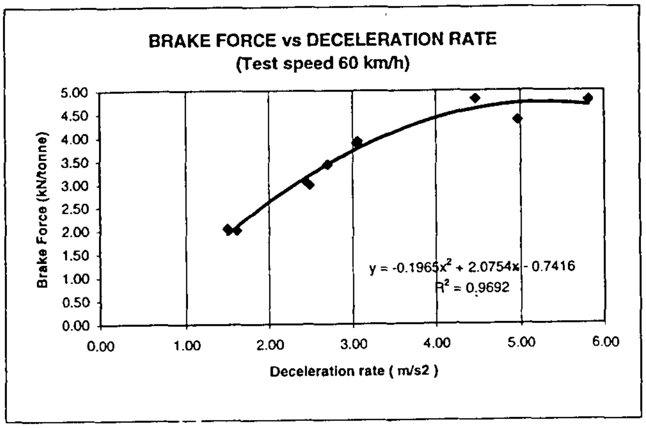
	Brake Force (kN/tonne)	Vehicle Speed (km/h)	Stopping Distance (m)
Average	**2.01**	**61.30**	**90.31**
Std. Dev	0.05	0.38	3.11
Average	**3.00**	**61.34**	**58.72**
Std. Dev	0.05	0.29	2.65
Average	**3.42**	**61.07**	**53.25**
Std Dev	0.04	0.14	1.47
Average	**4.81**	**61.14**	**32.40**
Std. Dev	0.11	0.31	2.29

Brake Force vs Stopping Distance (vehicle mass 5 tonnes)

	Brake Force (kN/tonne)	Vehicle Speed (km/h)	Stopping Distance (m)
Average	**2.05**	**61.62**	**97.48**
Std. Dev	0.12	0.54	4.14
Average	**3.08**	**61.68**	**60.53**
Std. Dev	0.06	0.46	2.85
Average	**3.88**	**61.33**	**47.77**
Std. Dev	0.10	0.48	2.84
Average	**4.80**	**61.18**	**25.13**
Std.	0.08	0.67	2.99

Figure 1 below shows the relationship between the braking force measured on the VIT and the deceleration of the vehicle during braking tests.

Figure 1



3.2 Brake Balance Requirement

Five tests at 70% balance were conducted with one driver and another five tests with another driver. In all cases the vehicle moved out of a 3.5m wide lane under braking. Only one test was conducted at the 30% balance figure as the test had to be aborted due to the violent reaction of the vehicle.

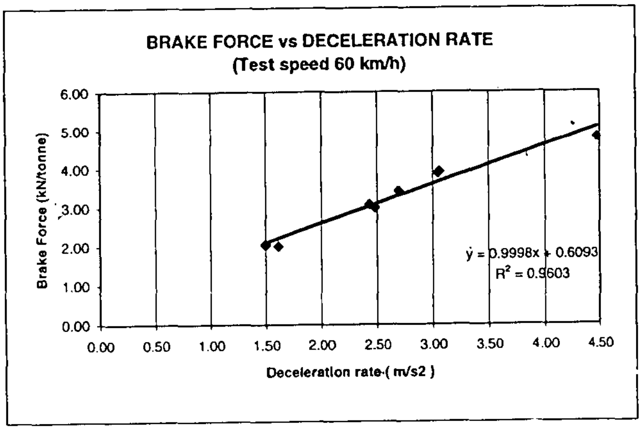
4.0 ANALYSIS

Figure 1 shows the results of the testing with a quadratic trendline fitted. The relationship between brake force and deceleration becomes non-linear at high brake forces. The two highest deceleration rates resulted from tests where the brakes were on full air pressure and had minimum rear axle weight. In one test series the vehicle weighed 5 tonnes and achieved a deceleration rate of 5.81m/s^2, with a measured brake force of 4.8 kN/tonne. In the other series of tests the vehicle weighed 9.2 tonnes and achieved a deceleration rate of 4.97 m/s^2, with a brake force of 4.36 kN/tonne.

It is believed that the non-linearity in the results may be related to the weight transfer of the vehicle during braking or the friction co-efficient between the tyre and the brake tester's rollers.

However, the main focus of brake testing is not the vehicles absolute braking performance. The focus is on establishing that brakes can meet a minimum performance standard. Figure 2 below shows the relationship between brake force and deceleration with the two highest deceleration results removed. The correlation is strongly linear. This linear relationship can then be used to establish the necessary braking force to achieve a given deceleration rate.

Figure 2



It was found that:-

$$B = D + 0.6$$

where D = deceleration in m/s2

B = braking force in kN/tonne vehicle weight

It was concluded that the existing requirement for better than 70% balance between wheels on one axle was reasonable.

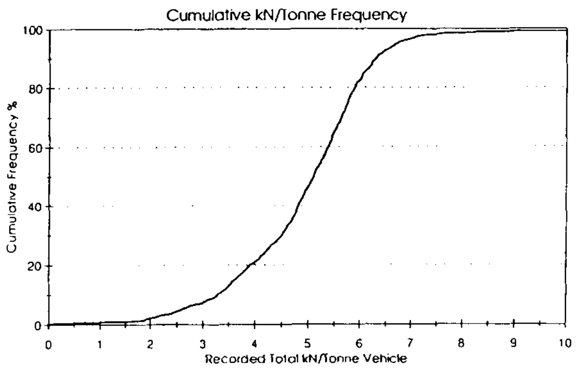
5.0 DISCUSSION

It can be seen from the above relationship that the current brake testing standard is inadequate for loaded vehicles. If all brakes of the test vehicle met the current 4 kN/wheel standard, the unladen vehicle (5 tonnes) would have a brake force of 3.2kN/Tonne. From Figure 3 it can be seen that this would produce a deceleration of 2.4m/s^2 which is less than the regulations require. If the vehicle weighed 12.3 tonnes the deceleration rate would be 0.7 m/s^2.

In late 1995 the RTA conducted a state wide survey of the roadworthiness of approximately 2000 heavy vehicles. The vehicles surveyed included different heavy vehicle types such as rigid truck, articulated drive units, articulated trailers, etc. The number of vehicles in each category surveyed was based on their proportion of the total heavy vehicles registered in NSW and the survey vehicles are considered to be representative of the vehicle fleet in NSW. Figures 3, 4 and 5 are extracts from the survey.

Figure 3 shows the brake force/tonne measured for rigid trucks. From Figure 1 it can be seen that to achieve a deceleration rate of 2.8m/s^{2}a heavy vehicle would need to produce a braking force of 3.4 kN/tonne. If this figure was used to assess the vehicles represented in Figure 3 approximately 10 percent would fail the test. If all vehicles were required to achieve the ADR deceleration rate of 3.76 m/s^2 (from a speed of 60 km/h) then a brake force of 4.4 kN/tonne is required by a vehicle. If this figure was used to assess the vehicles in Figure 3 the failure would be approximately 25%.

Figure 3 Rigid Trucks - NSW



Using the same assessment criteria of 3.4 kN/tonne and 4.4 kN/tonne, the failure rate for articulated drive units, Figure 4, would be approximately 20% and 40% and for articulated trailers, Figure 5, 30% and 50% respectively.

It is proposed in the short term to adopt a standard of 3.4 kN/tonne and 70% brake balance for roller brake testing. This standard will be adopted in conjunction with pattern approval for the roller brake testers. Pattern approval will establish the roller brake testers as certified measuring equipment whose readings will be accepted in court without expert witness evidence to corroborate.

It is proposed to conduct further work to investigate the reason for the variation in brake performance of the rigid vehicles and the articulated vehicles surveyed. Further work will be done to confirm that the relationship Figure

Figure 4 Articulated Drive Units - NSW

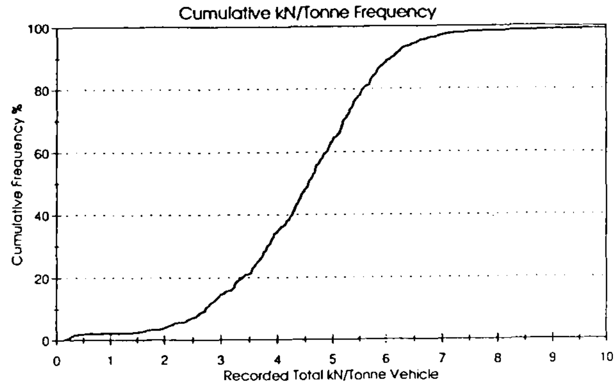
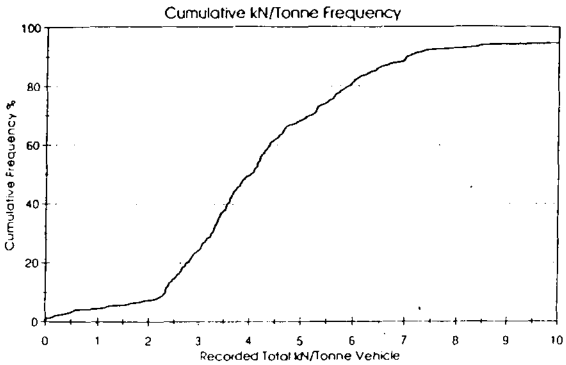


Figure 5 Articulated Trailers - NSW



established for brake force versus deceleration for rigid vehicles also holds for articulated vehicles.

6.0 SUMMARY AND RECOMMENDATIONS

The current requirement that the imbalance between brakes on one axle should be no greater than 70% was found to be reasonable and it is recommended that this standard be maintained. A vehicle with this amount of imbalance cannot be properly controlled under braking.

A relationship has been established between brake performance as measured on a dynamometer and the braking performance of a vehicle on the road. This relationship may be used to establish the minimum braking force required to meet the minimum vehicle decelerations specified in braking standards.

It is proposed that 3.4kN/tonne vehicle weight be used as the standard for roller brake testing.

This standard has been assessed against the data from a survey of the brake performance of the vehicle fleet and it was found that around 10% of the rigid vehicles surveyed would have failed the test. A higher proportion of articulated vehicles would have failed the test. It is proposed to conduct further work to establish if this higher failure rate for articulated vehicles is because a different correlation figure should have been used, or if there is in fact a problem with the performance of brakes on this class of vehicle.

ACKNOWLEDGEMENTS

The authors would like to take this oppurtunity to express appreciation to Bruce Rottenbury and Stephen Humphries of the Roads and Traffic Authority of NSW.

BIBLIOGRAPHY

Strandberg, Lennart "Braking Characteristics of 400 Heavy Trailer Combinations from Denmark, Finland, Norway and Sweden. From: The Twelfth International Technical Conference on Experimental Safety Vehicles, Gothenbury, Sweden May 29 - June 1, 1989.

Baker, A K "Vehicle Braking."

Limpert Rudolf, "Brake Design and Safety."

Sweatman, P "Truckalyser Standards. Road User Research Report 90-91-21", March 1991.

Radlinski, Richard W, Flick Mark A, Clark Gregory S, "Enhancing the Roller Braker Tester". SAE Technical Paper Series 922444

Newcombe T P & Spurr R T "Commerical Vehicle Braking."

Dawson V E & Heistad R H "Ten Years Experience with Brake Testing of Large Mining Trucks in British Columbia". SAE Technical Paper Series 860770

Radlinski, Richard W & Flick Mark A "Benefits of Front Brakes on Heavy Trucks". SAE Technical Paper Series 870493.

Radlinski, Richard W "Braking Performance of Heavy U.S Vehicles". SAE Technical Paper Series 870492.

Senate Report 102-148 "A Report on Various Aspects of the Braking Peformance of Medium and Heavy Trucks". US Department of Transportation DOT HS 807 910, Nov 1992.

"Improved Brake Systems for Commercial Motor Vehicles". US Department of Transportation DOT HS 807 706, Apr 1991.

"NHTSA Heavy Duty Vehicle Brake Research Program Report No. 1 Stopping Capability of Air Braked Vehicles". Volume 1 Technical Report. US Department of Transporation DOT HS 806 738, Apr 1985.

Todorovic J, Duboka C & Arsenic Z "The Real Meaning of Braking Test Results" C444/053/93. Braking of Road Vehicles p 61.

APPENDIX A: TEST EQUIPMENT

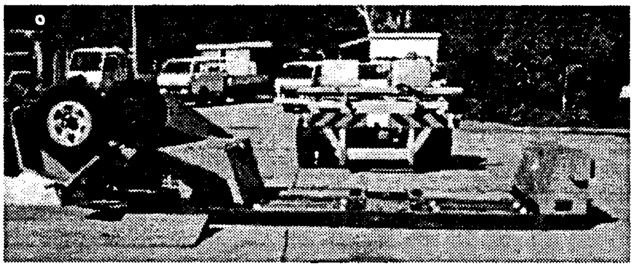
A1: TEST VEHICLE

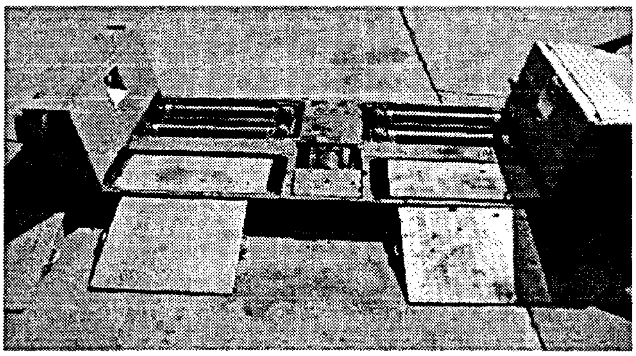
The vehicle used was an International ACCO 1800 truck, a two axle rigid truck with a GVM of 13.9 tonnes. The braking system of the vehicle was overhauled prior to the test and a ABS system was fitted to enable consistent maximum effort braking. Previous testing had shown it was not possible to achieve consistent stopping distances without ABS.

Figure A1 shows a schematic diagram of the braking operation, positioning of the auxilliary air tanks and pressure transducers

The truck was equipped with a purpose built tray to accommodate the test loads. The load consisted of concrete blocks and steel billets. The truck was tested in three load conditions corresponding to vehicle masses of 5, 9.0 and 12.3 tonnes respectively.

A2 Vehicle Inspection Trailer





A3 Correvit

See attachment

A3 DATA RECORDED

The following data was recorded during each test:

DATA	MEASURED BY
a) vehicle speed	Datron "Corevit" using the V1 Sensort
b) air line pressure - measured at: 1. delivery port of the off side front wheel 2. delivery port of the nearside front wheel 3. delivery port of the rear brake relay valve.	Pressure Transducers recording onto a data logger
c) vehicle deceleration	Datron "Corevit" using the V1 Sensort
d) braking distance	Datron "Corevit" using the V1 Sensort
e) deviation f rom straight lane	Measuring wheel
f) temperature of brake drums	Pyrometer (non contact)
g) brake forces at each wheel	VIT
h) vehicle weight	VIT

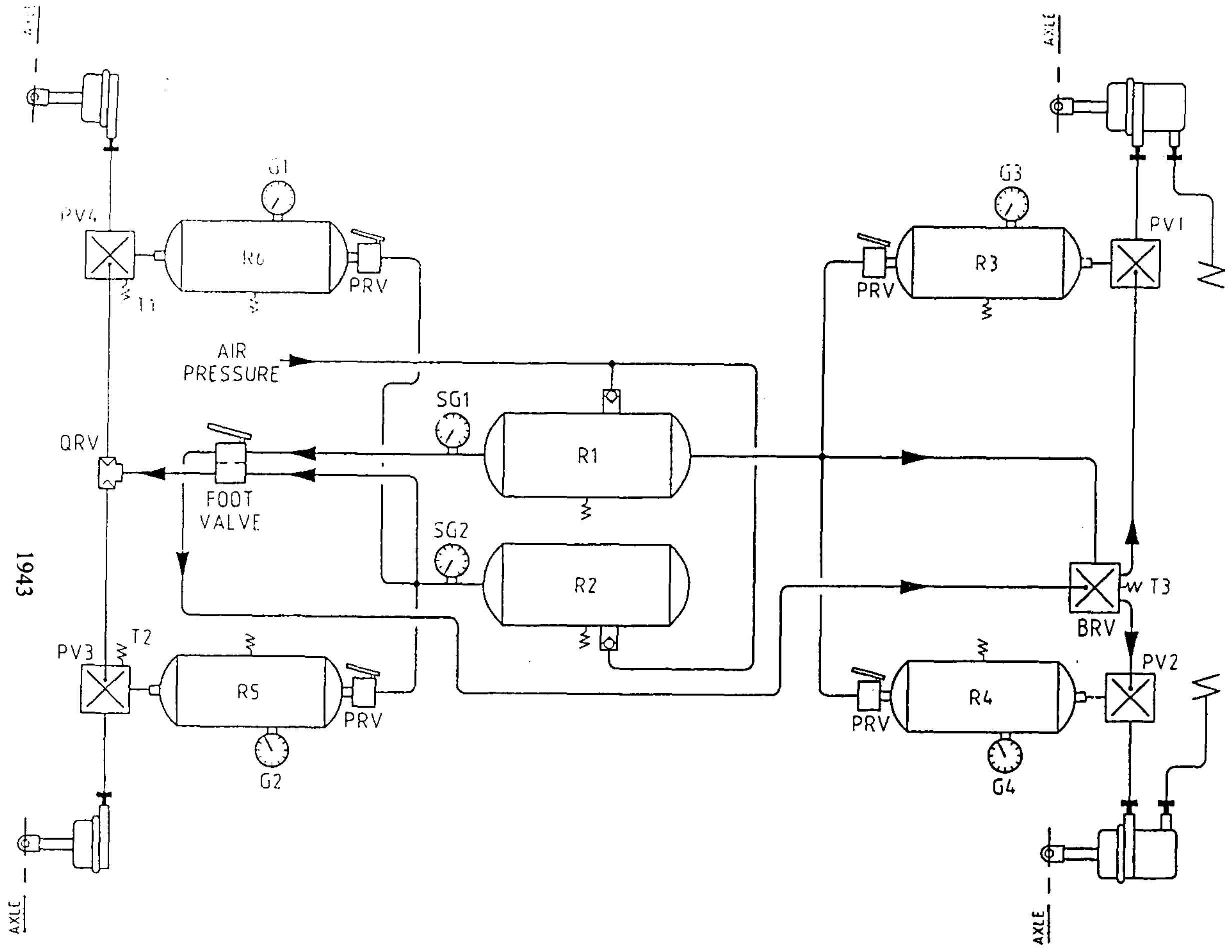


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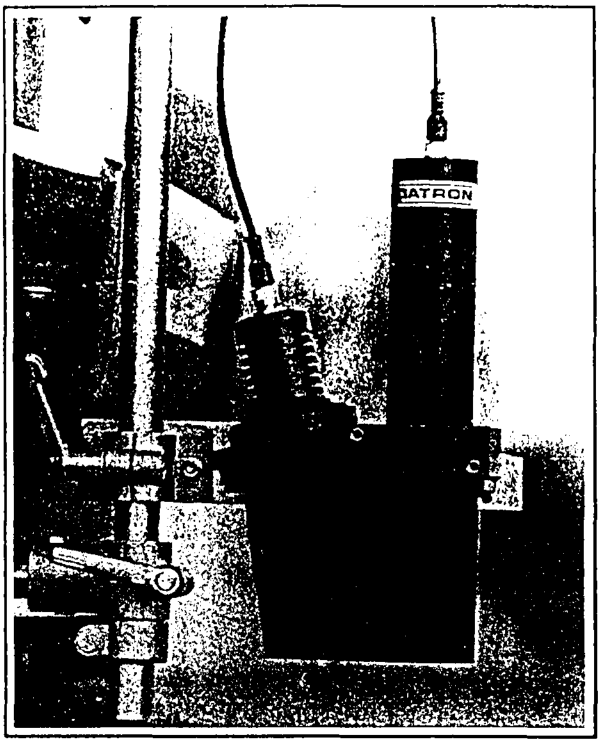
FIGURE A1

LEGEND

T1	#1 Transducer connects to the common delivery port of the pilot valve, provides data on actual pressure delivered to the corresponding wheel.
T2	#2 Transducer, as per #1 transducer connection, only reads the opposite wheel pressure.
T3	#3 Transducer provides data on unmodified brake modulated pressure.
R1	Reservior for primary braking on rear circuit. This reservior part of the normal brake system.
R2	Reservior for primary braking on front circuit.
R3	Additional reservior to create "control situation" for O/S/R vehicle quadrant.
R4	As per R3, control volume for N/S/R quadrant.
R5	As per R3, control volume for N/S/F quadrant.
R6	As per R3, control volume for O/S/F quadrant.
SG1	Indicates service pressure rear circuit.
SG2	Indicates service pressure front circuit.
G1,2,3,4	gauges show quadrant reservior pressures
PV1,2,3,4	low pressure opening relay valves providing individual pressure delivery to each quadrant governed by the setting of the PRV valves.
PRV	manually adjusted pressure regulating valves, used to charge outer tanks to "test" pressure.
QRV	quick release valve for exhaust in front brakes.
BRV	service brake relay valve.

Air Brake Engineering and Design Pty Ltd	Drawn R.P. Date MAR 96	Checked S.D.S Date MAR 96	Approved Date	Title RTA / AIR BRAKE ENGINEERING PNEUMATIC LAYOUT FOR 4x2 TRUCK	Scale : PLOT 1=1	Cad File : DD-01.DWG
					Drawing Number DD-01	Iss 00

A3



DATRON® V-SENSOR

The DATRON V-Sensor is designed as compact, light weight **optical speed vector-sensor** for non contact slip angle or drift angle measurements on test vehicles.

Its electro-optical double array design generates two correlated distance vector signals. Out of these, the following measuring values are computed in the data processor:

• Longitudinal distance:	digital signal
• Lateral distance:	digital signal
• Lateral direction:	digital signal
• Lateral speed:	analog signal
• Longitudinal speed:	analog signal

Alternatively to longitudinal & transversal speed:

• Drift angle α:	analog signal
• Speed amount:	analog signal

The DATRON DAVIT®-Bus allows direct link to the data processing PC. A comprehensive calibration and setup software package is supplied providing the following features:

Article No. 328 130 DV1-Sensor
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- Automatic sensor identification
- Free choice of measuring values
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- Direct interface for an optional light barrier for distance calibration
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TECHNICAL DATA

OUTPUT SIGNALS OF SENSOR ELECTRONICS

Frequency output:
0 to 40 kHz
3 digital outputs (RS 485 driver)
Measured values via mode selectable and calibratable

Analog output:
2 outputs
0 to 10V resp. -5 to +5V
Measured values via mode selectable and calibratable

Serial interface:
DATRON DAVIT-Bus interface for PC

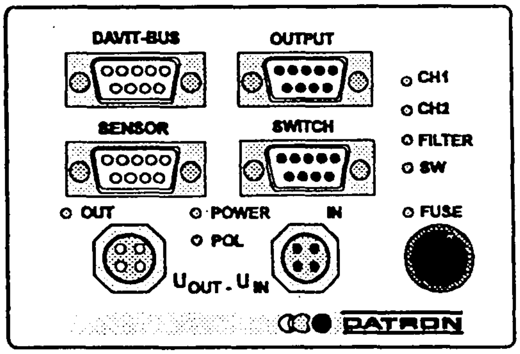
MEASURING DATA

Speed linearity:	< 0.15 % typical
Reproducibility:	< 0.1 % typical
Angle measuring range:	± 25°
Angle resolution:	$\Delta\alpha < 0.1°$
Measuring range of speed DATRON-V1:	Typical 0.50 to 310 kph longitudinal speed
Measuring range of speed DATRON-V2:	Typical 0.50 to 250 kph longitudinal speed
Stand off sensor DATRON-V1:	520 mm from lower surface of the mounting flange
Stand off sensor DATRON-V2:	310 mm from lower surface of the mounting flange
Optical tolerance DATRON-V1:	± 60 mm
Optical tolerance DATRON-V2:	± 20 mm (wheel mounting)
Value of measured field:	ø = 40 mm
Permissible angle error on the mounting:	Horizontal: ± 8° Vertical: ± 4° α: ≤ ± 5°, software compensated

VOLTAGE SUPPLY

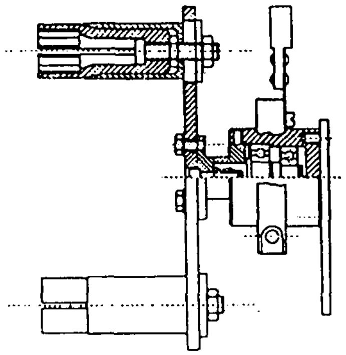
Electronics and halogen illumination:	10.5 to 15V DC 7 W + 50 W (75 W)
PERMISSIBLE TEMPERATURE RANGE:	-25° C to +80° C
WEIGHT Sensor:	1.2 kg
Electronic:	0.8 kg

SENSOR ELECTRONIC



DEVICE FOR WHEEL MOUNTING

(Option for DV2-sensor on request)



DATRON-MESSTECHNIK GmbH reserves the right to modifications and technical improvements without prior notification.

16.08.1994 Kö/Gö/Ho1.S DV1-2ENG.PM4

kN-tonne

APPENDIX B

Table B-1

Full Air **vehicle mass = 5 tonnes**

	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
Test No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	7.60	1.60	8.20	1.60	3.70	0.90	4.20	0.90	23.70	5.00	4.74
2	7.40	1.60	8.30	1.60	4.20	0.90	4.50	0.90	24.40	5.00	4.88
3	7.70	1.60	8.30	1.60	3.80	0.90	3.80	0.90	23.60	5.00	4.72
4	7.60	1.60	8.40	1.60	4.20	0.90	4.20	0.90	24.40	5.00	4.88
5	8.00	1.60	8.50	1.60	4.00	0.90	3.90	0.90	24.40	5.00	4.88
6	8.30	1.60	8.20	1.60	3.60	0.90	3.60	0.90	23.70	5.00	4.74
7	7.90	1.60	8.10	1.60	3.90	0.90	3.70	0.90	23.60	5.00	4.72
8	8.20	1.60	8.50	1.60	3.80	0.90	3.60	0.90	24.10	5.00	4.82
										Average	**4.80**
										Std Dev	**0.08**

Table B - 2

4 kN/tonne **vehicle mass = 5 tonnes**

	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
Test No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	6.40	1.60	6.30	1.60	3.50	0.90	3.20	0.90	19.40	5.00	3.88
2	6.40	1.60	6.10	1.60	3.00	0.90	3.60	0.90	19.10	5.00	3.82
3	6.40	1.60	6.10	1.60	3.60	0.90	3.00	0.90	19.10	5.00	3.82
4	6.30	1.60	6.40	1.60	3.60	0.90	3.30	0.90	19.60	5.00	3.92
5	6.30	1.60	7.00	1.60	3.80	0.90	3.30	0.90	20.40	5.00	4.08
6	5.60	1.60	6.30	1.60	3.60	0.90	3.30	0.90	18.80	5.00	3.76
7	6.40	1.60	6.30	1.60	3.40	0.90	3.00	0.90	19.10	5.00	3.82
8	6.20	1.60	6.30	1.60	3.60	0.90	3.40	0.90	19.50	5.00	3.90
										Average	**3.88**
										Std Dev	**0.10**

Table B - 3

3 kN/tonne **vehicle mass = 5 tonnes**

	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
Test No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	4.90	1.60	4.70	1.60	2.90	0.90	2.60	0.90	15.10	5.00	3.02
2	4.60	1.60	4.80	1.60	2.90	0.90	2.60	0.90	14.90	5.00	2.98
3	4.50	1.60	5.20	1.60	3.10	0.90	2.50	0.90	15.30	5.00	3.06
4	4.70	1.60	5.20	1.60	3.40	0.90	2.50	0.90	15.80	5.00	3.16
5	5.00	1.60	4.60	1.60	3.20	0.90	2.60	0.90	15.40	5.00	3.08
6	4.70	1.60	4.90	1.60	3.00	0.90	2.70	0.90	15.30	5.00	3.06
7	4.70	1.60	5.10	1.60	3.10	0.90	2.50	0.90	15.40	5.00	3.08
8	4.70	1.60	5.60	1.60	3.20	0.90	2.30	0.90	15.80	5.00	3.16
										Average	**3.08**
										Std Dev	**0.06**

APPENDIX B

Table B - 4

2 kN/tonne **vehicle mass = 5 tonnes**

	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
Test No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	3.30	1.60	3.60	1.60	1.90	0.90	2.10	0.90	10.90	5.00	2.18
2	3.10	1.60	2.90	1.60	1.80	0.90	1.50	0.90	9.30	5.00	1.86
3	3.40	1.60	3.20	1.60	2.00	0.90	2.10	0.90	10.70	5.00	2.14
4	3.30	1.60	3.60	1.60	2.40	0.90	1.60	0.90	10.90	5.00	2.18
5	3.10	1.60	2.80	1.60	2.40	0.90	1.70	0.90	10.00	5.00	2.00
6	3.10	1.60	2.80	1.60	2.60	0.90	1.80	0.90	10.30	5.00	2.06
7	3.40	1.60	3.20	1.60	1.80	0.90	1.90	0.90	10.30	5.00	2.06
8	3.10	1.60	2.70	1.60	1.80	0.90	1.90	0.90	9.50	5.00	1.90
										Average	**2.05**
										Std Dev	**0.12**

APPENDIX B

Table B - 5

Full Air **vehicle mass = 12.3 tonnes**

Test	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	12.10	2.25	11.80	2.45	17.90	3.85	17.50	3.75	59.30	12.30	4.82
2	11.50	2.25	12.20	2.45	17.00	3.85	17.10	3.75	57.80	12.30	4.70
3	11.50	2.25	12.40	2.45	16.40	3.85	16.60	3.75	56.90	12.30	4.63
4	12.30	2.25	12.40	2.45	17.10	3.85	17.10	3.75	58.90	12.30	4.79
5	12.50	2.25	12.20	2.45	18.90	3.85	17.80	3.75	61.40	12.30	4.99
6	12.60	2.25	12.20	2.45	18.10	3.85	17.40	3.75	60.30	12.30	4.90
7	12.50	2.25	12.30	2.45	17.70	3.85	16.80	3.75	59.30	12.30	4.82
8	12.50	2.25	12.60	2.45	17.80	3.85	16.60	3.75	59.50	12.30	4.84
										Average	4.81
										Std Dev	0.11

TableB - 6

4 kN/tonne **vehicle mass = 12.3 tonnes**

Test	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	8.70	2.25	9.20	2.45	14.80	3.85	15.20	3.75	47.90	12.30	3.89
2	8.60	2.25	9.70	2.45	14.10	3.85	15.00	3.75	47.40	12.30	3.85
3	8.60	2.25	10.00	2.45	14.90	3.85	15.40	3.75	48.90	12.30	3.98
4	8.60	2.25	8.90	2.45	14.70	3.85	15.80	3.75	48.00	12.30	3.90
5	8.60	2.25	9.20	2.45	14.50	3.85	15.80	3.75	48.10	12.30	3.91
6	8.40	2.25	9.40	2.45	14.90	3.85	15.60	3.75	48.30	12.30	3.93
7	8.40	2.25	10.00	2.45	14.90	3.85	15.60	3.75	48.90	12.30	3.98
8	8.60	2.25	9.50	2.45	15.40	3.85	15.10	3.75	48.60	12.30	3.95
										Average	3.92
										Std Dev	0.04

Table B - 7

3.5 kN/tonne **vehicle mass = 12.3 tonnes**

Test	FRONT AXLE				REAR AXLE				TOTAL		
	LEFT WHEEL		RIGHT WHEEL		LEFT WHEEL		RIGHT WHEEL				
No.	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	FORCE (kN)	WEIGHT (tonne)	KN/TONNE
1	8.50	2.25	8.10	2.45	12.40	3.85	12.90	3.75	41.90	12.30	3.41
2	8.20	2.25	7.80	2.45	14.20	3.85	12.40	3.75	42.60	12.30	3.46
3	8.10	2.25	7.50	2.45	13.60	3.85	12.60	3.75	41.80	12.30	3.40
4	8.00	2.25	7.40	2.45	13.60	3.85	12.80	3.75	41.80	12.30	3.40
5	8.30	2.25	7.60	2.45	12.60	3.85	13.30	3.75	41.80	12.30	3.40
6	8.20	2.25	8.50	2.45	13.60	3.85	12.60	3.75	42.90	12.30	3.49
7	7.80	2.25	8.20	2.45	13.40	3.85	12.50	3.75	41.90	12.30	3.41
8	8.10	2.25	7.70	2.45	13.50	3.85	12.60	3.75	41.90	12.30	3.41
										Average	3.42
										Std Dev	0.03

APPENDIX B

Table B - 8

3 kN/tonne vehicle mass = 12.3 tonnes

Test No.	FRONT AXLE LEFT WHEEL FORCE (kN)	FRONT AXLE LEFT WHEEL WEIGHT (tonne)	FRONT AXLE RIGHT WHEEL FORCE (kN)	FRONT AXLE RIGHT WHEEL WEIGHT (tonne)	REAR AXLE LEFT WHEEL FORCE (kN)	REAR AXLE LEFT WHEEL WEIGHT (tonne)	REAR AXLE RIGHT WHEEL FORCE (kN)	REAR AXLE RIGHT WHEEL WEIGHT (tonne)	TOTAL FORCE (kN)	TOTAL WEIGHT (tonne)	TOTAL KN/TONNE
1	6.70	2.25	7.00	2.45	11.00	3.85	11.50	3.75	36.20	12.30	2.94
2	6.80	2.25	7.30	2.45	10.80	3.85	11.80	3.75	36.70	12.30	2.98
3	6.70	2.25	7.60	2.45	11.10	3.85	11.40	3.75	36.80	12.30	2.99
4	6.80	2.25	7.20	2.45	11.00	3.85	11.80	3.75	36.80	12.30	2.99
5	6.70	2.25	7.10	2.45	11.80	3.85	11.50	3.75	37.10	12.30	3.02
6	6.70	2.25	7.50	2.45	10.90	3.85	12.00	3.75	37.10	12.30	3.02
7	7.00	2.25	7.90	2.45	11.30	3.85	11.90	3.75	38.10	12.30	3.10
8	6.50	2.25	7.60	2.45	11.40	3.85	11.00	3.75	36.50	12.30	2.97
										Average	3.00
										Std Dev	0.05

Table B - 9

2 kN/tonne vehicle mass = 12.3 tonnes

Test No.	FRONT AXLE LEFT WHEEL FORCE (kN)	FRONT AXLE LEFT WHEEL WEIGHT (tonne)	FRONT AXLE RIGHT WHEEL FORCE (kN)	FRONT AXLE RIGHT WHEEL WEIGHT (tonne)	REAR AXLE LEFT WHEEL FORCE (kN)	REAR AXLE LEFT WHEEL WEIGHT (tonne)	REAR AXLE RIGHT WHEEL FORCE (kN)	REAR AXLE RIGHT WHEEL WEIGHT (tonne)	TOTAL FORCE (kN)	TOTAL WEIGHT (tonne)	TOTAL KN/TONNE
1	4.60	2.25	4.20	2.45	6.80	3.85	8.00	3.75	23.60	12.30	1.92
2	4.60	2.25	4.20	2.45	7.80	3.85	8.10	3.75	24.70	12.30	2.01
3	4.80	2.25	4.70	2.45	8.00	3.85	7.70	3.75	25.20	12.30	2.05
4	4.50	2.25	4.80	2.45	8.00	3.85	7.50	3.75	24.80	12.30	2.02
5	4.60	2.25	4.50	2.45	8.10	3.85	7.30	3.75	24.50	12.30	1.99
6	4.60	2.25	4.10	2.45	8.30	3.85	7.20	3.75	24.20	12.30	1.97
7	4.60	2.25	4.10	2.45	8.50	3.85	7.90	3.75	25.10	12.30	2.04
8	4.60	2.25	4.70	2.45	8.50	3.85	8.00	3.75	25.80	12.30	2.10
										Average	2.01
										Std Dev	0.05

Table B - 10

full air vehicle mass = 9.2 tonnes

Test No.	FRONT AXLE LEFT WHEEL FORCE (kN)	FRONT AXLE LEFT WHEEL WEIGHT (tonne)	FRONT AXLE RIGHT WHEEL FORCE (kN)	FRONT AXLE RIGHT WHEEL WEIGHT (tonne)	REAR AXLE LEFT WHEEL FORCE (kN)	REAR AXLE LEFT WHEEL WEIGHT (tonne)	REAR AXLE RIGHT WHEEL FORCE (kN)	REAR AXLE RIGHT WHEEL WEIGHT (tonne)	TOTAL FORCE (kN)	TOTAL WEIGHT (tonne)	TOTAL KN/TONNE
1	9.50	1.70	8.70	1.60	11.30	2.85	10.00	2.90	39.50	9.05	4.36
2	8.90	1.70	8.30	1.60	11.10	2.85	9.70	2.90	38.00	9.05	4.20
3	9.20	1.70	8.60	1.60	12.50	2.85	10.70	2.90	41.00	9.05	4.53
4	9.20	1.70	8.60	1.60	11.60	2.85	9.90	2.90	39.30	9.05	4.34
5	8.50	1.70	8.50	1.60	12.20	2.85	10.50	2.90	39.70	9.05	4.39
6	8.20	1.70	8.40	1.60	12.10	2.85	10.60	2.90	39.30	9.05	4.34
7	8.00	1.70	8.40	1.60	12.00	2.85	10.70	2.90	39.10	9.05	4.32
										Average	4.36
										Std Dev	0.10

APPENDIX C

Table C-1

full air tests
vehicle mass = 12.3 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s$^{2)}$
1	61.40	34.60	4.20
2	60.70	33.90	4.19
3	61.30	35.80	4.05
4	60.90	32.20	4.44
5	61.50	33.00	4.42
6	60.90	29.10	4.92
7	61.50	31.00	4.71
8	60.70	28.60	4.97
9	61.30	32.50	4.46
10	61.20	33.30	4.34
average	**61.14**	**32.40**	**4.47**
std dev	**0.31**	**2.29**	**0.31**

Table C-2

full air tests
vehicle mass = 5 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s^2)
1	61.60	29.70	4.93
2	61.40	22.90	6.34
3	60.60	22.70	6.25
4	60.50	22.90	6.16
5	62.50	29.30	5.15
6	61.40	25.50	5.70
7	61.10	28.50	5.05
8	60.10	22.50	6.21
9	61.20	22.30	6.49
10	61.40	25.00	5.79
average	**61.18**	**25.13**	**5.81**
std dev	**0.67**	**2.99**	**0.58**

Table C-3

4kN tests
vehicle mass = 12.3 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s$^{2)}$
1	61.90	47.00	3.15
2	60.90	46.40	3.08
3	61.80	47.50	3.10
4	60.10	45.10	3.09
5	61.70	48.90	3.00
6	60.00	46.10	3.01
7	61.30	46.10	3.14
8	61.80	52.10	2.83
9	62.30	48.30	3.10
10	61.60	48.10	3.04
average	**61.34**	**47.56**	**3.06**
std dev	**0.79**	**2.09**	**0.09**

Table C-4

4kN tests
vehicle mass = 5 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s$^{2)}$
1	61.30	50.70	2.86
2	61.30	48.90	2.97
3	61.90	48.80	3.03
4	61.30	49.70	2.92
5	61.70	53.00	2.78
6	60.70	45.90	3.09
7	60.80	45.80	3.12
8	61.90	45.40	3.25
9	61.60	45.30	3.23
10	60.80	44.20	3.23
average	**61.33**	**47.77**	**3.05**
std dev	**0.48**	**2.84**	**0.16**

APPENDIX C

Table C-5

3.5kN tests
vehicle mass = 12.3 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s²)
1	61.10	53.70	2.68
2	61.10	51.80	2.78
3	61.10	53.70	2.68
4	61.30	54.70	2.65
5	61.00	52.20	2.75
6	60.80	52.60	2.71
7	61.10	55.60	2.59
8	61.00	52.60	2.73
9	61.00	51.20	2.80
10	61.20	54.40	2.66
average	**61.07**	**53.25**	**2.70**
std dev	**0.14**	**1.47**	**0.07**

Table C-6

3kN tests
vehicle mass = 12.3 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s²)
1	61.40	53.70	2.71
2	61.70	60.60	2.42
3	61.30	60.30	2.40
4	60.80	55.90	2.55
5	61.80	62.50	2.36
6	61.50	61.30	2.38
7	61.30	59.10	2.45
8	61.20	57.30	2.52
9	61.30	58.70	2.47
10	61.10	57.80	2.49
average	**61.34**	**58.72**	**2.48**
std dev	**0.29**	**2.65**	**0.10**

Table C-7

3kN tests
vehicle mass = 5 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s²)
1	61.80	63.60	2.32
2	61.80	58.10	2.53
3	61.70	59.00	2.49
4	62.30	63.00	2.38
5	61.60	61.40	2.38
6	61.30	58.10	2.50
7	61.30	62.00	2.34
8	61.90	59.60	2.48
9	60.80	55.80	2.58
10	62.30	64.70	2.32
average	**61.68**	**60.53**	**2.43**
std dev	**0.46**	**2.85**	**0.09**

APPENDIX C

Table C-8

2kN tests
vehicle mass = 12.3 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s^{2})
1	60.80	86.00	1.66
2	61.70	95.10	1.55
3	61.20	90.60	1.59
4	61.60	93.60	1.56
5	61.80	94.30	1.56
6	60.80	89.70	1.59
7	61.60	90.20	1.62
8	61.40	88.50	1.65
9	61.20	87.50	1.65
10	60.90	87.60	1.63
average	**61.30**	**90.31**	**1.61**
std dev	**0.38**	**3.11**	**0.04**

Table C-9

2kN tests
vehicle mass = 5 tonne

Test Number	Speed	Stopping Distance	Decel. Rate
	(km/h)	(m)	(m/s^{2})
1	61.80	100.20	1.47
2	60.70	97.30	1.46
3	61.80	102.90	1.43
4	62.10	93.50	1.59
5	61.70	93.50	1.57
average	61.62	97.48	1.50
std dev	0.54	4.14	0.07

APPENDIX C

Table C-10

full air tests vehicle mass = 9.1 tonne

test number	speed	stopping	decel
		distance	
	km/h	m	m/s2
1	60.10	28.80	4.84
2	60.80	28.60	4.98
3	61.40	32.80	4.43
4	60.90	29.00	4.94
5	60.10	27.60	5.05
6	61.20	30.90	4.68
7	60.40	30.70	4.58
8	61.80	28.70	5.14
9	60.50	26.60	5.31
10	61.20	25.30	5.72
average	**60.84**	**28.90**	**4.97**
std dev	**0.57**	**2.17**	**0.37**

FLASHING WARNING LIGHTS FOR SCHOOL BUSES

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Paper Number 96-S11-W-22

ABSTRACT

Motorists who are approaching a bus which is picking up or dropping off school children should be alert to the possibility of children crossing the road. In country areas of New South Wales the motorists may be travelling at speeds around 100km/h. At this speed the warning signal should be readily seen at 250 metres in order for the motorist to be able to detect and react to the signal and to slow down without heavy braking. In bright daylight conventional vehicle signalling systems, such as direction indicator lamps, do not provide this required signal range. Traffic signals practice suggests that much brighter lights are required.

A dilemma is that bright warning lights might cause discomfort and glare at dusk or at night. The authors examined the geometry of a typical scenario for a car encountering a bus at the side of the road. It was found that a warning light system could be specified which achieved the required signal range but which, due to its high mounting position on the bus and sharp vertical cut-off of the light distribution downwards, enabled motorists to move into a lower intensity portion of the beam as they approached the bus.

INTRODUCTION

School children who are hurrying to catch a bus in the morning or who have just disembarked from a bus in the afternoon might not cross the road with care (RTA 1992, Staysafe 1994). Motorists in the vicinity of the bus should be alert to the possibility of children on the road. These motorists should be travelling at a speed which gives them a reasonable chance to stop in time if a hazardous situation arises.

In New South Wales (NSW) current practice is to have "wig wag" yellow flashing lights and signs at the front and rear of the bus. The authors were engaged by the NSW Department of Transport to investigate the suitability of several proposed signalling systems, together with the current system. This paper describes the outcome of an analysis of the technical and visual ergonomic requirements of signalling systems fitted to school buses.

FUNCTIONAL REQUIREMENTS

The function of a school bus signalling system is to alert motorists who are approaching from either direction to the possibility of children on the road in the immediate vicinity of a bus which is stationary or has just departed. This must occur at a sufficient distance to enable the motorist to take action to avoid an accident.

To be effective the system must satisfy each of three requirements (after Lay, 1981):

i. It must be *readily seen* by approaching motorists and it must *command their attention*. It must be conspicuous from other signals and signs and the general visual clutter at the front and the rear of buses. It must stand out in adverse lighting conditions such as bright daylight.

ii. It must be *recognised* as indicating the possibility of school children in the immediate vicinity of the bus, in a clear, credible and unambiguous manner.

iii. It must elicit an *appropriate response* from the motorists, such as slowing down and preparing to stop to avoid an accident.

What is a sufficient distance?

It is assumed that a motorist is to be travelling at no more than 40km/h when passing a bus with its flashing lamps operating. Research into pedestrian-vehicle collisions has shown that the proportion of these accidents which are fatal increases sharply as the speed of collision rises. This increase occurs at about 40km/h (Fisher and Hall 1972). Roads adjacent to many NSW schools now have a 40km/h speed limit which applies during school travel hours.

The motorist will require a distance away to see the signal (the signal range) which takes into account the distance travelled during the response time to the signal, the distance travelled during slowing down to 40km/h and the distance over which to stop from 40km/h, if necessary (the buffer zone). These three stages are illustrated in Figure 1.

The response time (driver's reaction time to the signal plus time before vehicle starts to decelerate) is typically taken to be 2.5 seconds in Australian traffic engineering practice (Lay, 1981). This, and a shorter, more optimistic time of 1.5s, will be used in the analysis.

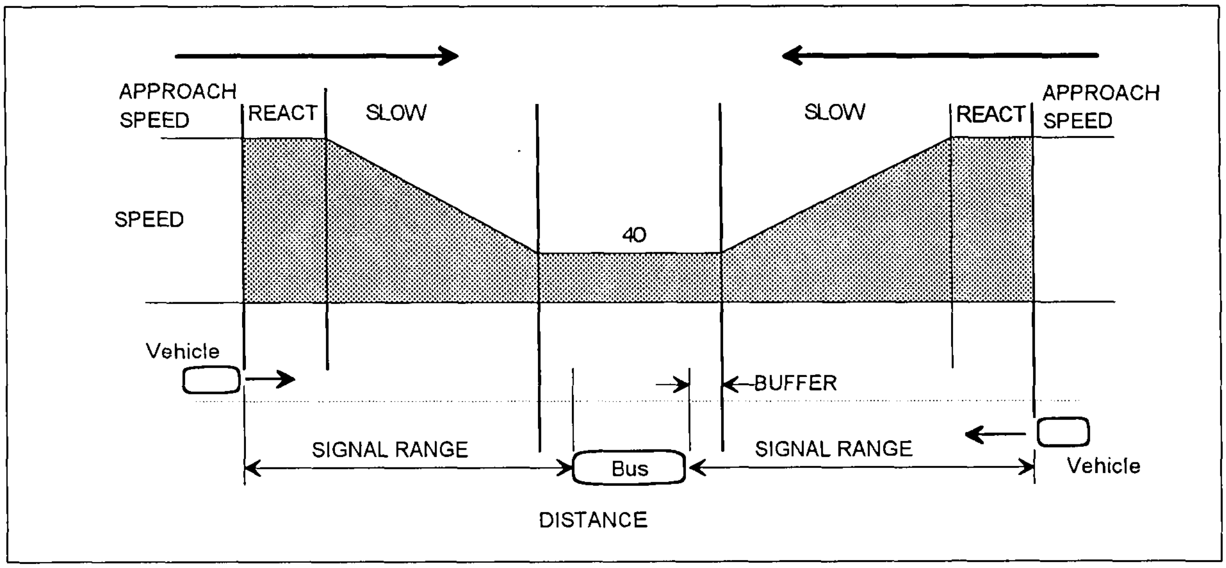

Figure 1. Derivation of signal range for vehicles approaching the bus from either direction.

It is preferable that the motorist does not brake heavily because this may be a hazard to following traffic and it could also lead to reluctance to slow down if school buses with lights flashing are repeatedly encountered on the road. On a level road at 100km/h a typical vehicle will decelerate at between 0.5 and 1 metres per second per second (m/s/s) without the use of brakes. Under gentle braking a deceleration of 2m/s/s is regarded as comfortable. Heavy braking involves decelerations of around 5m/s/s (all decelerations described in this paper are average, not peak).

From these values the distance at which a signalling system on the bus has to be first seen by an approaching motorist can be calculated. The formula is:

$$s = ((V^2 - v^2)/2a) + Vt + d \qquad (1.)$$

Where
s = distance from motorist to bus, signal range (m)
V = initial speed (m/s)
v = final speed (m/s, 11.1m/s = 40km/h)
a = average deceleration (m/s/s)
t = motorist response time (s)
d = buffer zone; distance before bus at which the final speed is to be achieved to enable the motorist to stop if necessary (m)

The buffer zone distance can be derived from equation (1) by substituting a final speed of zero and is about 30m for an initial speed of 40km/h and an alert response time with heavy braking.

Table 1 shows the application of Equation 1 to several scenarios.

Table 1
Signal Range Required to Slow from 100km/h to 40km/h, Including a 30m Buffer Zone

Type of braking	Deceleration m/s/s	Distance for typical reaction time (2.5s)	Distance for alert reaction time (1.5s)
None (engine braking)	1.0	424	396
Gentle	2.0	261	234
Heavy	5.0	164	136

The distances involved are often not appreciated by motorists who might not realise that, at 100km/h, they have typically travelled some 70m after a hazard/signal first became visible before their foot even hits the brake pedal. To enable a motorist to see and respond to a signal and slow down under engine-braking from 100km/h to 40km/h the signal range must be about 400m. If the signal range is 250m then gentle braking will usually be required in order to slow to 40km/h. A signal range less than about 150m will usually require heavy braking.

On the basis of this analysis, the signal on a school bus should be visible and recognisable at no less than 250m for buses operating in 100km/h areas (this assumes some gentle braking will be required and it includes a 30m buffer). A minimum of 100m is required for buses operating in 60km/h areas but a common signal range of 250m for all buses is preferable for uniformity.

SIGNAL LIGHTS FOR DAYTIME USE

There is a sound knowledge of signal light requirements derived from research and practical experience on which to base requirements of signal lights.

The human eye is more sensitive to a light source the closer that source is to the line of sight. This means that the further a signal is from the line of sight the brighter it will need to be to elicit a response. The necessary luminous intensity of a signal will also increase as the square of the distance away. The relationship is:

$$I = 2Kd^2L_Bx10^{-6} \qquad (2.)$$

where

I = Optimum luminous intensity of a steady red signal for a required signal range (cd)

$K = (a/3)^{1.33}$

a = angle of the signal from line of sight (degrees, minimum 1^0)

d = required signal range (m)

L_B= background brightness (cd/m^2)

The formula is the outcome of considerable research (Cole & Brown, 1968, Fisher & Cole, 1974). The optimum intensity is that which invokes, essentially, 100% probability of seeing, coupled with a near minimum reaction time. This and other data form the basis of Australian Standard AS2144 (AS 1989) and international recommendations (CIE 1988) on the photometric specification for traffic signals.

It should be noted that the intensity is directly proportional to the brightness of the background to the signal. Typical values of background luminance range from 10,000 cd/m2 on a bright day to 100 cd/m2 or less around dusk. Therefore the range of a signal of given intensity can vary by a factor of more than 10 depending on background lighting conditions (intensity is

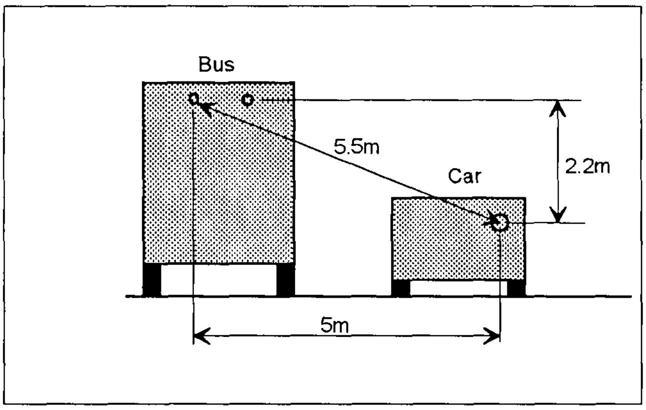

Figure 2. Derivation of offset distance for a typical car/bus geometry. Looking from rear with right-hand drive vehicles.

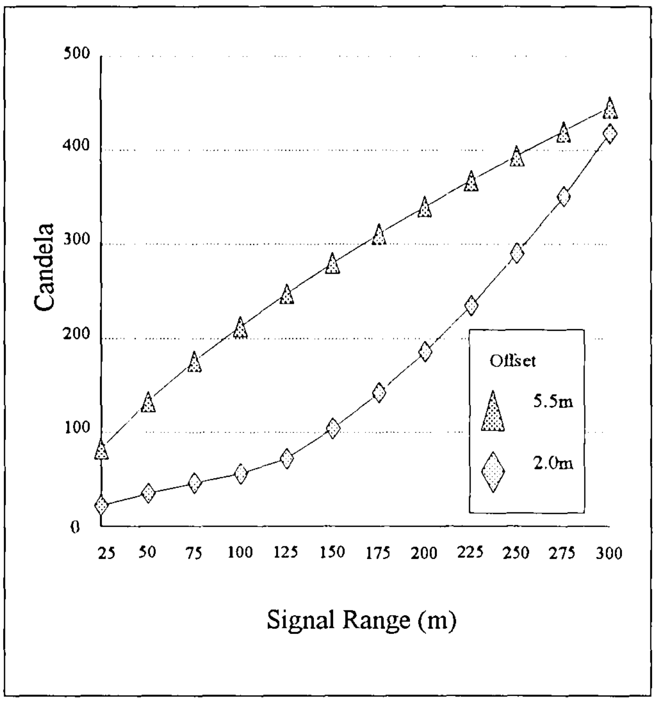

Figure 3. Relationship between signal intensity & signal range for a steady red light, based on constant offset and a background brightness of 10,000cd/m².

proportional to the square of range). This is why signals of relatively low intensity can appear quite adequate for long distances under favourable (dull) lighting conditions while being unsuitable for bright conditions.

For a given signal offset (Figure 2.), the angle of the signal will be proportionally closer to the line of sight as the distance increases. Applying this effect to Equation 1, the luminous intensity requirements for a *steady red signal light* for various signal ranges are given in Figure 3. These are shown for an offset of 5.5m, which is typical for a car approaching a school bus which is pulled off to the side of the road (see Figure 2), and an offset of 2m, which is more typical of a car following another car. The bus-car geometry assumes that the lights are mounted as high as practicable on the bus. This has advantages in reduced discomfort and glare for motorists approaching the bus under dull background lighting conditions (described later) and it also provides maximum range when the bus stops beyond a crest in the road.

The intensity values for yellow signals need to be three times that for red for equal visual performance (Fisher & Cole, 1974). This will not normally be a problem in practice since a yellow lens can transmit about 3 times the light from an incandescent lamp over that for a red lens and therefore the wattage of the lamps needed will be the same.

Using Equation 2, the following signal intensity requirements can be deduced, as shown in Table 2.

Table 2.
Signal Intensities for Two Signal Ranges with *Steady* Signals Viewed Against a Sky Background of 10,000cd/m² and an Offset of 5.5m

Signal Range (m)	Signal Intensity (cd)	
	Steady Red Signal	Steady Yellow Signal
100	210	630
250	390	1170

These intensities relate to in-service equipment; some addition on these values is needed to take into account dirt, deterioration and flashing of the signals. On the other hand, these intensities are for a high, but not uncommon, brightness of sky background (Fisher & Cole, 1974), without any black backboard. They also allow for the observers gaze to be not directly towards the signal.

Road Traffic Control Signals

In Australian Standard AS2144 (AS 1989) the minimum luminous intensity of traffic signals are specified, as shown in Table 3:

Table 3.
AS2144 Minimum Traffic Signal Intensity (cd)

Type of signal	Range (m)	Red	Yellow
General Purpose	100	200	600
Extended range	240	600	1800

These values apply to new equipment, are on-axis values and provide the range when viewed against a sky background of 10,000cd/m², the signals being fitted with black backboards.

The values at 100m signal range match those of Table 2. The values for extended range traffic signals exceed those of Table 2 since traffic signals have a greater offset (Hulscher 1975).

Vehicle Signals

The large majority of vehicles in Australia are fitted with single intensity lamps which are used day and night. These are a compromise between the necessity of a relatively high intensity by day and limiting the intensity at night so lamps are not excessively bright.

In the case of yellow aftermarket lamps intended for use as either front or rear vehicle turn signals, a manufacturer would logically aim for an intensity around 200cd which is the maximum permitted for single-intensity rear mounted turn signals. In bright daylight these would provide a signal range of about 100m when used on a car or small trailer but they become ineffective when high-mounted on a large vehicle such as a bus. Referring to Figure 3, a 200cd yellow signal is equivalent to a 67cd red signal which has a range of about 100m when used on a car but less than 25m when high-mounted on a bus.

SAE Standard J887

Many school buses in the USA are fitted with bright red and yellow flashing warning lamps. SAE Standard J887 "School Bus Warning Lamps" (SAE 1987) which sets out requirements for these signal lights, including photometric performance. The signal units are tested at operational voltage (e.g 12.8V or 25.6V). Requirements are for total luminous intensity in prescribed zones. The Standard also includes guidelines for meeting the zonal requirements. These guidelines are summarised in Table 4.

Table 4.
SAE J887 Guidelines for Yellow Signal Units

Degrees Up & Down (-ve)	Degrees Left (Right is mirror image)				
	30	20	10	5	0
10				50	125
5		375	750	750	750
0	75	450	1000	1250	1500
-5	75	500	750	1125	1125
-10				100	100

The intensity at the reference axis (0,0) in Table 4 is similar to the required values for yellow signals at 250m signal range given in Table 2. The values are even closer if the reduced effective intensity of flashing signals is taken into account in evaluating the requirements of the SAE standard. The values in the SAE standard are minima, no maximum values are given. There appears to be no guard against the signals being excessively bright at night.

Intensity Requirements for School Bus Signals

The requirements set out in Table 2 are for steady lights against a bright background sky, without target or backboard. Several factors would need to be taken into account when applying these requirements to the school bus scenario.

Flashing Signals - Lights may be made to flash. Contrary to popular belief, a flashing light is more difficult to detect initially than a steady one of the same intensity. However, once detected a flashing light is more likely to demand inquiry or be taken notice of than a steady light. In order to maintain the same signal range, the intensity of a flashing light will need to be increased over that of a steady light (Cole 1972, Holmes 1971).

Assuming a signal to flash at 60 cycles per minute (typical for flashing turn signals), with the off time equal to the on time, then the intensity will need to be increased by a factor of about 1.4 times to that derived from Equation 2. Even greater intensity would be required for a faster rate of flashing but, in any case, there are technical limits to the rate at which automotive lamps can be flashed (e.g. losses due to incomplete heating up of the filament and decreased service life).

Cycle Time -A property related to flashing rate is cycle time. The message should become unambiguous when a complete cycle of the signal system has elapsed and the next cycle begins. In the case of single colour wig-wag signals this will be after three light operations (e.g. left, right then left) and the total time will be about 1.5 seconds. This duration is similar to the response time used in Equation 1. In effect the cycle time is part of the process of recognition of the signal.

Dirt & Deterioration - The signal may become dirty and the hardware deteriorate over time. Taking these factors into account a nominal factor of 1.1 is used to cover the in-service deterioration of signal intensity.

Backboards - In the case of buses it is not practical to fit a black backboard of sufficient size to improve the signal range. This is because the angle between the edge of the signal and the outer edge of the backboard needs to be about 1° in order to effectively isolate the signal from the background (Fisher & Cole 1974). This translates to a backboard diameter of about 4m when viewed from 250m. No allowance is therefore made for backboards.

Derived signal intensities - Applying these factors to the values in Table 2, and rounding the results, leads the values in Table 5.

Table 5.
Necessary Signal Intensities for *Flashing* Signals on School Buses

Signal Range (m)	Signal Intensity (cd)	
	Red	Yellow
250	600	1800
100	300	900
50	200	600

DUSK & NIGHT-TIME CONDITIONS

The intensity requirements for the school bus signals are those for a bright day background. For low ambient brightness, particularly at night, care needs to be taken to guard against the possibility that high intensity signals might be overbright. This has the potential to produce glare, manifested by making the view of the signal discomforting to the approaching motorist and possibly degrading visibility.

The limitation of these adverse effects is generally given much attention in the provision of lighting and signalling at night. Light directly towards the eyes of motorists is kept to the minimum practicable.

The specified maximum intensity limit for red traffic signals is 1000cd (AS 1989), there being no limit to the yellow signal "in view of the relatively short intervals for which such signals are normally displayed". The standard suggests that the 1000cd should normally satisfactorily limit glare, at night, from signals used on roads where traffic route lighting is installed. However where roads have local road lighting or are unlit authorities are advised to consider installing signals with intensities not greater than 350cd.

Essentially similar values of intensity are embodied in road lighting standards (AS 1973) viz, 1000cd and 500cd maximum intensities for the light emitted at the horizontal from luminaires used for traffic route and local road lighting respectively.

In Australia the maximum values for vehicle yellow turn signals are 700cd and 200cd for front and rear signals respectively. The maximum intensity from the white low beam headlight in the direction of oncoming motorists is 437.5cd.

There is evidence that the intensity of a yellow light can be higher than that of a white light before being deemed unsatisfactory; the results of some investigations suggest that it can be 40% greater (van Bommel & de Boer 1980).

Practice leads to the conclusion that, in order for a light not to be glaring when viewed at night, it should have a maximum intensity of about 1000cd in the direction of view, preferably less if the road is poorly lit or unlit. Reference to Table 5 shows that the required peak intensity of the light beam of a yellow bus signal (1800cd) needs to be greater than this in order to fulfil its alerting role.

A SCHOOL BUS SIGNAL SPECIFICATION

There arises the common problem in road traffic signalling of reconciling the need for high intensity by day and low intensity by night. This problem has been tackled in a number of ways. One is by the use of a dual day-night system, with dimming of the signal at night;

although this is the best solution it has not found favour in application in Australia. Another is to have a compromise day-night system. This has been generally applied to vehicle lighting in Australia.

A third way is to give careful attention to the light beam shape. This is done for the vehicle headlight low beam in which the high intensity portion for forward seeing and the low intensity portion for limiting glare are sharply separated. The authors therefore examined whether this approach could be applied to the school bus signal.

Only at 250m away is it necessary for the motorist to experience the elevated intensity (1800cd), whilst closer to the bus (100m) the required signal intensity decreases substantially (900cd), even though still producing a clear signal. When very close to the bus (50m and less) the motorist should only be subjected to the same intensity as would be experienced with conventional turn signals, i.e 200cd to 700cd.

In order to set out a specification for the complete angular light intensity distribution for a signal light it is necessary to analyse the angular position of the signal in the field of view as the motorist approaches the bus. A desirable outcome is that motorists are in the high-intensity part of the beam some distance from the bus in order to be alerted and then move into a lower intensity portion of the beam when they get closer to the bus, to alleviate any potential over brightness of the signal.

Using the offsets of the motorist to the bus shown in figure 2. (viz eyes to far signal light; 2.2m vertical and 5.0m horizontal), the angular offsets during approach to a bus are obtained as shown in Table 6.

Table 6.
Angular Offsets for Various Distances from the Bus and the Required Signal Intensity for a Yellow Flashing Signal

Distance Away d (m)	Angular Offset (degrees)		Required Signal Intensity (cd)
	Horizontal a_H	Vertical a_V	
250	1.2	0.5	1800 min
100	2.8	1.3	900 min
50	5.7	2.5	600 min
25	11.3	5.0	(600 max)
12.5	21.8	10.0	200 max

Also shown are the required signal intensities on approach to a yellow signal, taken from Table 5. The value at 12.5m is the maximum allowed for a night/day rear turn signals on vehicles in Australia.

To cope with some vertical misalignment of the signal the maximum intensity requirements at d=25m. (a_v=5°) should be 600cd; this value will provide the required signal intensity but will also restrict potential over-brightness.

The values of the required intensities for 50m and beyond are minimum values. These need to be associated with maximum values to avoid the potential for excessive brightness of the signal. Taking into account available technology a maximum intensity not more than 1.5 times the minimum intensity was applied. The minimum values in Table 6 have therefore been reduced by half this tolerance (i.e. by 25%). Thus the maximum values will be only 25% above the values in Table 6. The adjusted minimum values will result in only a 10% reduction in signal range, whilst providing a tolerance in design and manufacture. In practice manufacturers are likely to design signal lights well within the tolerance range and the resulting intensities are likely to be close to those given in Table 5. A model specification based on these considerations can be constructed and is given in Table 7.

Table 7
Recommended Intensities for a Flashing Yellow Signal Light (cd)

Degrees from Reference Axis		Degrees from Reference Axis				
		Left (Right is mirror image)				
		30	15	10	2.5	0
Up	5					500
	3					700
	1.5					1400
	0		500	700	1400	1400
Down	1.5					1400
	3					700
	5					500
	10	*200*	*200*	*200*	*200*	*200*

Notes:

i. The intensities shown are minimum values except those at 10° down which are maximum *(italicised).*

ii. The minimum intensities shall not be exceeded by more than 50%.

iii. The intensity between test points shall change in a smooth manner.

iv. The intensity shall be measured for a steady light run at the signal operating voltage (12.8V or 25.6V).

v. The intensities include provision for a manufacturing tolerance.

vi. Colour of signals should be in accordance with international standards (CIE 1975).

vii. Flashing red signals should be one third of the intensities shown in table 7 (rounded to nearest 50cd).

By reference to Table 4 it can be seen that there are similarities between this specification and the SAE standard for school bus signals. The axial (0,0) values and the horizontal spread of the light distribution are very similar. However the fall off in intensity vertically downwards is much less in the SAE standard, the intensity at 5° being more than twice that required. In addition there are no maximum limits to the intensities given in the SAE standard.

Available Technology

In order to obtain the relatively high intensities necessary a signal unit needs to consist of a light source of modest wattage, a reflector to efficiently collect and project the light and a front refractor (to spread the light into the required beam shape to provide angular coverage and to colour the light). Lighting technology is readily available to produce the required light distribution and was confirmed by photometric tests.

CONCLUSIONS

In order to been seen and command attention school bus signal lights must fulfil the following requirements:

i. They must have a signal range of at least 250m; this value will cover the various speed limits of roads over which school buses operate and it will provide sufficient warning to enable motorists to slow down without heavy braking.

ii. A yellow flashing signal must have an on-axis intensity of 1800 candela.

iii. In order not to be potentially glaring to approaching motorists the signal light beam must be carefully controlled.

These requirements are met by a signal complying with the specifications set out in Table 7 and mounted as high as practicable on the bus.

Field trials confirmed that signals of this intensity were clearly seen at 250m by a group of motorists. Whether the purpose of the signal will be recognised and whether it elicits the appropriate response from approaching motorists will depend on the uniqueness of the signal system and driver education. But that is another story.

ACKNOWLEDGMENTS

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REFERENCES

Australian Standard AS1158.1 (1973) "Public Light Code: Lighting of Urban Traffic Routes". Standards Australia, (now AS1158.1. 1986).

Australian Standard AS2144 (1989) "Traffic Signal Lanterns". Standards Australia.

CIE (1988) "Guide for the Design of Road Traffic Lights", Publication 79. Commission Internationale de l'Eclairage (Vienna).

CIE (1975) "Colours of Light Signals", Publication 2.2. Commission Internationale de l'Eclairage (Vienna).

Cole, B.L. and Brown. B.(1978) "A Specification of Road Traffic Signal Light Intensity". Human Factors 10.(3).

Cole, B.L. (1972) "Visual Aspects of Road Engineering". Proceedings of Australian Road Research Board 6.(1).

Fisher, A.J. and Cole, B.L.(1974) "The Photometric Requirements of Vehicular Traffic Signal Lantern". Proceedings Australian Road Research Board. 7(5).

Fisher, A.J. and Hall, R.R. (1972) "The Influence of Car Front Design on Pedestrian Accident Trauma". Accident Analysis and Prevention 4, pp47-58.

Holmes, J.G. (1971) "The Language of Flashing Lights" in "The Perception and Application of Flashing Lights". Adam Hilger Ltd (London).

Hulscher, F.R. (1975) "Photometric Requirements for Long Range Road Traffic Light Signals". Australian Road Research 7(5).

Lay, M. (1981) "Source Book for Australian Roads". Australian Road Research Board

RTA (1992) "Safety of School Children Near Buses". Road Safety Bureau, Roads and Traffic Authority (NSW)

SAE J887 (1987) "School Bus Warning Lamps". Society of Automotive Engineers (Warrendale).

Staysafe (1994) "Pedestrian Safety 1. School Children Around Buses". Parliament of NSW Standing Committee on Road Safety.

Van Bommel W.J.M and de Boer J.B. (1980) "Road Lighting". Kluwer Technische Boeken B.V. (Antwerp).

USE OF WORKLOAD ASSESSMENT MEASURES AND METHODS TO ASSESS SAFETY-RELEVANT IMPACTS OF IN-VEHICLE DEVICE USE AMONG HEAVY VEHICLE DRIVERS

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ABSTRACT

As a result of Intelligent Transportation System (ITS) initiatives in the United States and abroad, a wide variety of in-vehicle information systems are being proposed and developed for use in heavy trucks and cars. Such systems can improve transport efficiency, driver satisfaction, and highway safety. However, these technologies must be designed such that their use does not distract the driver or otherwise interfere with the driving task. This interference is what is referred to by the term "driver workload" in this paper. What is needed is a workload assessment protocol that can be used to evaluate the safety impacts of in-vehicle systems and promote a driver-centered design.

In response to this need, a program of research was undertaken to develop a safety-relevant workload assessment protocol. This paper presents: a brief description of the resulting protocol document; approaches taken to establish the safety relevance of the measurement system; application of the protocol to cellular phone use and text message displays in heavy vehicles; and future directions.

INTRODUCTION

Intelligent Transportation System (ITS) initiatives have led to various types of driver information systems that are being proposed and developed for use in heavy trucks and cars. These systems include land navigation and route guidance systems; text displays (e.g., pick-up address, package type); vehicle subsystem monitoring and status systems (e.g., tire pressure, oil pressure, brake failure, load shifting); computerized trip recorders (e.g., automatic record of speed, RPM, stops; driver entry of fuel purchase; state-line crossings); sophisticated communication links (e.g., cellular phone systems); and collision avoidance systems (e.g., radar, infra-red, and TV systems). If properly designed, such technologies have great potential to improve the efficiency of commercial and public transport, increase driver satisfaction, and enhance highway safety.

Studies suggest that driver inattention is a primary or contributing factor in as many as 50% of all traffic accidents (Sussman, Bishop, Nadnick, and Walter, 1985). This suggests that there is good reason to be concerned about the potential for a new in-cab device to distract the driver from the primary driving task. This device-induced distraction or interference with safe driving is what is meant by the term "driver workload" in this paper. Without a driver-oriented assessment of device-induced workload, the safety impacts of a system remain largely unknown. Furthermore, a workload assessment can be useful in developing a driver-oriented product design.

What is needed is a system of safety-relevant measures and methods to assess the safety implications of a device from the driver's perspective, i.e., a workload assessment protocol. In response to this need, the National Highway Traffic Safety Administration (NHTSA) initiated the program of research entitled, "Heavy Vehicle Driver Workload Assessment." The goal of this program was the development of a heavy vehicle driver workload assessment protocol that can serve as a basis for standard practice in the field of driver human factors test and evaluation. That protocol is described in Tijerina, Kiger, Rockwell, and Wierwille (1995). Additional reports from the program of research are referenced and summarized in Tijerina (1995).

This paper presents a brief description of the protocol document, approaches taken to establish the safety relevance of the measurement system, application of the protocol to cellular phone use and text message displays in heavy vehicles, and future directions. Additional discussion of this project may be found in Tijerina, Kantowitz, Kiger, and Rockwell (1994).

THE WORKLOAD ASSESSMENT PROTOCOL AND MEASUREMENT SYSTEM

The Tijerina, Kiger, Rockwell, and Wierwille (1995) report (henceforth referred to as the protocol document) begins with an introduction that provides background material on the rationale for candidate workload measure selection and omission. It also discusses various means of assessing the validity and safety relevance of workload measures. The protocol itself is organized in terms of the steps depicted in

Figure 1. This is a prescriptive set of processes needed to develop a comprehensive workload assessment approach, prepare the detailed evaluation plan, execute that plan, analyze the data and report the test findings. Throughout each section of the protocol, questions are provided that the evaluator should be asking, and suggestions are given for how to complete a given step. The protocol, as depicted in the flow diagram, is complex because it is comprehensive. It is also generalizable to a wide variety of in-cab technologies. However, it is expected that the protocol developed for a specific assessment will tailor the steps accordingly. Furthermore, continuing work on the protocol seeks to develop protocols tailored for each of several generic types of in-vehicle driver systems: vehicle navigation and route guidance systems; voice communications systems; single/integrated status displays; text communication systems; and crash avoidance systems.

The protocol document includes several appendices that form the heart of the measurement system. Appendices are provided on visual allocation measures; steering, pedal and manual activity measures; driver-vehicle performance measures; and subjective workload assessment measures. Each of these appendices provides a brief literature review on how such measures have been applied in the past, describe instrumentation needs, and provides operational definitions and workload interpretations for workload measures. These definitions and interpretations include graphical, narrative, and mathematical descriptions, as appropriate. An example is provided in the Appendix to this paper. This material provides a basis for a standardized approach to the assessment of device-induced driver demand.

Two additional appendices appear in the document. One describes the actuarial approach for establishing the safety relevance of visual allocation measures (see below). The other appendix presents experimental design strategies for data collection and analysis.

This document is targeted to several potential user groups. It is intended to be of use for new or novice evaluation team personnel and for test engineers who may have little or no experience with driver-oriented data collection and assessment. Insofar as the document suggests milestones for carrying out a driver-oriented safety evaluation, the U.S. Department of Transportation (DOT) may use it as a guidance document to manage contractors retained to carry out safety evaluations or operational tests. The document will also be of use to researchers in the field of driver workload. Experience has shown that there are special aspects of driver-centered device evaluation that are different from both psychological measurement or engineering assessments. For this reason, there is value in having a guide to the development and conduct of a safety-oriented device evaluation. Finally, the protocol may provide the basis for the structured test and evaluation process being incorporated into he data management platform known as the Test Planning, Analysis, and Evaluation System (Test PAES) (Gawron and Goodman, 1996). Test PAES, originally developed to support military aircraft flight tests, is currently being converted to support safety evaluations of ground transportation systems.

The protocol presents guidance for the conduct of an on-the-road field test with an instrumented vehicle. This reflects the view that field observations are the most valid way of assessing how an in-cab device impacts drivers on the road. There are sometimes safety concerns that limit the range of workload that may be imposed on the driver in a test situation. Therefore, a driving simulator or test track assessment may also be useful to assess the impact of device use on factors such as object and event detection, factors that cannot be staged safely or easily on the road. The system of workload measures should be equally applicable to these situations as well.

SCIENTIFIC BASES FOR THE SAFETY RELEVANCE OF SELECTED WORKLOAD MEASURES

An important part of the workload protocol's development was establishment of the safety-relevance of selected workload measures. This is a difficult problem, as a workshop on safety evaluations for Intelligent Transportation Systems (ITS) recently illustrated (Tijerina, Freedman, and Farber, 1995; Dingus, 1995). Several scientific bases that might be used to relate workload assessment measures to safety include: theoretical constructs derived from a model or theory of driving, archival analysis to relate crash incidence to different levels of a workload measure, and principles of physics. Examples reported on in the workload protocol are provided below.

Safety Relevance of Workload Measures Derived from a Model of Driving

A model of driving was used to develop candidate measures of driver behavior and performance that can be sensitive to workload effects associated with in-vehicle device use. In a standard control-theoretic model of lanekeeping (e.g., Hess, 1987), the driver receives inputs (largely visual in nature) about the current lane position (y) and heading angle (ψ). These inputs are considered by the driver in light of his or her particular goals, situational understanding of the current driving conditions, driving style, and vehicle characteristics (this is what is intended to be conveyed by a Driver Behavior block). The driver then changes the steering wheel angle (δ_w) as appropriate. This steering wheel input, along with steering disturbances from wind gusts, road surface characteristics,

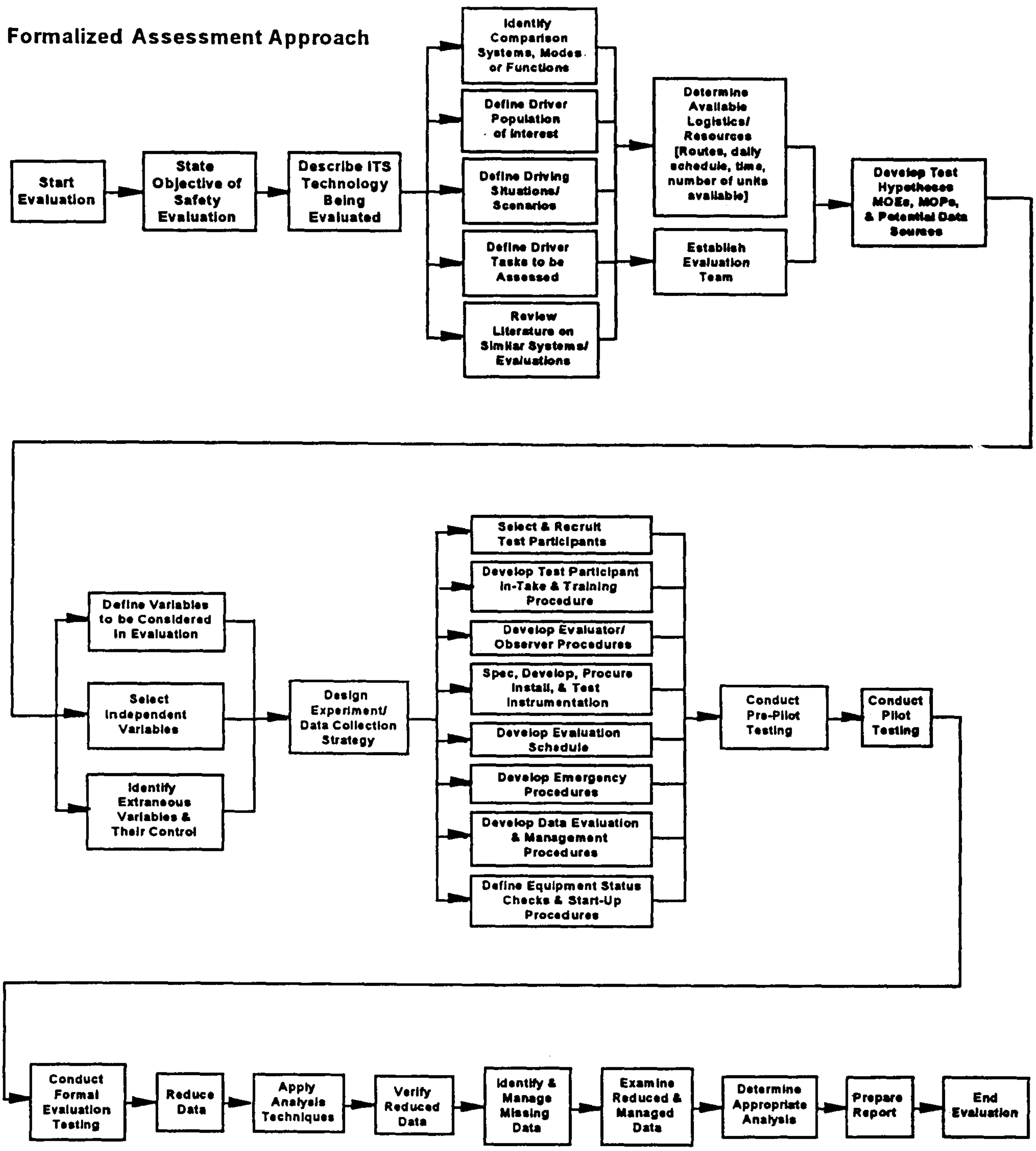


Figure 1. Flow Diagram of the Driver Workload Assessment Protocol (Source: Tijerina, Kiger, Rockwell, and Wierwille, 1995).

and the like combine with vehicle dynamics to determine the vehicle's heading angle (ψ) moment by moment, and also lane position (y). Even if steering disturbances were zero, heading angle is one time integration removed from steering angle and lane position (on a straightaway, at least) is two time integrations removed from steering angle inputs by the driver. This suggests that driver-vehicle performance measures may be less sensitive than driver steering or pedal inputs as workload indicators. In turn, these may be less sensitive to workload demand than visual allocation measures because of the many factors that can influence control input and vehicle performance measures.

Similar concepts apply to speed maintenance, headway maintenance, and other aspects of longitudinal control. Visual inputs of optical flow, objects, and events are considered by the driver in light of his or her particular goals, situational understanding of the current driving conditions, driving style, and vehicle characteristics. The driver changes the accelerator pedal angle (δ_p) or applies brakes, as deemed appropriate. These longitudinal control measures may be influenced by factors other than device workload, factors such as vehicle dynamics (e.g., momentum, braking efficiency, etc.) and disturbance inputs (head- or tail-winds, vertical roadway alignment, etc.). Mechanical relationships also introduce damping or lags in driver inputs to longitudinal control. Therefore, the previous paragraph's comments about relative sensitivity of measures applies equally well here.

This model suggests a set of workload measurements that may show intrusion of in-vehicle device use into the primary task of safely controlling the vehicle at all times. These categories of measurement collectively form the corpus of the workload measurement system:

- Visual Allocation Measures. These include measures of how long, how frequently, and how likely it is that a driver looks at a particular location (e.g., in-vehicle device), as well as the sequence of glances. Given that visual attention is the primary input to safe driving, such measures should be relevant. Furthermore, since they are most readily under the driver's control, they are likely to be the most sensitive workload measures as well.

- Driver Steering, Pedal, and Manual Activity Measures. These measures capture the inputs drivers make based on the visual information received (or not received), coupled with driver strategies and corrections for various disturbances.

- Driver-Vehicle Performance Measures. These are measures of lateral control (i.e., lanekeeping measures), longitudinal control (e.g., measures of speed, headway, accelerations and decelerations), and way finding (measures such as time-to-arrival, missed turns, exit ramps, and entrance ramps). These measures assess the overall quality of driving in terms of meeting goals in a safe and efficient manner.

- Driver Subjective Assessments. These are measures that do not fall out of the simple model of driving, per se, but may nonetheless be important. Driver subjective assessments may include subjective workload assessment measures. They also include driver feedback on debriefing questions about the in-vehicle device under evaluation. The reason for including subjective assessments is that the driver may be in an excellent position to identify problems or concerns with a new technology. Therefore, some means to capture such information is part of a comprehensive workload assessment protocol. Driver subjective assessments can provide additional information on the demands posed by performing the driving task in conjunction with the load of in-cab services (i.e., demand-driven workload).

Because of the relative sensitivity of these classes of measures, they form a hierarchy. Visual allocation measures are likely to be most sensitive to momentary workload. Driver in-cab behaviors and driver-vehicle performance measures are relatively less sensitive to momentary workload, all else being equal. Subjective assessments may provide complementary information to the performance and behavioral measures

Measures Not Included in the Current Version of the Workload Assessment Protocol

Several more measurement classes deserve mention. One class of response measures that might be integrated into driver workload assessment is in-cab device performance measures, e.g., task completion time, errors, recovery procedures followed, etc. These are not formally included in this protocol because the performance on the in-cab device is taken as a "given". That is, the protocol emphasizes the consequences of in-cab device use on the measures introduced above. If these consequences are aggravated with, say, driver errors while using the device, this is simply taken as a part of that device's characteristics. However, in-cab device performance measures are not incompatible with other workload measures, and may be captured as additional information for device design improvement.

A second class of response measures that might be included is macroscopic driver-vehicle performance. Examples of such measures might include number of missed turns, stop light violations, stop sign violations, or time-to-arrival at a way point or destination. Clearly, these measures may be included in a safety evaluation of driver workload.

However, the safety precautions required for on-the-road safety evaluations may render many such measures purely happenstance. Thus, while such macroscopic behavior may and should be recorded, the workload protocol does not rely on such measures extensively.

A third class of safety-relevant measures address measurement of traffic conflicts (Dingus, 1995). Originally proposed as a means to improve roadway design, e.g., intersection design (Older and Spicer, 1976), the traffic conflict technique examines near-crash or potential crash situations to provide information about hazardous conditions. These situations are characterized by human observers interpreting high decelerations (characterizing abrupt stopping maneuvers), skids, or evasive steering maneuvers as evidence of traffic conflicts. There is assumed to be a relationship between traffic conflicts and crashes such that traffic conflicts may be much more numerous (perhaps 1000 traffic conflicts per every one crash that occurs). Thus, it is more likely that one can observe traffic conflicts than crashes.

This theory provides for an appealing approach. However, the traffic conflict technique has been criticized on the grounds that evaluation studies fail to confirm the predictive benefits of the method (Williams, 1981). Areas for improvement include more objective and standardized measurements of what constitute traffic conflicts and methods that do not depend on evasive maneuvers to predict crash occurrence (because many crashes occur without being preceded by an evasive maneuver). There is also concern by the present authors that conduct of a workload assessment must often be carried out so as to minimize the potential for traffic conflicts to be observed. Finally, the likelihood of observing a traffic conflict is expected to be low over the short-run of an on-the-road evaluation. For example, if traffic conflicts occur at a rate of 1000 to 1 with respect to traffic crashes, and a traffic crash occurs once every 10 years, on average, then if these likelihoods are evenly distributed (which they are probably not for the driver participating as a test participant in a controlled evaluation), then one must observe the driver for at least 3-4 days to obtain one traffic conflict. Thus, while traffic conflicts must of course be noted and included in the reporting of a device evaluation, traffic conflicts do not currently play a substantial role in the measurement system presented in the workload protocol document. The workload measures described there could, however, provide evidence for identification of traffic conflicts.

An Actuarial Approach to Establishing the Safety Relevance of Visual Allocation Measures

A theory or model of driving indicates the safety relevance of visual attentional allocation. Because vision is the primary means of gathering information about the driving task, the driver cannot take eyes off the road scene for more than a moment without risking a crash. Beyond this, archival research that links high visual demand to crash incidence has recently been attempted by Wierwille and Tijerina (1994) and Wierwille and Tijerina (in press), through work conducted as part of this project. Wierwille and Tijerina (1994) describe the results of a study in which detailed police narratives from an accident database maintained by the Highway Safety Research Center of North Carolina were reviewed for the presence of keywords potentially indicative of in-vehicle distraction. This approach had earlier been used by Perel (1976, 1988) to examine control incompatibilities in driver/vehicle systems. Based on a review of almost 18,000 records, results showed that numerous accidents are associated with visual allocation into the vehicle. Figure 2 presents some of the results of that study; it shows the number of crash cases in 1989 from the North Carolina data base attributed to driver attentional diversion or workload, further subdivided into interior (in-vehicle) sources of distraction and dash/console/steering column distraction sources.

Subsequently, Wierwille and Tijerina (in press) developed a quantitative relationship between in-vehicle visual demand (weighted by in-vehicle device use) and crash incidence for those crashes identified in the earlier research. In order to accomplish this, estimates of visual demand and frequency of device use were needed as predictor variables in a regression model that had crash incidence or number of crashes from the previous analysis as the criterion variable. The approach taken was to use data in the human factors literature to develop estimates of the frequency of use of selected in-vehicle devices (e.g., radio, speedometer, windshield wiper, etc.) and estimates of the visual demand of those same devices.

Tijerina, Kiger, Rockwell, and Wierwille (1995) presents the entire set of analyses. The human factors literature was used to identify visual demand data for similar in-vehicle devices. From these, mean glance duration and average number of glances required to service various in-vehicle devices were collated for use in the present analysis. For a given device use (e.g., radio tuning), visual demand was estimated to be the product of mean glance duration and mean number of glances.

The principal approach taken to estimate device frequency-of-use was a logical approach with engineering judgement applied when necessary to develop the necessary relative-use values. Given the limited data available in the literature, engineering judgement was sometimes needed to arrive at a metric for frequency-of-use for several types of in-vehicle transactions.

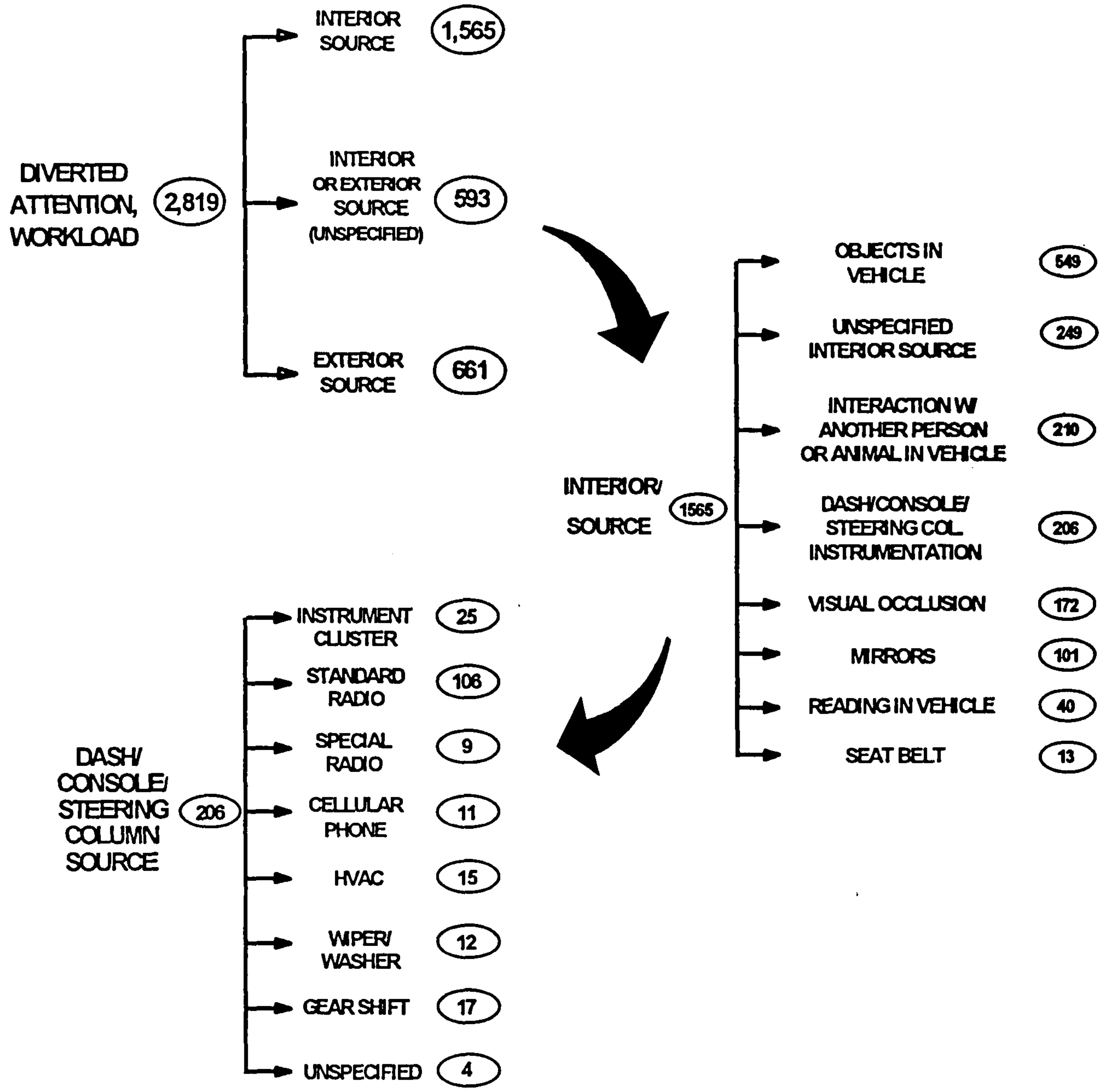


Figure 2. Number of Crashes Distributed by Sources of Attentional Distraction, Broken Down into Interior Source and Dash/Console/Steering Column Instrumentation Group (Source: Wierwille and Tijerina, 1994).

Exposure was defined as a function of visual demand (the product of mean glance duration and mean glance frequency per in-vehicle device use) and device frequency-of-use (scaled to a common time frame, e.g., uses per week). Three types of exposure were computed for a given in-vehicle device, j:

Type 1 Exposure j = (mean glance duration$_j$)x(mean glance frequency$_j$)x(use frequency$_j$)

Type 2 Exposure j = (mean glance duration$_j$)$^{3/2}$ x(mean glance frequency$_j$)x(use frequency$_j$)

Type 3 Exposure j = (mean glance duration$_j$)^2 x(mean glance frequency$_j$)(use frequency$_j$)

Type 2 and Type 3 exposure weight longer glance durations more heavily under the assumption that longer single glance durations increase crash hazard exposure more than might be implied by a linear increase. Figure 3 presents one regression analysis using exposure as the predictor variable and crash incidence from Wierwille and Tijerina (1994). In general, the regression fits are excellent regardless of the exposure type, with correlations ranging from 0.898 to 0.982. This study is a unique attempt to use actuarial data to relate visual allocation measures to crash incidence.

Establishing the Safety Relevance of Driver-Vehicle Performance Measures

Key measures of driver-vehicle performance included in the workload protocol address lanekeeping, speed control, and time headway. The safely relevance of each of these classes of measures is addressed below.

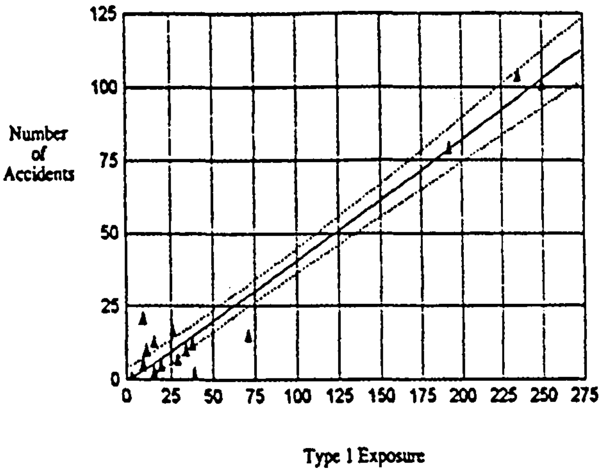


Figure 3. Plot of Crash Incidence vs. Type 1 Exposure.

It is self-evident that the driver must control the vehicle and remain in the travel lane, moving from it only in a controlled fashion. Failure to properly keep in one's lane is the proximal physical event that leads to such crash types as lane change crashes, opposite-direction crashes, and single vehicle roadway departures. Thus, measures of lanekeeping such as lane exceedences are directly safety-relevant. Furthermore, increases in lane position variability or mean lane position may also be interpreted as safety-relevant to the extent that driving closer to a lane line reduces the driver's margin for recovery in the event of an emergency, all else being equal. The same principles apply to measures such as Time-To-Line Crossing (TLC) (Godthelp, 1984), Time-to-Trajectory Divergence (TTD), and other measures related to lanekeeping performance. While it is true that not all lane exceedences lead to crashes, various crash types are precipitated by lane exceedences. Thus, in addition to the logical relations contained in the simple model of driving presented earlier, there are archival principles of vehicle control and relationships to safety implied from the crash record to recommend such measures for a workload assessment protocol.

It is not uncommon for a driver under high workload to slow the vehicle. However, there is evidence that crash incidence rises with speed variability. Cirillo (1968) used crash data to show that the driver traveling closer to the average speed of the travel stream has a lower crash risk than the driver traveling at higher or lower average speeds. More recently, Garber and Gadiraju (1989) presented regression models relating crash rate to speed variance. These plots indicate that a vehicle traveling significantly slower or faster than the prevailing travel speed (regardless of posted speed), may be more likely to be involved in a crash.

In addition to archival data supporting the safety relevance of speed variation measures, mean speed measures are also important. Nilsson (1990, as cited in Evans, 1991) examined changes in crashes and casualties associated with speed limit changes and derived quantitative prediction models that correspond well to accident statistics in the U. S. when speed limits were increased from 55 mph to 65 mph in 1987. More recently, Hendricks, et al. (1992) and Mironer and Hendricks (1994) have determined that a substantial number of roadway departure crashes at curves are associated with excessive speed with respect to roadway geometry and traction. Should a distracted driver allow speed to creep up during in-vehicle device use, this increase may be a potential safety threat. Similar comments apply to braking behavior as well.

Rear-end crashes are the single most common crash type in the United States (Tijerina, 1995). The vast majority of these crashes involve driver inattention and/or following too closely. Furthermore, Evans and Wasielewski (1982) showed that time headway adopted on a section of highway was a significant discriminator of traffic violators from non-violators, that time headways were often below 1.0 s for the traffic violators, and that such short headways greatly increase the risk of rear-end crashes. Thus, there is at least some archival evidence that car following measures such as time headway have safety relevance. Principles of physics also can be used to relate close car following to crash involvement (Knipling et al., 1993).

This section and its various subsections illustrate the types of scientific information available and developed to relate the workload measures in the protocol document to safety. Additional research is needed to develop such

relationships further.

APPLICATION OF THE WORKLOAD ASSESSMENT PROTOCOL

Task 7 of the program of research involved evaluation of two high-technology systems using the developed protocol. The objective of this task was to apply the workload assessment protocol and measurement system to the selected technologies and determine characteristics and conditions of implementing those technologies that can have undesirable safety consequences. The results of the device use would be compared to baseline workload measures taken to provide indications of the driving conditions and device characteristics under which it would be safe to use or operate the technologies.

A prototype text message display system and a cellular phone system were chosen for evaluation. These choices were based on work from Task 3 of the research program that indicated such systems would provide a range of workload assessment challenges. Furthermore, the in-cab task taxonomy developed in Task 4 of the research program indicated that these two technologies would involve a range of tasks and associated demands with which to determine the sensitivity of candidate workload measures. These two technologies also serve as surrogates for a broader range of technologies with similar attributes or driver demand characteristics. Thus, results from this study can be used to gauge the workload impact of systems with similar attributes. Based on a taxonomy of task types, it was also determined that these two systems would involve visual, manual, and cognitive in-vehicle tasks.

The study assessed driver workload imposed by a text messaging system and cellular phone on heavy vehicle drivers under various driving conditions. Sixteen (16) professional commercial vehicle operation (CVO) licensed drivers drove an instrumented heavy truck over a 4-hour period on public roads under various conditions of ambient lighting (day or night), traffic density (light or heavy), and road type (divided or undivided). Within driving condition combinations, various levels of text message reading, cellular phone dialing, radio tuning, and cellular phone dialogue were completed by the driver. Continuous measures were taken of visual allocation, steering and accelerator activity, speed maintenance and lanekeeping performance.

Results were presented in the Task 7 final report (see Tijerina, 1995 for full references) for the following three main components of the study: One component of the study focused on reading text messages of various lengths (1-, 2-, or 4-lines) and with various content from a prototype CRT text message display. A second component of the study focussed on manually dialing a cellular phone in any of three dialing configurations (auto-dial, 7-digit dial, or 10-digit dial), along with manually tuning a radio as a baseline. A third component of the study focused on engaging in question-and-answer dialogue with either biographic questions or arithmetic questions on a cellular phone, along with open road driving as a baseline.

The text message display analysis indicated that 2-line and 4-line messages like those used in the study can have substantial effects on visual allocation (increased time looking away from the road scene, shortened glances to the road scene during message reading) and lanekeeping performance (e.g., greater incidence of unplanned lane exceedences). Thus, a recommendation is offered that text messaging systems be kept to a one-line display of perhaps 55 characters, with the display parameters of character size, luminance, polarity, and contrast set to levels established by ergonomics research. It was also mentioned that, though not pursued in this study, there is evidence that increased workload and comprehension demands may be associated with attempts to put too much information by displayed abbreviations into even the one-line display format. This is an area in need of further research. However, past research strongly suggests that use of abbreviations for display will be fraught with problems. Such problems may be aggravated by the demands of driving.

The analysis of manual activity focussed on various levels of manual dialing of a cellular phone. Manual radio tuning was included as a baseline condition based on previous research also conducted as part of this project. Results indicated substantial differences in visual demand associated with 7-digit and 10-digit dialing. There were no substantial effects of manual task on speed maintenance or lanekeeping performance. However, lane exceedences were observed on 27 percent of all trials. Given that the drivers were probably very vigilant since they knew they are participating in a study, this is disturbing. As a point of reference, only about 14 percent of the trials involved lane exceedences when drivers read a 1-line "What is the current time?" CRT text message. Furthermore, the manual radio tuning task was chosen as a baseline because it represents a societally accepted, though high-demand task. However, manual radio tuning is itself associated with crashes, as demonstrated in the actuarial analysis in Task 5. Thus, even with professional truck drivers, it is advisable to streamline the manual dialing aspects of cellular phone dialing, either with auto-dial features that minimize the number of keystrokes required or perhaps a voice-dial feature that does not require manual input or eyes off the road at all.

Heavy vehicle drivers tend to spend a great deal of time engaging in dialogues on CB radios. This has the benefit of keeping the driver alert while driving. However, the present study showed that even relatively simple question-and-answer dialogues can have subtle effects on safety-relevant driving

behaviors. In particular, the results indicated that visual scanning, as measured by mirror sampling, was cut by almost 50 percent on average when the driver was engaged in dialogue as compared to engaged in open road driving without dialogue. This is a potential cause for concern in that it represents an increase in crash hazard exposure. From this, one may hypothesize that such in-vehicle device workload does not degrade the highly over learned skills of driver-vehicle speed and lanekeeping performance among professional truck drivers. Instead, in-cab device workload decreases driver monitoring for hazards on the roadway.

It is interesting to consider also subjective assessments made by the drivers during the data collection debrief. When subjects were debriefed after the run, they reported some difficulty in phone use but over half reported no difficulty in executing the tasks. When asked to rate workload imposed by the four road sections, i.e., divided (I-270) roadway- day, divided roadway-night, undivided roadway (SR-161)- day and undivided roadway - night, the subjects rated SR–161 to have a higher workload than I-270 and night operation with a higher workload than daytime operation. Thus, SR-161 night workload averaged 39.7 on an overall workload scale of 100 vs. 12.3 for I-270 day. The absolute value of these scores are less important than the relative scores. When asked to rate the in-cab tasks in terms of workload the drivers gave average workload ratings ranging from 19.5 for the 3-digit dialing task to 27.3 for the 10-digit dialing task with CRT reading and cognitive load falling between these two values.

When asked to rate workload (again on a 100 point scale) for the highest workload road condition (SR-161 night) and the highest task workload (10-digit dialing) the subjects gave a mean response of 56.9 suggesting an additive effect. Most of the drivers believed the in-cab tasks were realistic although many expressed some concern about phone usage. This latter response is understandable since few had cellular phone experience and none had used them in regular truck driving. Thus, drivers in this study were apparently aware of the potential hazards associated with the technologies to which they were exposed.

This study was intended to demonstrate the sensitivity of candidate workload measures to assess workload variation with two in-cab devices. In terms of establishing the sensitivity of the workload measurement system to variations in heavy vehicle driver workload, this study met this goal. However, the original intent of the task was to establish the conditions under which it would be safe to use or operate the technologies tested. Here, the study is equivocal. This is because the state of the art in driver workload assessment is such that relative assessments are feasible but absolute assessments that predict crash occurrence are not feasible. For a detailed discussion of the difficulties associated with predictive safety impact assessments, see the workload protocol document.

FUTURE DIRECTIONS

The workload assessment protocol and research conducted to support its development represent an early step in what is hoped will be a process of continuous evolution and improvement of driver-oriented, safety-relevant test and evaluation. This work is most properly considered a beginning rather than an endpoint in terms of device evaluation methodologies. Some fruitful areas for future research to extend the work conducted under this program are provided below.

Further Applications of the Workload Assessment Protocol. Clearly, the utility of the workload assessment protocol and measurement system will depend on the results obtained from applications of it. In particular, the workload assessment methodologies should be applied to Intelligent Transportation System (ITS) products. This will be productive to refine the workload measurement process , to provide data to enhance the design of new systems for use in trucks and cars, and to improve highway safety.

Workload Assessment Under Naturalistic Driving Conditions. There is a need to apply the workload protocol to normal driving. The presence of the on-board experimenter in this program of research likely impacted on the workload measures taken. It should be possible, with emerging data acquisition systems such as the Data Acquisition System for Crash Avoidance Research (DASCAR) (Gawron and Goodman, 1996), to collect data on truly naturalistic driving with minimum intrusion and over an extended period of time. In addition to device evaluations, the measurement system can capture valuable driver behavior and performance data useful for the design of new systems (e.g., crash avoidance systems), driver training, and law enforcement. A new DOT program of research, named ORACLE (Operator on-Road Assessment and Comprehensive Longitudinal Evaluation)is directed toward capturing naturalistic driving over an extended period of time. This effect will provide data to better characterize traffic conflicts, develop indicators of driver attentional status and intent to engage in various driving maneuvers, as well as gauge variations in driver workload over many different driving conditions..

Collecting Frequency-of-Use Data on Technologies. Crash hazard potential is a combination of both device-induced workload demand (assessed by the methods and measures in the research protocol) and device frequency-of-use. Frequency-of-use estimates for various in-cab transactions or high technology devices (or analogues) would be useful in furthering an understanding of the safety impacts of existing and new technologies.

Application of the Workload Assessment Protocol to

Passenger Vehicles. The focus in this research program was heavy vehicle drivers and heavy vehicle operation. This focus stemmed from several assumptions. First, it was assumed that commercial operations would likely be the first consumers of new technologies for use in trucks to improve operational efficiency and profitability. Second, heavy vehicle drivers were thought to be more homogeneous with respect to factors such age, driving experience, and training than passenger car drivers at large. This would serve to reduce the potential complications of driver differences in a device evaluation, Third, because heavy vehicle drivers spend considerably more time on the road and travel more miles on the nation's highways than do passenger car drivers, heavy vehicle drivers are exposed to greater crash hazards, all else being equal. Thus, assessment of technologies targeted to heavy vehicle drivers would have potential safety benefits. However, there is a need to extend the application of workload assessment to passenger car drivers. As the price of high technology devices drops, more of these devices will find their way into passenger cars and automobiles driven by a wider range of persons in terms of age, sex, driving experience, and timesharing skills. The results obtained in this program of research with heavy vehicle drivers are likely to differ from that of passenger car drivers.

Augmenting the Workload Protocol. The heavy vehicle driver workload assessment protocol is intended to be a systematic and thorough guide to the planning and execution of field-oriented test and evaluation of ITS and related high-technology system. It depends on instrumented vehicles, on-the-road data collection, and potentially complex data gathering and analysis strategies, especially as one moves to include more research questions into the data collection. A useful adjunct to this approach is one wherein some portion of the assessment could be conducted prior to, or possibly in lieu of, on-the-road empirical assessments. Analysis of device functions, checklist evaluations, and possibly simple video-game simulator assessments might serve as preliminary assessment stages before the more expensive assessments associated with driving simulator and on-the-road field testing were undertaken. This would serve as a screening evaluation, the next step of which is the more rigorous empirical evaluation. It appears that there is a need for several levels of workload assessment protocol tools. While the current protocol document is well suited to large-scale, well funded ITS demonstrations and field studies, it is not currently well suited to the small entrepreneur who may wish to integrate human factors into the design of an ITS product, but cannot muster the resources to execute (or have someone else execute) the current protocol early and perhaps repeatedly in the design process. The earlier in the design process that workload assessments are made, the better the chances that the device design will be revised based on the results of the early-on evaluation. Thus, data collected by application of the workload protocol can be used to support development of design guidelines for system developers.

Development of New Measures and Methods for Workload Assessment. There is a need to expand the array of measures and techniques that were developed under this research program. For example, visual allocation measures were found to be sensitive, robust, and safety-relevant. It is possible that, given the primacy of visual attention to safe driving, that visual allocation will serve as a continuous gauge of momentary driver attentional status, including drowsiness and intoxication. Other measures from the workload protocol's measurement system can also play a role in this continuous monitoring function. The capture and real-time processing of such data merit future development. The video camera techniques for visual allocation measurement used in this research program are likely to be too coarse for such applications and also for some device assessments (e.g., Head-Up Displays or HUDs). Pursuit of new measurement methods and measures are likely to lead to the next major advance in truly intelligent transportation systems.

REFERENCES

Cirillo, J.A. (1968). Interstate system accident research study II, interim report II. *Public Roads, 35*, 71-75.

Dingus, T.A. (in press). Moving from measures of performance (MOPs) to measures of effectiveness (MOEs) in the safety evaluation of ITS products or demonstrations. In D. Nelson (Ed.), *Proceedings of the ITS Safety Evaluation Workshop*. Washington, DC: ITS America.

Evans, L. (1995). *Traffic safety and driver behavior.* New York: Van Nostrand Reinhold.

Evans, L., Wasielewski, P. (1982). Do accident involved drivers exhibit riskier everyday driving behavior? *Accident Analysis and Prevention, 14*, 57-64.

Garber, N.J. & Gadiraju, R. (1989). Factors affecting speed variance and its influence on accidents. *Transportation Research Record, 1213*, 64-71.

Gawron, V., & Goodman, M. J. (1996). An integrated test system for ITS. *Proceedings of the ITS America Sixth Annual Meeting.*

Godthelp, H. (1984). *Studies on human vehicle control.* Soesterberg, The Netherlands: The Institute for Perception.

Hess, R.A. (1987). Feedback control models. In G. Salvendy

(Ed.), *Handbook of human factors* (pp. 1212-1241). New York: Wiley.

Knipling, R.R., Mironer, M., Hendricks, D.L., Tijerina, L., Everson, J., Allen, J.C., & Wilson, C. (1993, May). *Assessment of (IVHS countermeasures for collision avoidance: Rear-end crashes* (Report No. DOT HS 807 995). Washington, DC: U.S. Department of Transportation National Highway Traffic Safety Administration.

Nilsson, G. (1990). The effect of speed limits on traffic accidents in Sweden. *VTI Report No. 68* (pp. 1-10). Linkoping, Sweden: National Road and Traffic Research Institute. Cited in Evans, (1995).

Older, J.S., Spicer, B.R. (1976). Traffic conflicts - a development in accident research. *Human Factors, 18(4)*, 335-350.

Perel, M. (1976). *Analyzing the role of driver/vehicle incompatibilities in accident causation using police reports* (Report No. DOT HS 801 858). Washington, DC: National Highway Traffic Safety Administration.

Perel, M. (1988). *An analysis of pedal-related accidents using police narratives*. Washington, DC: Office of Crash Avoidance Research, National Highway Traffic Safety Administration.

Sussman, E.D., Bishop, H., Madnick, B., & Walter, R. (1985). Driver inattention and highway safety. *Transportation Research Record*, 40-48.

Tijerina, L. (1995, September). *Final report -- Program executive summary: Heavy vehicle driver workload assessment*(Contract No. DTNH22-91-C-07003). Columbus, OH: Battelle.

Tijerina, L., Freedman, M., & Farber, E. (in press). *A synopsis of the ITS AMERICA/NHTSA Workshop on ITS Safety Evaluations*. Paper presented at the Second World Congress on Intelligent Transportation Systems, Yokohama, Japan, November 9-11, 1995.

Tijerina, L., Kantowitz, B., H., Kiger, S., & Rockwell, T. H. (1994, May). *Driver workload assessment of in-cab high technology devices* (Paper No. 94-S2-O-06). Paper presented at the XIVth International Technical Conference on Enhanced Safety of Vehicles, Munich, Germany, May 23 - 26, 1994.

Tijerina, L., Kiger, S. M., Rockwell, T. H., & Wierwille, W. W. (1995, June). *NHTSA heavy vehicle driver workload assessment final report supplement -- Task 5: Heavy vehicle driver workload assessment protocol* (Contract No. DTNH22-91-C-07003). Columbus, OH: Battelle.

Williams, M.J. (1981). Validity of the traffic conflicts technique. *Accident Analysis & Prevention, 13*, 133-145.

Wierwille, W. W., & Tijerina, L. (1994). An analysis of driving accident narratives as a means of determining problems caused by in-vehicle visual allocation and visual workload. In A. G. Gale et al. (Eds.), *Vision in Vehicles V*. Amsterdam: North-Holland.

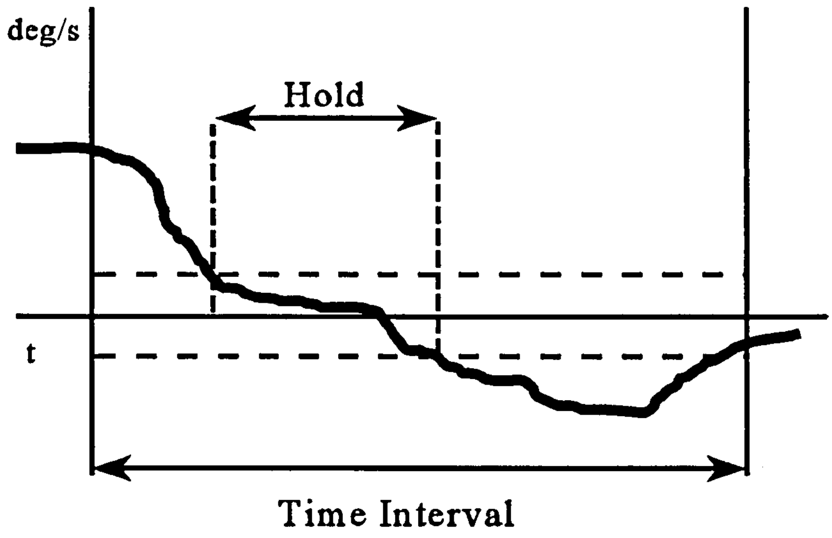
Wierwille, W. W., & Tijerina, (in press). *Modeling the relationship between driver In-vehicle visual demands and accident occurrence.* Paper presented at the Sixth International Conference on Vision in Vehicles, Derby, England, September 12 - 15, 1995.

Appendix: Excerpt from the Driver Workload Assessment Protocol: Definition of Steering Holds and Workload Interpretation.

Number of Steering Holds = Total number of holds within a sample time interval.

Workload interpretation: If in-vehicle device demand is high, the driver will have to direct his or her attention to the device, numerous times. During such periods, the driver may hold the wheel relatively still, then make a corrective input after taking a glance to the roadway. Thus, the number of steering holds may increase as task demand increases.

Note that number of steering holds and steering hold duration may trade off within a fixed sample interval. That is, very long hold durations may be indicative of high workload demand, yet may be associated with fewer rather than more steering holds. Thus, it is important to consider the two measures together, especially if the sample interval is fixed rather than allowed to reflect task completion time.



Crashes Involving Road Trains in Western Australia

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Paper Number 96-S11-W-26

ABSTRACT

Road trains consist of a prime mover with two or more trailers attached, and are used extensively by the agricultural and mining industries in the rural and remote regions of the state. For the five year period 1988-1992, 91 crashes involving road trains were identified in the Road Injury Database of the Road Accident Prevention Research Unit, Department of Public Health, the University of Western Australia. This database consists of linked data from police crash records, hospital admission records, ambulance records and death registry records. Police crash report forms were then examined to obtain more details of each crash.

The crash involvement rate per 100 million vehicle kilometres is lower outside of Perth, but the rate increases with the number of trailers in tow. The rate for three trailer road trains is over twice that for two trailer trains. About one quarter of road train crashes involved a fatality, compared with under 10% for semitrailers. Opposite direction and overtaking crashes had a high proportion of fatalities, in which the occupants of the other vehicle were at much greater risk than the road train occupants. The risk of injury to road train occupants is in crashes associated with rollovers, which occurred in 13 of 33 single vehicle crashes. About 4% of road train drivers died in the 91 casualty crashes, twice the rate for car drivers in casualty crashes. About 20% of road train crashes were associated with fatigue, 80% of these were single vehicle crashes. More detailed investigations are underway to define the mechanisms of crash and injury causation involved in the high-risk situations described above.

INTRODUCTION

Road trains consist of a prime mover (or tractor) towing two or three trailers. They can be up to 48 metres in total length and are used primarily in the remote and rural regions of the state for transporting mineral and agricultural products.

METHOD

Road train crashes occurring in Western Australia from 1988 to 1992 were identified using the Road Injury Database of the Road Accident Prevention Research Unit. The police report forms for these crashes were then examined in detail, in order to obtain information that was not coded and entered into the database. The narrative and the crash diagram were used to determine detailed road user movements, mechanisms of injury and injury details and also, for example, indications of fatigue. Data from the ABS Survey of Motor Vehicle Usage was used to estimate crash involvement rates for type of vehicle and region.

RESULTS

Over the five years 1988-1992, 91 road train crashes causing injury or death were identified on the Road Injury Database. Almost 80% of the road trains consisted of two trailers (72, 79.1%), the other 19 (20.9%) consisted of three trailers. Over 97% of road train crashes occurred in the rural and remote areas of the state, compared with 55% for semi-trailers, (Table 1). However, 94.7% of travel by road trains takes place in the rural and remote regions, so there were proportionately more crashes in these regions than would be expected (Table 2).

Table 1.
Location of crash by region, road trains and semitrailers, WA, 1988-1992

Region	Semi-trailers		Road trains	
	N	%	N	%
Perth	171	(45.2)	2	(2.5)
Rural	153	(40.5)	30	(37.0)
Remote	54	(14.3)	49	(60.5)
Total	378	(100.0)	81	(100.0)

(Frequency missing = 98)

Table 2.
Road Trains and Semitrailers -
Millions of Kilometres Travelled (%)

Region	Semitrailers	Road Trains
Perth	92.2 (22.4)	3.6 (5.3)
Rural & Remote	319.7 (77.6)	64.8 (94.7)
Total	411.9 (100.0)	68.5 (100.0)

Outside of Perth road trains have higher casualty crash involvement rates than semi-trailers or rigid trucks, but lower rates in the Perth region (Table 3). The latter rates are based on very few crashes in the case of road trains which operate largely outside of Perth. It is interesting to note that the crash involvement rate for casualty crashes outside of Perth increases as the number of trailers being towed increases.

Table 3.
Type of truck, region and casualty crash rate, WA, 1988-1992 (per 100 million vehicle kilometres)

Truck type	Region	
	Perth	Rest of WA
Rigid	81.26	19.81
Semi-trailer	71.02	19.94
2-trailer road train	50.22	23.88
3-trailer road train	0.00	51.91

Almost a quarter of road train crashes involved a fatality (22.2%) compared with less than 10% of semi-trailers (Table 4.).

Table 4.
Crash severity, road trains and semitrailers, WA, 1988-1992

Injury Severity	Semi-trailers		Road trains	
	N	%	N	%
Fatal	31	(8.2)	18	(22.2)
Hospital admission	133	(35.2)	32	(39.5)
Med. Attn.	177	(46.8)	23	(28.4)
Injury Unknown	37	(9.8)	8	(9.9)
Total	378	(100.00)	81	(100.00)

(Frequency missing = 98)
(df = 3, 2 = 17.851, p = 0.000)

The most common type of crash involving a road train were single vehicle crashes (33, 36.3%), followed closely by same direction crashes, ie rear end and sideswipe, (19, 20.9%), and then opposite direction crashes, ie head on and sideswipe, (15, 16.5%) (Table 5). Nine (9.9%) occurred at intersections, 7 (7.7%) occurred during overtaking, and smaller numbers of crashes occurred involving parked vehicles (2, 2.2%), animals (1, 1.1%), driveways (1, 1.1%), and the one miscellaneous crash where a road train hit a railway train. Compared with casualty crashes, crashes resulting in a fatality involved more opposite direction and overtaking crashes. Six of 15 opposite direction crashes resulted in at least one death, as did four of seven overtaking crashes, and three of 33 single vehicle crashes.

Table 5.
Type of crash and severity, road trains, WA, 1988-1992

Type of Crash	Severity			
	Fatal		Casualty	
	N	%	N	%
Intersection	2	(11.1)	7	(11.0)
Opposite Direction	6	(33.3)	9	(12.3)
Same Direction	3	(16.7)	16	(21.9)
Manoeuvring	0	(0.0)	1	(1.4)
Over Taking	4	(22.2)	3	(4.1)
On Path	0	(0.0)	3	(4.1)
Single	3	(33.3)	30	(41.1)
Miscellaneous	0	(0.0)	1	(1.4)
Pedestrian	0	(0.0)	3	(4.1)
Total	18	(100.0)	73	(100.00)

The eighteen fatal crashes involving road trains resulted in 19 deaths. Five deaths occurred to occupants of road trains, three of whom died in single vehicle crashes, the other two in collisions. Four of the five road train occupants were drivers, therefore 4/91 (4.4 %) of road train drivers involved in police-reported casualty crashes were killed. This is a higher rate than for drivers of cars, as found in the Road Injury Database in which 600 (2%) drivers died, of 30,000 involved in casualty crashes from 1988-1992.

Of the five crashes resulting in a road train occupant fatality, three were single vehicle crashes involving a roll over, one was a head on collision, also resulting in the truck rolling over, and the fifth crash was an intersection collision.

Of the 14 occupants of other vehicles that died, five resulted from opposite direction crashes, four from overtaking and three from same direction crashes (Table 6)

Table 6.
Fatal road train crashes, type of crash and vehicle occupied by person killed, WA, 1988-1992

Type of Crash	Road Train	Other Vehicle
Intersection	1	1
Opposite Direction	1	5
Same Direction	0	3
Over Taking	0	4
Single	3	0
Total	5	13

Of the 45 hospital admissions from road train crashes, 14 were road train occupants injured in single vehicle crashes. Two other admissions were road train occupants injured in collisions with other vehicles,

finally, there were 29 occupants of other vehicles who were injured in the same collisions.

From the above it appears that the drivers of road trains have a greater risk of dying than car drivers, if involved in a casualty crash, and that occupants of other vehicles are at risk of injury in collisions with road trains. The risk of fatality is particularly high in opposite direction and overtaking crashes.

Of the 33 single vehicle road train crashes, 21 (63.6%) involved a road train leaving a road on a straight, 8 (24.2%) on a curve, and 4 (12.1%) at an intersection. Subsequently, 7 (7.7%) struck an object (such as an embankment, a pole, or a culvert), or rolled over (9, 27.3%), or both (3, 9.1%).

Thirteen (14.3%) of the 91 road train crashes involved a rollover, but a higher incidence was found in the crashes fatal to road train occupants (4/5, 80%), and in crashes in which road train occupants were admitted to hospital (9/16, 56.3%). Therefore, roll over of a road train seems to be associated with injury to the occupants.

In this study, police crash reports were examined to determine the presence of fatigue. The decision to assign fatigue as a contributing factor was based upon a combination of the police report, statements and comments collected from drivers and witnesses, and any other information, such as details of drivers' sleep, or crash circumstances (eg a road train running off the road with no sign of skid marks to indicate attempts to avert a crash).

Of the 91 road train crashes, 18, or 19.8% were identified as being fatigue related, over half of which occurred between midnight and 6am. Eighty percent of these were single vehicle crashes, compared with just over one quarter of the non-fatigue crashes. Of the 33 single vehicle crashes, 15 (45.4%) were identified as fatigue related. Of the 58 other road train crashes, three (5.2%) were fatigue related. Of these 18 fatigue related crashes, only 2 resulted in a fatality. One was a head-on collision where the driver of the other vehicle died, and one was a single vehicle rollover in which the road train driver died.

DISCUSSION

Road trains are operated primarily in the rural and remote regions of Western Australia. The crash involvement rate per 100 million vehicle kilometres is lower outside of Perth, but the rate increases with the number of trailers in tow. The rate for three trailer road trains is over twice that for two trailer trains. About one quarter of road train crashes involved a fatality, compared with under 10% for semitrailers.
Opposite direction and overtaking crashes had a high proportion of fatalities, in which the occupants of the other vehicle were at much greater risk than the road train occupants. The risk of injury to road train occupants is in crashes associated with rollovers, which occurred in 13 of 33 single vehicle crashes. No drivers were reported to have jumped clear of the vehicle before the crash. About 4% of road train drivers died in the 91 casualty crashes, twice the rate for car drivers in casualty crashes. About 20% of road train crashes were associated with fatigue, 80% of these were single vehicle crashes.

CONCLUSION

This study has identified that three trailer road trains have a crash involvement much higher than one and two trailer vehicles. The drivers of road trains have a higher risk of fatal injury than car drivers. This risk appears to be associated with fatigue, single vehicle crashes, and rollovers. The occupants of other vehicles colliding with road trains in opposite direction and overtaking crashes have a higher risk of injury. More detailed investigations are underway to define the mechanisms of crash and injury causation involved in the high-risk situations described above.

SECURING LOADS IN TELECOM VEHICLES TO WITHSTAND IMPACT

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Paper Number 96-S11-W-27

ABSTRACT

Research and development work carried out worldwide on vehicle safety tends to focus heavily on protecting vehicle occupants from being injured during the initial collision between their vehicle and another vehicle or object. This paper outlines work carried out by Telstra (Telecom Australia) to secure loads carried in vehicles such as station wagons and forward control vans, where the load can break free during a collision and strike the vehicle occupants - they can therefore be victims of two collisions in one accident. Australia leads the world in setting standards for cargo barriers, but these are limited in their ability to stop flying loads, and should only be treated as a secondary line of defence. Anchorage systems developed by Telstra have restrained loads of up to one tonne in vans during impact with a concrete barrier at speeds up to 50 kph.

INTRODUCTION

Telstra has a policy of providing a safe working environment for its employees, which includes motor vehicles. In accordance with this policy, investigations were carried out to identify the level of safety that existed in vans loaded up to one tonne with various types of tools and equipment.

Forward control vans such as the Toyota Hi Ace and Ford Econovans are commonly used by Jointers who install and connect telephone cables in metropolitan and country regions. The equipment carried inside the van includes items such as shovels and crowbars, various types of components and fittings, hand tools and expensive measuring instruments. Externally they are fitted with roof racks for carrying two ladders and conduit, and in some cases aluminium manhole guards. The total weight on the roof is restricted to 100 kg. The vans may also be fitted with a combination step/towbar. These vans are essentially mobile storage units.

The equipment carried inside the van can vary between Jointers, depending on the type of job and its geographic location. Individual items are normally stored in shelves and bins inside a steel frame which is secured to the vehicle body with steel straps. Large bulky items may be at times left on the floor in the centre isle. To accommodate the specific needs of individual Jointers, the binning system has adjustable shelves and removable storage containers.

The driver's cab is separated from the cargo area by a steel wire mesh cargo barrier built and fitted in accordance with Australian and New Zealand Standard AS/NZS:4034:1992. These barriers can withstand a total load of 200 kg, which includes a single mass of 60 kg, impacted horizontally at 48.3 kph. This is equivalent to stopping a 60 kg load dropped from a height of 9.06 m.

Initial Investigations

To evaluate the structural integrity of the load carrying system inside the vans, and the ladder rack assembly on the roof, a series of crash tests was conducted with various load and speed combinations.

The first test van was fitted with internal shelves and storage bins, and a complete ladder rack assembly on the roof, similar to a typical Jointers van. The payload was 750 kg, which is greater than the load normally carried by Jointers but less than the maximum allowable load of 1000 kg for this vehicle. Two 50 percentile test dummies were used in the driver's cab. Load transducers were fitted to the seat belts and two accelerometers were fitted behind the B-pillar on each side of the firewall. High speed cameras were used to capture the impact on film in slow motion. Based on existing industry standards it was considered that this system was structurally sound. All of the components and assemblies were commercially available products; however they were not specifically designed to withstand impact. Basic details are shown in Figure 1.

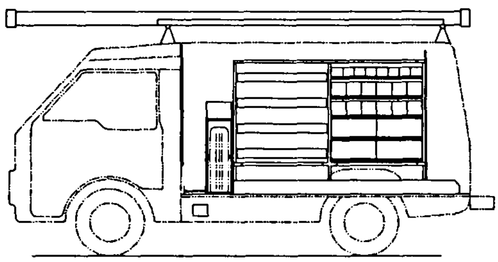

Figure 1. Typical configuration of cargo frame and ladder rack assembly.

The vehicle hit the concrete barrier at 41 kph. All the load broke free from the vehicle anchorage system and hit the cargo barrier, causing it to break away from its mounts and push the test dummies with sufficient force to snap the seat belt on the passenger dummy and dent the steering wheel with the dummy on the driver's side. The entire ladder rack assembly broke free from the roof and flew over the concrete barrier.

Revised Designs

Analysis of the failed components revealed fundamental flaws in various areas which led to the redesign of the entire system. The following modifications were made to the frame - see Figure 2:

- Reinforcing steel straps were welded to the corners to prevent the vertical legs from shearing from the horizontal cross members. These straps also acted as hinges, allowing the frame to deform, thus absorbing impact energy.
- Each shelf was secured to the vertical legs with self tapping screws to make the system absorb the impact load as a complete structure rather that by the individual members within the structure.
- 'Energy absorbing' straps were used to connect the entire assembly to the rear door hinges and to the floor.
- A new design anchor plate was developed and inserted in the cant rail.
- The ladder rack mounting system was redesigned and tested separately.

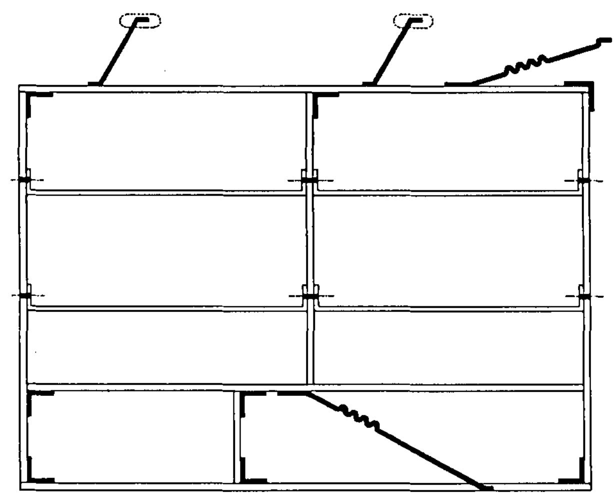

Figure 2. Modifications to cargo frame.

These features were incorporated in two different frame configurations and fitted to two Toyota Hi Ace vans. Test dummies were no longer used in these and subsequent tests. The steel wire mesh cargo barrier was replaced with a clear polycarbonate barrier behind the front seats. Both vans were loaded with the maximum payload, to full Gross Vehicle Mass (GVM). All tests loads were weighed and recorded, and both vans had similar loads placed in their corresponding shelves and bins. However the loose loads in the centre isles were varied to evaluate their effect on performance.

The 'g' forces were recorded with two Bruel & Kjaer accelerometers (piezoelectric type) mounted on the firewall near the B-pillar. The signal from each accelerometer was amplified through an in-line Bruel & Kjaer charge amplifier and then fed into a four channel FM tape recorder. A Hewlett Packard Dual Channel Frequency Analyser also was used for the measurements of the frequencies of the recorded signals for filtering purposes.

The primary aim of these tests was to restrain the loads in the vans during impact with a concrete barrier at a speed of 48.3 kph or greater. No load was to enter the driver's cab - this was the single most important requirement. The load restraint system was to remain largely intact, with deformation kept to a minimum but consistent with that required to absorb the impact energy.

The impact speed of the first van was 43.9 kph and the average maximum 'g' force was 39.5. The impact speed of the second van was 45.7 kph and the average maximum 'g' force was 45.5. In both cases, no load entered the driver's cab, and the performance of the load restraint system was vastly superior to the original system. However, in both cases the minimum required impact speed was not attained for various technical reasons, and further modifications were required for the system to comply fully with performance specifications.

The final modifications were carried out and a third van was crash tested at an impact speed of 49.2 kph, producing a deceleration of 52.7 g. Two high speed cameras were used to capture the performance on film. One camera was located on the vehicle, at the rear, showing the view toward the driver. The second camera filmed the performance from the side, through the side door opening.

All loads were successfully restrained within the van. The entire system remained connected to the vehicle, including the ladder rack assembly. This test was a complete success!

Current Research

The weakest link in a vehicle load restraint system is normally the connection between the frame or structure which carries the load and the vehicle body, such as the cant rail. This is typically only 0.8 mm thick and may need to withstand loads of 20 to 60 g under impact, which could be in the order of 2 - 3 tonnes.

After extensive research and testing, Telstra has developed an anchor plate which successfully withstands such loads. It has been designed to slice through the cant rail once the maximum load has been exceeded, leaving a small slot. In the process it absorbs the impact energy, without being pulled out of the cant rail. The anchor plate also has other features which maximise it load carrying capacity. Basic details are shown in Figure 3.

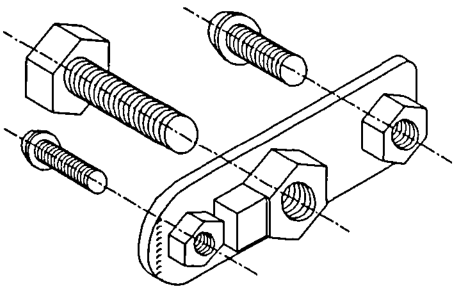

Figure 3. Telstra anchor plate.

To get a general indication of performance, static tests were conducted both on the Telstra anchor plate and on a plate used to secure commercially available cargo barriers. In the forward direction, parallel to the cant rail, the commercial plate pulled out of the cant rail at 1230 kg applied force; the Telstra plate began to slice through the cant rail at 2740 kg. With the load applied perpendicular to the cant rail, the commercial plate pulled out at 735 kg; the Telstra plate pulled out 1750 kg.

To evaluate dynamic performance, numerous tests were conducted using a trolley with an energy absorbing front end which has deceleration characteristics similar to vans. The trolley deck was fitted with two parallel steel sheets, 0.8 mm thick. Test masses were secured to the anchor plates (which were attached to the under side of these sheets) with various types of steel straps, to simulate a vehicle body attachment (Figures 4a - 4c). Accelerometers were fitted to each test mass and to the trolley. The aim of these tests was to evaluate the performance of both the anchor plates and 'energy absorbing' straps. Several types of straps were tested side by side during each collision, including an S shaped strap, as in Figure 4b, and a wrinkle strap, as in Figure 4c. These straps were made from 3 mm and 5 mm thick steel.

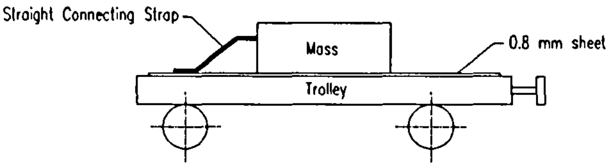

Figure 4(a). Trolley test with straight connecting straps.

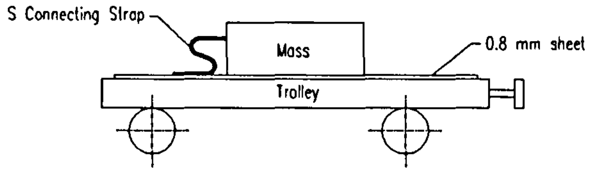

Figure 4(b). Trolley test with S shaped connecting straps.

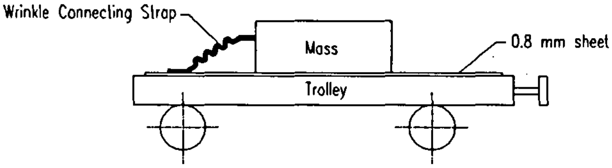

Figure 4(c). Trolley test with wrinkle connecting straps.

Contrary to expectations, 'energy absorbing' straps had the opposite effect - they did not reduce the 'g' force on the test mass, but actually increased it, to the extent that with some configurations, the deceleration of the test mass was considerably higher than the trolley - see Figure 5.

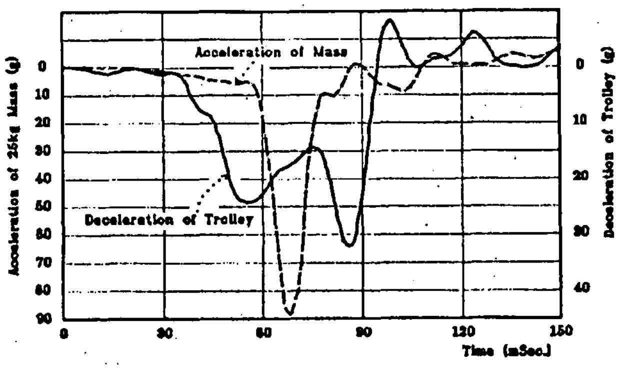

Figure 5. Graph showing 'g' forces on trolley and test mass.

On each occasion, the straight strap (as in Figure 4a) produced the lowest 'g' force on the test mass. Stiffer straps produced lower 'g' forces; the greater the relative velocity between the test mass and the trolley, the larger the 'g' force. These results were confirmed by:

- measurements recorded with the accelerometers;
- the physical deformations and relative displacements of the anchor plates;
- high speed photography by a cameras mounted on the trolley;
- finite element analysis;
- the consistency of the results - there was no variation in any test.

Further Developments

For cargo barriers to conform to the Australian and New Zealand standard, they are tested in a vehicle shell which has the rear end cut away. The shell is then mounted vertically in a test rig and a 60 kg mass is dropped from 9.06 m (or equivalent) onto the barrier. To confirm that the load restraint system discussed above had universal application, a drop test was conducted on a cargo barrier connected to Telstra anchor plates in lieu of the standard anchor plates supplied by the cargo barrier manufacturer. The mass however was increased to 90 kg (50 % increase) and the standard 'energy absorbing' straps were replaced with plain straight straps. The cargo barrier successfully withstood the impact!

CONCLUSION

A vehicle collision typically lasts 100 ms. During this time the loads carried in the vehicle increase by 20 - 60 g (and possibly more) depending on the severity of impact. This means that the vehicle body, which is normally 0.8 mm thick, needs to withstand forces in the vicinity of 2 - 3 tonnes. Existing commercially available anchorage systems cannot cope with such loads, consequently the load can break free from its vehicle mount and fly unrestrained forward towards the occupants. A cargo barrier, if fitted, will not stop this load if it exceeds 60 kg single mass, or 200 kg in total. The research and development work carried out to date by Telstra shows that cargo can be secured safely.

RECOMMENDATIONS

It is imperative that vehicle occupants are protected from being injured or killed by the cargo they carry in their vehicles. Apart from the serious efforts made in Australia to develop cargo barriers, and the extensive research and development undertaken by Telstra to secure loads, very little work has been done in this area. At the very least, motor vehicle manufacturers, standards committees and government organisations responsible for setting design rules, should address this issue by specifying minimum performance standards for securing loads in vehicles, particularly where the occupants and cargo share the same internal space.

Loads carried on roof racks also can have disastrous consequences, if not adequately secured to the vehicle roof. Existing Australian (and no doubt international) standards concentrate on operational performance, totally neglecting the fact that these assemblies can become airborne in a collision. In Australia (New South Wales) a school girl was killed last year in such an accident while seated in a bus which was hit in the rear by a van.

Vehicles which are designed to carry cargo must incorporate anchorage systems which can safely restrain this cargo in the event of a vehicle collision.

ACKNOWLEDGMENTS

The author would like to take this opportunity to express appreciation to Dr Essi Bidhendi from the University of South Australia for measuring, recording and analysing impact loads; Grad Zivkovic from Automotive Safety Engineering in Lonsdale, South Australia for conducting the crash tests; Frosty Gorostaga from Split Images in Adelaide, South Australia for providing the high speed photography; Ross Vidler from Raven Design Group in Queensland (former Telecom engineer) for initial testing and developing an alternative internal layout; and to my engineering colleagues at Fleet Services, Telstra - Gordon Brown, Jim Fitzgibbon, Alan Surtees, Ross Brown and Graham Cross, for their participation and assistance in conducting the research and development and in preparing this paper.

TILTING OF TRUCKS: A DRIVER EDUCATION SYSTEM AND WARNING SYSTEM

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Paper Number 96-S11-W-28

ABSTRACT

To reduce the risk of tilting, TNO has developed a tilt warning system for commercial vehicles. This system is able to monitor vehicle weight, lateral acceleration and velocity during normal operation. The system CPU is constantly comparing the measured lateral acceleration to a calculated limit value. It can be connected to a PC, providing the opportunity to on-line or off-line analyze trip data. The system has proven itself as a useful educational and off-line warning tool for commercial vehicle drivers. TNO has patented the system.

1. INTRODUCTION

1.1 Accident figures

In the last decade the number of tilt accidents of commercial vehicles seemed to have increased very rapidly. In the Netherlands not a day passes where radio traffic information doesn't contain a message of a tilted truck. One explanation is certainly that the press is better informed than 10 years ago, due to an increased and improved information network. Especially when it concerns accidents with trucks carrying dangerous goods, such as chemicals, there will be a nation-wide coverage of the accident, since it is still seen as very dangerous, in spite of the fact that legislation on national and E.C. level is very strict.
Obviously when a truck combination carrying dangerous goods is involved in an accident, the risk for the people and the environment cannot be neglected.

In most situations however, the tilt accidents cause a severe disruption of traffic, leading to a large economical damage. The estimated average loss of money caused by such an accident varies from 100.000 ECU up to 1.000.000 ECU [1]. These figures contain direct damage to vehicle and cargo. Environmental damage, the support costs (police, ambulance, etc.) and economical damage, caused by the traffic jam, and (fatal) injuries are not included. A tilt accident could therefore easily add up to an amount of 10.000.000 ECU.
To obtain an impression of the total amount of money involved, the number of tilt accidents have to be registrated. Here, the actual problem becomes evident. The exact number of tilt accidents in The Netherlands is not known. When exploring the accident statistics, they disappear in the large category of one vehicle accidents. A list was kept of the tilt accidents that were broadcasted via traffic information, causing severe traffic jams. The total number of registrated tilt accidents in one year (july 1993 to july 1994) exceeded 40 (see Figure 1).

Figure 1 Tilt accidents in The Netherlands

1.1 Problem solving

1.1.1 *Legislation*

In the past a lot of attention has been paid to the lateral stability of commercial vehicles. Research on this topic is carried out by Ervin, Fancher, Nordström [2] and Sweatman [3]. These activities have not yet lead to an internationally accepted standard, but it improved knowledge concerning the causes of lateral instability. The most concrete guideline, defined by Nordström as well as Sweatman, is the minimum lateral velocity of 4 m/s^2 for a fully loaded commercial vehicle.

1.1.2 *ISO*

In the ISO TC22/SC9 WG 6, the primary objective is to determine the lateral stability of heavy commercial vehicle combinations and articulated buses. Under preparation are definitions of characteristic values and functions in time domain and frequency domain which are considered necessary to characterize the transient response of vehicle combinations. The characteristics are rearward amplification of lateral acceleration and yaw velocity, dynamic off-tracking, critical speed for oscillatory instability, yaw damping including mode-shape information.

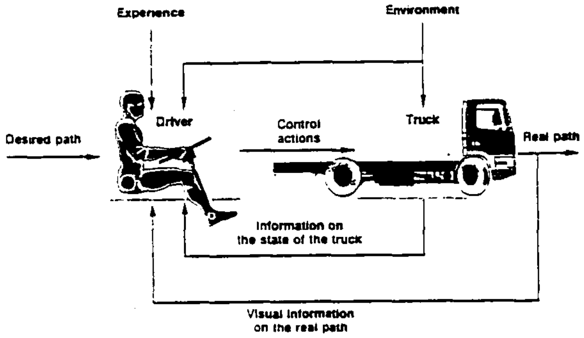

Figure 2 Capabilities, information and effort

1.1.3 *Development*

Commercial vehicle manufacturers pay a lot of attention to the handling capabilities of their vehicles. Handling, as a safety related issue, has become a selling item, beside comfort. Basic to the approach of handling judgement is to split it up over the three aspects, indicated in Figure 2.

Capability
The capability of the vehicle means: is the vehicle in itself capable of performing the required manoeuvres, maintaining a sufficient acceptable level of safety?

Information
This aspect concerns the information to the driver. The question is whether he receives the accurate, consistent and unbiased information as needed to perform his controlling tasks successfully. This information may be biased by the environment (road conditions, cross-wind, etc.). Here also the experience of the driver is important.

Effort
The effort, required by the driver to control his vehicle can be direct (course changes), indirect (corrective effort to keep course) and ambient (the fatiguing effect of vehicle movement, bad information etc.). These three aspects need to be accounted for in the assessment of criteria for safe vehicle handling.

By this fundamental approach maximum insight is gained in what, in the end, determines the handling qualities of a commercial vehicle. This approach allows for a clear distinction between characteristics which concern the vehicle alone and characteristics which concern the vehicle driver interface.

Problems with lateral stability of commercial vehicles occur when the driver is not aware of the actual condition of his vehicle, which might be close to its limits (no information, therefore getting the impression there is no danger (straight ahead stability) or overrating the vehicle (cornering)). By improving the information flow of vehicle status to the driver this danger could be diminished.
For commercial vehicles, with a large difference between laden and unladen situation resulting in a completely change of behaviour, this aspect is very important. Therefore, improvement of information flow has become a design objective.

1.1.4 *Others*

One other possibility to avoid tilt accidents of commercial vehicles is to improve the education of truck drivers. If the driver is aware of the capabilities of his vehicle and knows what he should do in dangerous situations this could help in avoid or at least diminish the results of an accident.

2. THE TILT WARNING SYSTEM

To provide in a tool that can help in educating and warning the driver, TNO has developed a system that monitors the vehicle lateral behaviour and is able to warn the driver for possible tilting of the vehicle. The system is developed for the Dutch transport company of liquified petroleum gas, BK-GAS B.V.

Pressure

The total vehicle weight is measured by pressure sensors, connected to the air suspension system of the tractor. The pressure in the air suspension is an indication for the actual vehicle load. By combining the left and right pressure the influence of a tilted road is taken into account when measuring the total actual weight. Also the sensor calibration can be performed on a tilted road, having no result on the determined weight.

During the trip, the signal from the pressure sensors is filtered by a low-pass software filter so that road unevenness does not disturb the measured weight and that loading or unloading cargo is detected.

Lateral acceleration

The accelerometer, mounted on the chassis of the tractor, is constantly monitoring the vehicle lateral acceleration. The mounting position on the tractor, like the pressure sensors, ensures an installation on only one articulation of the vehicle. When another semi trailer of the same kind is coupled to the tractor, the system does not have to be installed a second time. Furthermore, the system functions fully autonomously and does not require actions from the driver.

Tacho

The system also takes also information from the vehicles tacho to obtain information about actual speed and trip distance.

Black box

The black box consists of a Central Processing Unit (CPU) and an EPROM (Electronically Programmable Read Only Memory), containing the lateral acceleration limit at close to tilting of the vehicle (see Section 4). Four times a second the measured lateral acceleration is compared to the acceleration limit, for the specific weight condition, as measured by the pressure sensors. If the measured level of acceleration exceeds the limit value, coming from a model of the vehicle, a warning signal could be given to the driver, providing him with the opportunity to respond adequately.

The system logs the highest acceleration level, together with the weight, velocity and trip distance of every one second and stores it in the systems memory. These values are shown in a histogram, representing 10 categories of lateral acceleration. Furthermore, the ten largest registered accelerations are shown with their appropriate values of vehicle weight and speed.

Normally the system works on the vehicle source, but in case the contact is shut off, there is a battery backup to feed the memory.

The black box has a RS232 output to connect a PC to the system. The PC can be used as an on-line monitoring device during the trip, or can analyze trip data after it is send to PC. This makes the system a monitoring device and therefore an educational tool.

3. THE MATHEMATICAL MODEL

3.1 In general

As mentioned before, the limit value of the lateral acceleration of a specific vehicle is calculated by a mathematical model of the vehicle. For every possible weight of the vehicle, from empty to fully laden, the maximum lateral acceleration is calculated.

The chosen limit represents the moment when the truck-trailer combination lifts one wheel from the road (so when the vertical force of one of the wheels becomes zero). For a specific vehicle (the system can be used for truck and tractor-semi trailer combinations) a number of parameters are needed to identify the acceleration limit. When the EPROM is programmed, it can be plugged into the black box.

Since the system was developed for BK-GAS, the vehicle to model was a tractor-semi trailer with tank to transport liquified petroleum gas. To show system results, the acceleration is determined for the tank trailer combination.

3.2 The tractor - semi trailer model

The dynamic behaviour of a tractor-semi trailer combination, carrying a liquid load, can be seen as a worst case scenario. The difference between a full and empty vehicle is large, resulting in a completely changed dynamic behaviour. The load has its own dynamic properties, influencing the dynamic behaviour of the vehicle and resulting in a possibly increased lateral acceleration level and therefore increased tilt danger compared to a vehicle with the same weight but fixed load. The vehicle to be modelled is a 3-axle tractor with one driven axle and a three axle super single tank semi trailer.

The parameters of the vehicle are shown in Table 1.

Modelling of the vehicle is done in the multi body code BAMMS (Bondgraph based Algorithms for Modelling Multi body Systems). The code offers the user with a toolkit to choose, define or develop subsystems of the vehicle, from very elementary joints to complete axles. The code creates a stand alone programme, with which the vehicle behaviour can be simulated.

The tractor model consists of a 2 axle vehicle, where the rear axle represents both rear axles of the real tractor. Cab suspension is not taken into account.

The semi trailer is modelled as a one axle vehicle, where the only axle represents the three super single axles.

Of all vehicles the roll stiffness is modelled as a torsional stiffness and damping between sprung an unsprung mass. Linear tyre behaviour is expected. The king pin between tractor and trailer is represented as a ball joint with

Table 1 Vehicle model parameters

Tractor	
Tractor mass (incl. axles)	9000 kg
Centre of gravity	0.92 m
Wheel base	3.5 m
Track front	2.04 m
Track rear	1.83 m
Roll stiffness (axle 1)	620.000 Nm/rad
Roll stiffness (axle 2&3)	1.000.000 Nm/rad
Trailer	
Trailer mass(incl. axles)	16000 kg
Centre of gravity trailer	2.25 m
Mass liquid	25000 kg
Centre of gravity liquid	variable
Wheel base	7.00 m
Track	2.04 m
Roll stiffness (axle 1,2&3)	2.200.000 Nm/rad

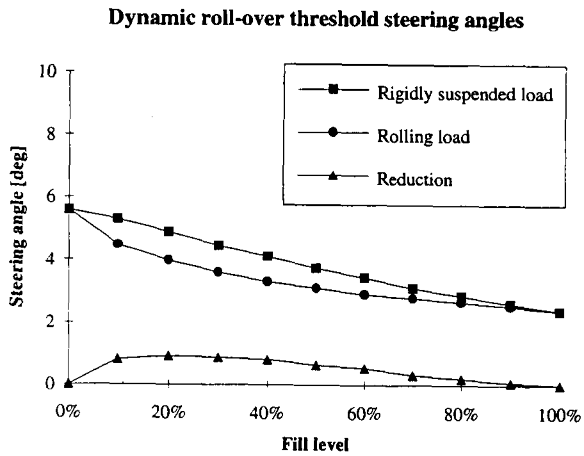

Figure 3 Limit acceleration value of tank vehicle with dynamic and fixed load influence.

restricted angle rotations around lateral and longitudinal axes. The liquid is modelled as a point mass connected to the tank with linear springs in longitudinal, lateral and vertical direction. The total liquid mass is modelled in one centre of gravity.

3.3 Simulations

To calculate the limit acceleration values at different levels of vehicle weight, the steady state curve behaviour is simulated. Because the accelerometer is mounted on the chassis of the tractor, therefore not in the centre of gravity of the complete vehicle, the model has to compensate for the positional shift in longitudinal direction.
A number of simulation runs carried out to establish the tilt acceleration at a fixed vehicle weight. This is done for a number of weights of the vehicle (from 0% to 100% load). For the tank vehicle the limit acceleration level as a function of vehicle weight is displayed in Figure 3, together with the effect of a fixed load.

4 EVALUATION OF THE SYSTEM

4.1 Data gathering

The system was tested by BK-GAS B.V. in 1993/1994, defining a route on which normal gas deliveries took place. More than 70 drivers drove with the system. Two drivers were asked to drive a larger number of trips. Totally over 1000 km was driven with the system. During these trips 4 times the system gave a warning to the driver, but vehicles never tilted.
The trip data was collected from memory by transferring it to PC. Together with the driver the data was analyzed, identifying high lateral accelerations.
Analysis here was performed on a PC with on a spread sheet programme.

4.2 Data analysis

At TNO, data analysis was carried out with N-SOFT. Time plots were made of lateral acceleration and vehicle weight, exceeding a threshold of 1 m/s^2. Also 3-D histogram plots were made of lateral acceleration against vehicle weight and lateral acceleration against velocity. All these plots were made for every trip, for all trips of the two drivers and for all trips as a total.

Figures 4 and 5 are typical trip time plots of lateral acceleration and velocity. Figures 6 gives the accompanying total trip data in histograms. Decrease of weight at a gas delivery is very well recognisable. The variation around one specific vehicle weight is caused by road irregularities and motion of the liquid. After the first few test trips, the software filter of the pressure sensor data was adjusted to decrease the influence of these disturbances.

In Figure 7 the total number of samples, collected during all tests, are presented in one graph. This graph supports earlier research [2], which indicated that drivers tend to overestimate the capabilities of their vehicle during low speed cornering manoeuvres. The highest lateral accelerations occur around 20 km/h.

Figures 8 and 9 give an impression of differences in driving behaviour of two drivers The diffusion of lateral acceleration against speed is evident. Especially at low speeds the difference between driver one and two become obvious.

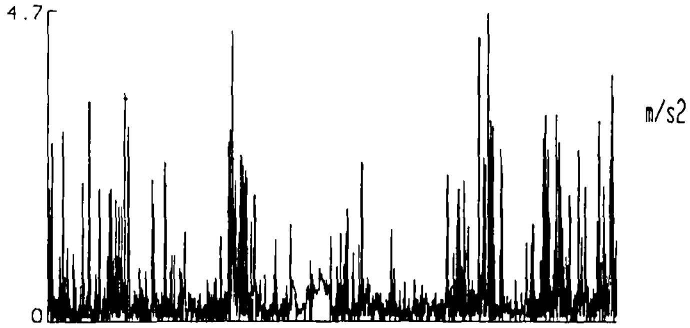

Figure 4 Time plot a_y

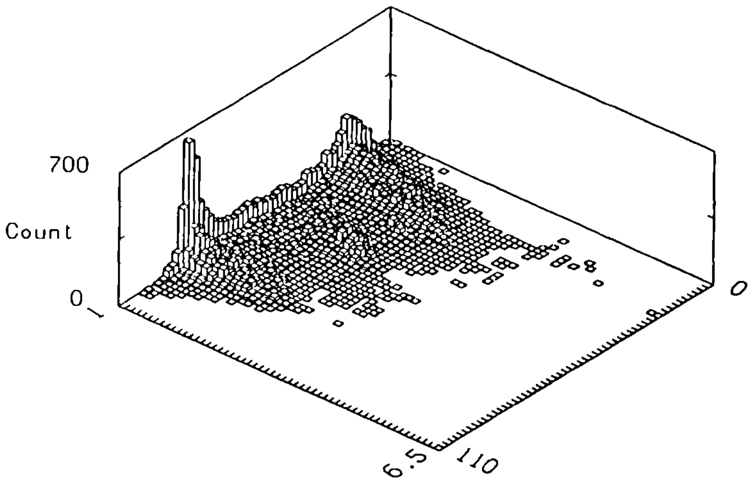

Figure 7 Total of gathered data

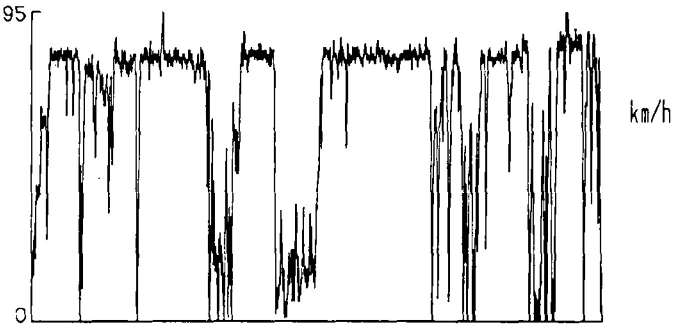

Figure 5 Time plot velocity

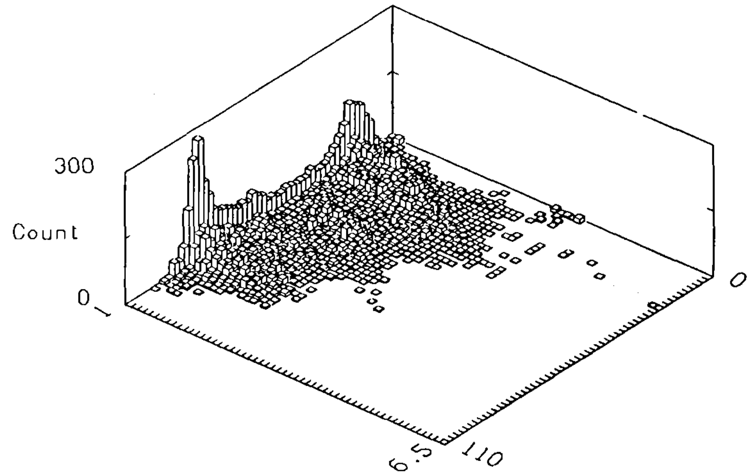

Figure 8 Driver 1

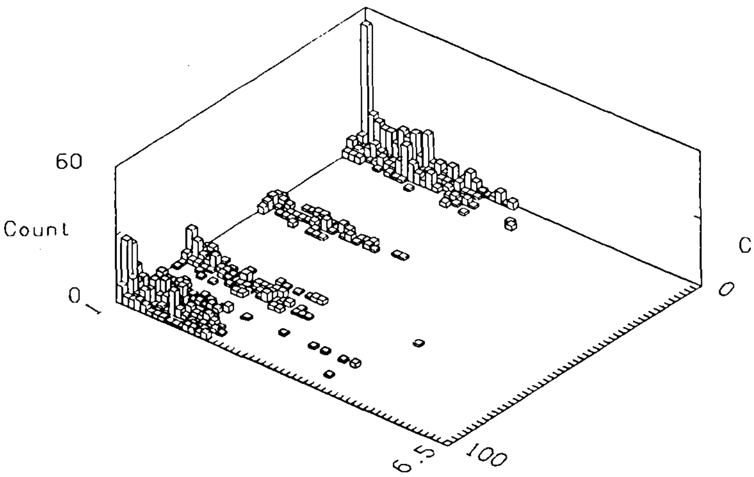

Figure 6 a_y - weight

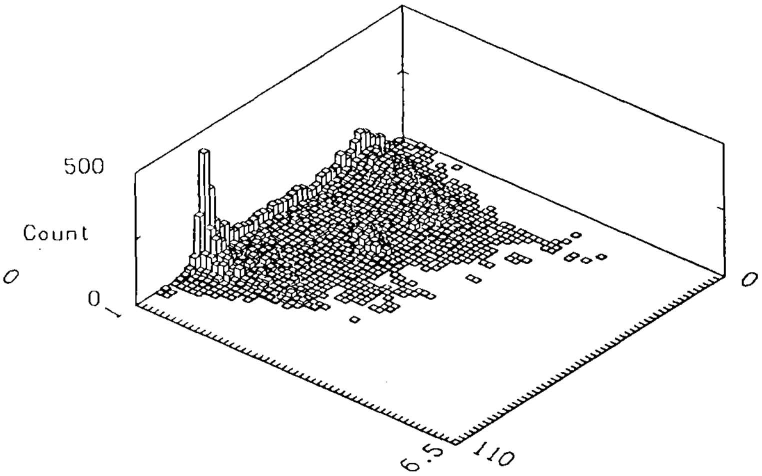

Figure 9 Driver 2

5 CONCLUSIONS

- to obtain better insight in the number, cause and effects (social, economical) of tilt accidents, registration of these accidents should be improved, from police reports (for accident reconstruction) to categorization of accidents in a database.
- the data analysis confirms conclusions from earlier research that tilting most likely occurs at speeds around 25 km/h, where the driver tends to overestimate the capabilities of his vehicle;
- the Tilt Warning System in general can be a efficient and cost-effective tool to educate drivers about vehicle capabilities, therefore reducing the number of situations which could result in tilting of the vehicle;
- differences in driver behaviour can be identified by the system, creating the opportunity to provide the driver with individual feedback;
- after initial reserved feeling towards the system, most drivers accepted it after test drives as a useful tool to improve personal safety;
- the Tilt Warning System indicates a potential usage as a driver warning and support system. The influence on driver behaviour and time lag between warning and tilting should be further investigated;
- extension to other registration functions for commercial vehicles is possible (on-board computers, freight monitoring, other telematics applications).

6. REFERENCES

[1] Kusters L.J.J.; Increasing roll-over safety of commercial vehicles by application of electronic systems; Smart Vehicles Conference, Delft, The Netherlands, February 1995

[2] Nordström O.; Heavy duty dynamics related to braking, steering and tyres. Swedish research and proposals by VTI; SAE 892502 (SP-801), 1989

[3] Sweatman P., Mai L.; Rollover of articulated vehicles; SAE 852185 (P-196), 1985

BELT SYSTEMS IN PASSENGER COACHES

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ABSTRACT

Touring coaches are the safest means of transportation, safer than aircraft, railway, truck and passenger car. Nevertheless, spectacular accidents happen and attract the attention of the general public. Especially when coaches overturn, there are severe injuries and in individual cases even fatalities to be regretted. The paper deals with accident situations of coaches. Collision types with relevant deceleration phases and collision velocities will be deduced from that. The kinematics of dummies, the dummy-loadings, the belt forces to be transferred to the structure as well as the safety potential will be determined by computer simulation (MADYMO 3D). Relevant collision types are the 90° rollover, and, to a far lesser extent, the frontal crash. The two-point belt proves to be superior to the conventional three-point belt.

INTRODUCTION

As a result of a number of serious bus accidents in the recent past, there has been increased public discussion about the safety of buses and questions concerning how to increase their safety have been raised. Studies dealing with accident types and accident frequencies and with safety measures and their implementation have been initiated or undertaken by bus manufacturers, bus operators, insurance companies, research institutes and legislative organs [1-6].

One particularly promising measure is theinstallation and use of safety belts [7]. In contrast to the situation with passenger cars, the installation and use of belts on passenger seats of motor coaches is not yet required by law. Today belts are installed on passenger seats only upon request by the customer. However, at present there exist no standardized testing specifications for determining the effectiveness of belts installed on passenger seats in motor coaches.

Before concrete steps can be taken to introduce belts in touring coaches, the accident situation must be analysed, requirements for the belts have to be formulated, and the consequences of using belts have to be predicted. The protection potential as well as the hazard potential have to be analysed. These questions were investigated in a research project carried out at the Institut für Straßen- und Schienenverkehr (Institute for Road and Railway Traffic) of the University of Berlin commissioned by the FAT (Forschungsverband Automobil Technik, Research Association of Automotive Technology). Computerized occupant simulation in the collision types which are relevant for the safety of bus occupants and the effect of belts as a restraint system constituted a substantial component of the studies.

LEGISLATION

Based on a resolution of the European Conference of Transport Ministers the coordination of technical specifications for coaches was taken up by the ECE working group WP 29 in 1967 as their working goal. In the process, a high level of safety was supposed to be maintained [4,5].

Four ECE regulations resulted from these tedious negotiations, which were shaped by compromises:

No. 36	Construction and function specifications for single-deck coaches
No. 52	Construction and function specifications for buses with small capacity
No. 66	Stability of bodywork
No. 80	Stability of seats and their anchoring

These ECE regulations came into force between 1976 and 1989. The application of ECE Regulation No. 66 for touring coaches is required by the national law in Great Britain and Spain. Although the Federal Republic of Germany has accepted the ECE regulations, it has not yet considered making their introduction obligatory because it is waiting until the final decisions about the future EU Guideline "Coaches" have been made.

Among other things, this future EU Guideline "Coaches" will contain among other things the ECE regulations for "structure stability" and "seat stability" and will cover altogether the following areas:

For normal operation: safe entering and exiting,
safe transport,
safe handling of the vehicle,

In the case of a catastrophe:	avoidance of injuries reduction of severity of injuries, emergency exits, evacuation, reduction of fire risk.

For the passive safety of touring coaches there are only two ECE regulations today which are of importance, Regulation No. 66 (seat stability) and Regulation No. 80 (structure stability). Although these regulations are not compulsory in Germany, they are taken into account by the bus manufacturers in the development and for the approval of new types by the authorities [8,9].

ECE Regulation No. 66: Testing of the stability of the seat backs and the seat anchoring in the case of a head-on collision when the passenger who is not wearing a safety belt hits the seat or seat back ahead of him. The testing conditions and specifications are described in Figure 1..

ECE Regulation No. 80: Testing of the roof structure of the bus because after the bus has overturned onto the edge of its roof, a defined survival space must be preserved. Figure 2. shows the testing conditions and specifications. Proof can be supplied by a test or by computation [6].

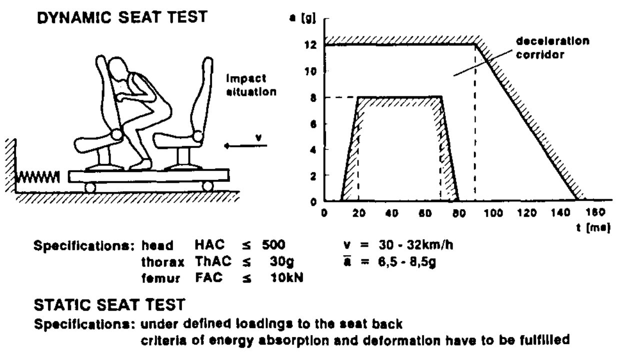


Figure 1. ECE regulation no. 80 for buses resistance of seats and their anchoring.

According to the latest version of the EU Guideline, safety belts are to be installed in buses only in "those seats with no passenger ahead", which means on seats in the very first row which are in an exposed position, on seats next to the doors and on seats in front of tables. The bus manufacturers in Germany demand just like the EU Commission in Brussels that the installation and use of two point belts on all seats in touring coaches over 5 t be made compulsory. For small buses (3.5 to 5 t) manufacturers should be able to choose between two point and three point belts, and in mini-buses (up to 3.5 t) three point belts should be installed.

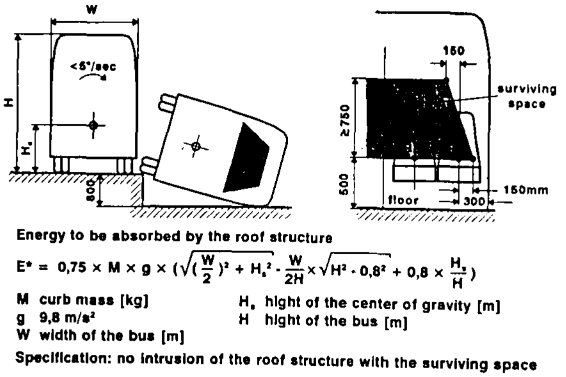


Figure 2. ECE regulation no. 66 for buses resistance of structure.

ACCIDENT ANALYSIS, COLLISION TYPES

First of all it must be remarked that coaches are the safest means of transportation. In Germany, for example, the risk of fatal injuries for bus occupants in relation to the transport service provided was only 9 % of that for passenger car occupants in 1992, see Figure 3..

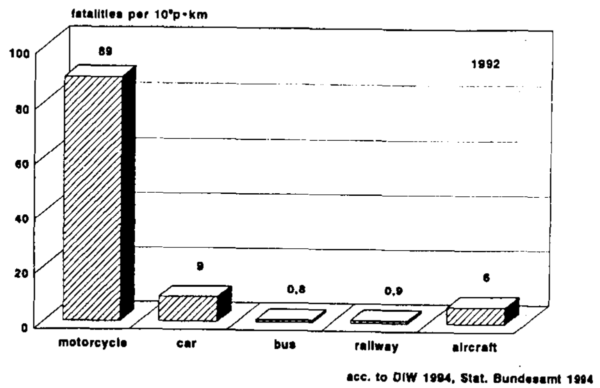


Figure 3. Fatalities resulting from different means of transportation.

It is known that the most common collision type is the frontal impact, followed by the frontal oblique impact, the rear-end collision and the overturn. Of these the most dangerous collision type is the overturn which on an average involves more than four fatalities per accident [6, 10, 11].

The accident analysis in this paper uses an accident investigation carried out by the DEKRA as commissioned by the FAT (Forschungsvereinigung Automobiltechnik e.V.) as an orientation. Their accident collection, compiled between the years 1985 and 1993 and

containing data for 48 accidents involving 50 buses, forms the data basis for the accident analysis of bus accidents, with the majority of them representing accidents reconstructed by motor vehicle specialists as part of the forensic clarification of the accidents. As far as the reliability of the evidence of these accident cases is concerned, it must be observed that these cases were investigated based on the assumption that there were injured bus occupants or such deformations of the vehicle as would make injuries of the occupants probable. For this reason the investigation data cannot correspond exactly to the general distribution of bus accidents. It is only relevant for accidents with severe consequences for the vehicle or its occupants. In order to ensure that the data record is representative and therefore possesses general validity, comparisons with other accident investigations were carried out. The data which form the basis for the comparisions were obtained from an evaluation of accident data made by the BASt (Bundesanstalt für Straßenwesen, Federal Traffic Institution) [11] and from an accident data record of severe bus accidents compiled by the HUK (Verband der Schadensversicherer, Association of Accident Insurances) between 1978 and 1985 [10].

Figure 4. contains a graphic representation of the distribution of the collision types in the various accident data collections. A comparison of the distribution of collision types for bus accidents occurring in the original West German states in the year 1991 (Federal Statistics) with that for the 48 accidents compiled by the DEKRA from 1985 to 1993 shows distinct differences. Single accidents of buses (10 cases or 20.4 %) and collisions with trucks (19 cases or 38.8 %) in particular have especially serious consequences for the vehicle and its occupants. Nearly 60 % of the 48 cases involve these two collision types alone. In comparison, they only make up 12.3 % in the Federal Statistics. Also in the Federal Statistics over half of the bus accidents are bus-passenger car collisions (53.1 %), whereas in the DEKRA cases they constitute the comparably low percentage of 26.5 % (13 cases).

As the accidents contained in the DEKRA material were selected according to the aspect of the danger of injury to the bus occupants and the risk of injury to other parties involved in bus accidents (in particular passenger car occupants, pedestrians, riders of two-wheeled vehicles) was not taken into account, this explains the fact that the corresponding collision opponents are not represented at all or only underproportionately. A comparision of the Federal Statistics from different years with respect to collision types shows agreement to a very large extent.

The DEKRA accidents in a data record containing severe bus accidents with injured bus occupants compiled between 1978 and 1985 by the HUK-Verband are comparable. For this reason, it can be assumed that the 48 DEKRA accidents are representative for serious bus accidents with casualties for the bus occupants, but not for the bus accident situtation in general. If the collision type bus-passenger car is disregarded, then 73.5 % of the DEKRA cases can be attributed to collision types which in the Federal Statistics of 1991 together comprise only 12.9 %, namely 7.5 % single accidents, 4.8 % bus/truck collisions and 0.6 % bus/bus collsions. This observation indicates that a relatively low number of accidents involving specific collision types lead to severe and fatal injuries of bus occupants.

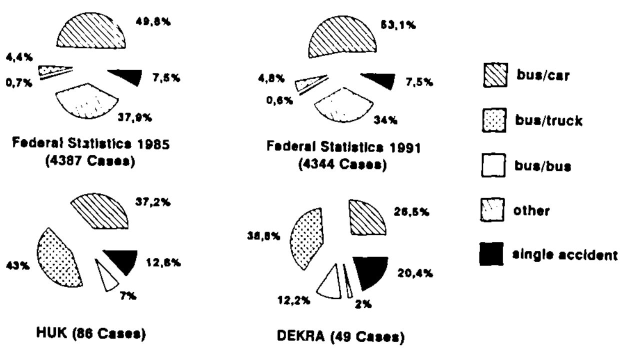
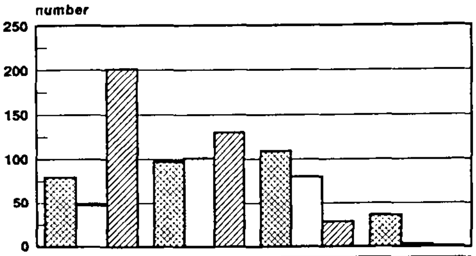


Figure 4. Types of bus accidents, different data sources.

As with the collision types, the distributions of the accident locations in the Federal Statistics and in the accidents compiled by the DEKRA differ from each other. It becomes apparent that the vast majority of bus accidents occur within towns. In contrast, of the accidents recorded by the DEKRA only 16.3 % occurred within towns whereas accidents on federal superhighways as well as on federal, state and district roads show a higher representation when compared with the Federal Statistics. The bus occupants face the most risks in interurban and touring coach traffic, where the driving and collision velocities are correspondingly higher.

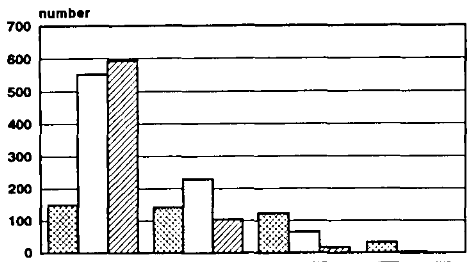
The analysis of accidents which ar dangerous for the occupants will be carried out on the basis of the relevant collision types (see Figure 5.). In addition to these, the collision type overturn/rollover will be introduced. A total of 8 out of the 48 accidents are of this collision type. One case must be accorded special status because of its specific causes of injury and is not regarded since it would influence the statistics considerably. It is astonishing that 50.2 % of all severely injured persons and even 90.0 % of all fatalities are to be attributed to the 8 accidents of the collision type overturn/rollover.

Before conclusions are drawn from this evaluation, the data material should be tested once again by a comparison with the accident data for severe bus accidents collected by the HUK-Verband to ensure its representative character (see Figure 6.). In the HUK-Verband data material as well the majority of severely injured persons can be found in the collision types bus/truck and overturn/rollover. Particularly the fatally injured bus passengers are again to be regretted in the overturn/rollover accidents of buses. Therefore the DEKRA accidents can be considered representative with respect to the distribution of the severity of injury to bus occupants in serious accidents.



	uninjured	injured	severe injured	fatalities
Overturn/Rollover	79	97	109	38
Frontal Bus/Truck	47	101	80	3
Other Cases	201	130	28	1

Figure 5. Injury severity in differnt collision types (48 DEKRA cases).



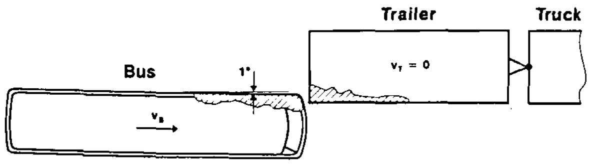
	uninjured	injured	severe injured	fatalities
Overturn/Rollover	150	143	124	34
Frontal Bus/Truck	552	229	66	5
Other Cases	593	105	18	1

Figure 6. Injury Severity in Different Collision Types (97 HUK Cases)

It can be observed that there are considerable differences in the consequences of the accidents for the bus occupants depending on the collisioype. Especially serious consequences are the result when the bus overturns or rolls over. Such cases almost always cause severe and very often fatal injuries to the bus occupants.

The collision type frontal impact of bus against truck

In Figure 7. the impact of the left-hand side of a bus against a standing truck-trailer is recognizable as a typical frontal impact (Case No. 10753 of the Hanover Medical College). Of the 23 occupants 16 were injured, and most severely with AIS 3 the driver and some passengers sitting on the left-hand side. The longitudinal deceleration of the bus must have been under 5 g. The severe injuries were caused by the intrusions on the left-hand side.



collision velocity v_B	=	97 km/h	acc. to Accident Analysis,
speed variation Δv_B	=	31 km/h	Case No. 10753, MH
equivalent energy speed EES_B	=	47 km/h	Hannover
collision angle	=	1°	
overlap	=	20 %	
VDI-code		06 F Y A W 9 50	

Figure 7. Bus collision type I. frontal impact.

In a crash test of the DEKRA a bus impacted frontally against a fixed concrete barrier with an overlap of 30 % and at a speed of 31 km/h. With a deformation of 1.2 m and a crash duration of 200 ms, the deceleration was at 4 g on an average.

The evaluation of 10 frontal impact collisions bus/truck (5 rear-end and 5 head-on collisions) from the accident collection [12] aimed at analysing the accident characterizations

relative impact speed,
overlap and
crash deceleration.

The deformation energy absorbed in the collision is

$$W_B + W_T = \frac{1}{2}\frac{m_B \cdot m_T}{m_B + m_T}(1 - k^2)(v_B - v_T)^2$$

W_B, W_T	Deformation energies of bus, truck
	m_B, m_T Masses of bus, truck
k	Restitution coefficient (0.25 - 0.70)
v_B, v_T	Speeds of bus, truck before the collision

The mean crash deceleration a_B of the bus can be determined from the specific deformation energy of the bus W_{Bsp} and the crush of the bus s_B:

$$W_{Bsp} = \frac{W_B}{m_B} = \frac{m_B \cdot \bar{a}_B \cdot s_B}{m_B}$$

$$\bar{a}_B = \frac{W_{Bsp}}{s_B}$$

For this it is presupposed that the acceleration vs. time remains constant and that appropriate assumptions about the distribution of crash energy W_B/W_T over bus and truck can be made.

In Figure 8. the specific energy W_{Bsp} is represented over the bus deformation for the ten collisions. Here the two extreme values

$W_B/W_T =$ 100/00 and 50/50 [%]

are added to the probable energy distribution

$W_B/W_T =$ 75/25 [%].

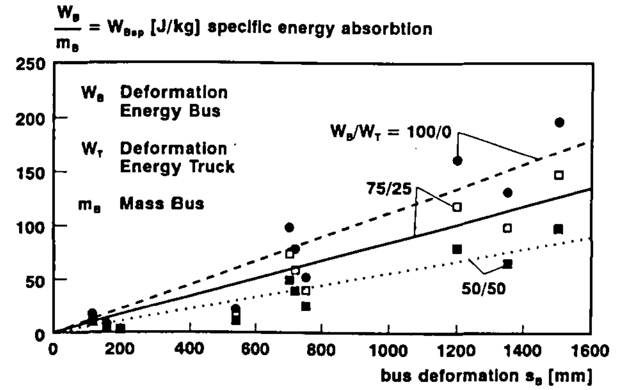


Figure 8. Specific energy absorption in bus/truck collisions(5 head-on, 5 rear-end collsions).

The regression line for the ten accidents with the distribution of 75/25 has a slope of approximately 8 g. This deceleration is higher than the deceleration measured in [12] because in the real accidents there often is an offset. The overlaps lay between 60 and 70 % on an average.

The collision type overturn/rollover

The most important subclassifications of the collision type overturn/rollover are represented in Figure 9.. Lateral skidding caused by a combination of longitudinal and transverse motion occur in 75 % of the cases in a driving state without braking at a relatively high medium speed of 62 km/h. Lateral skidding and/or driving down an incline or into a ditch lead to the following overturn types:

1 Overturning onto the flat side
2 Overturning onto local obstacles, for example guardrails
3 Overturning into a depression without rolling over
4 Overturning into a depression with rolling over.

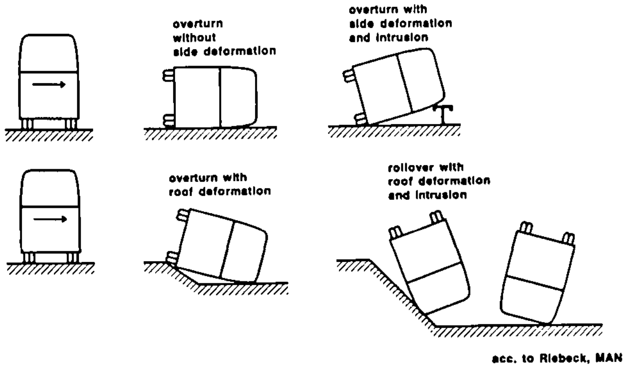


Figure 9. Bus collision type II overturn, rollover.

It is evident that in particular both impacting against guardrails owing to the intrusions and rolling over on account of denting of the roof can lead to disastrous consequences.

Causes of injury in the collision type overturn/rollover

For accidents of the collision type overturn/rollover the parts which in the accident assessors' reports are declared to be the cause of the injuries should be studied more closely so that information on the occupant kinematics during the accident can be obtained (see Figure 10.). At the same time this enables conclusions to be drawn about the most advantageous design of individual construction elements with regard to safety and about the reduction of the danger of injury by installating and using belts.

Seats/head-rests, side windows and the roof area are mentioned especially often. Impacting against the seats is basically inevitable because the seat is the element which the bus passenger is in closest proximity to. However, as seats are also named as a cause of injury in almost all of the other collision types in which occupants have in part only minor injuries, it seems likely that seats only lead to minor injuries in most cases. That the roof area is often mentioned, which includes the overhead racks for carry-

on luggage and to a certain extent the side windows, is on the other hand an indication that the occupants are thrown about during the overturning process. The padding of these constrution elements could contribute to improving the passive safety of buses. This also applies to ashtrays, which are often designated as a cause of injury in the other collision types. The side windows were mentioned five times, which leads to the conclusion that when the bus overturned, some persons were partially flung out, subsequently suffering considerable injuries from glass fragments and contact with the road surface. One further cause mentioned is the "being catapulted out of the bus", with which a total of six casualties is connected.

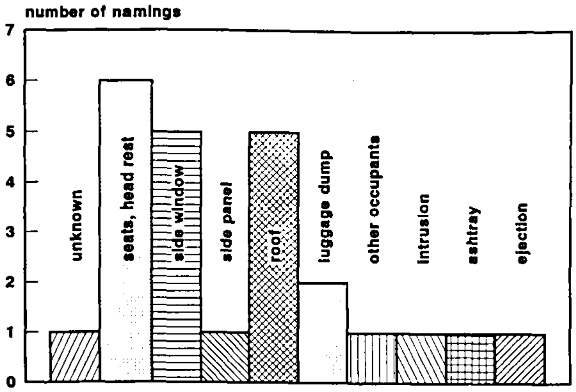


Figure 10. Causes of injury (48 DEKRA cases).

The following points, which were of importance for the occupant simulation of these accidents, could be gathered from the accident assessments:

- In seven out of eight cases the bus turned on its side. Only in one case did the bus roll over so that turning on its side can be considered representative.
- When the bus did not fall against a fixed obstacle such as a guiderail, the side structures were homogeneously deformed, with only slight crushing being observed.

COMPUTER SIMULATION OF THE OCCUPANT KINEMATICS AND OCCUPANT DYNAMICS

Computer simulation is carried out for the frontal impact and the overturn. The respective bus kinematics are defined as smooth motion. The occupant simulations are carried out with 3D-MBS models for the occupants (Hybrid III, 50 % male dummy and 5 % female dummy) and for the construction elements (seat, seat back, side, roof). The belts are incorporated as FE-models. The following parameters are varied:

- Restraint (no belt, 2 pt. belt, 3 pt. belt)
- Spacing of seats (720 - 850 mm)
- Belt slack (0, 40, 60, 80, 120 mm)
- Resistance of seat anchoring
- Resistance of seat backs
- Belt strain (8, 10, 12, 14 %)
- Belt force limitation (0, 2000, 2500, 3000 N)
- Height of side panel (600 - 750 mm)
- Arm rests (yes, no).

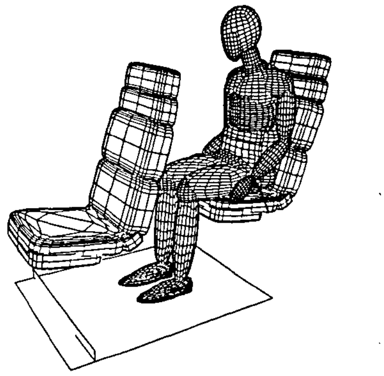
The two essential questions to be posed are:

1. Which restraint should be given preference?
2. Which forces arise at the anchor points of the belts?

Simulation of the frontal impact

The Madymo model is depicted in Figure 11.. The dummy sits on a seat and there is another seat in front of it which allows the impact against the back of the front seat to be tested. The bus motion is described by using the following representative accident characterizations [14]:

Speed variation	Δv	=	32 km/h
Average deceleration (constant)	a	$\approx$	5 g
Duration of the crash pulse	Δt	$\approx$	186 ms.

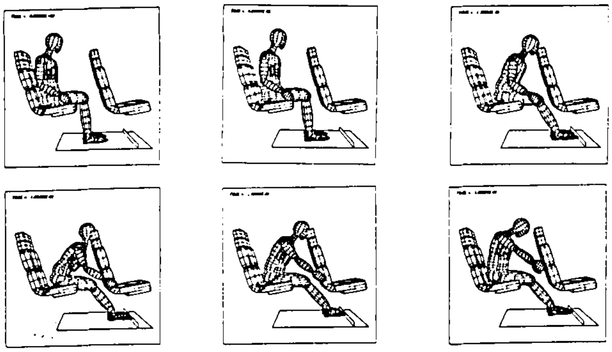


dummy hybrid III 50% male, 2Pt belt, seat distance 850mm

Figure 11. MADYMO model for simulation of the frontal impact.

The simulation results show that with use of a 2 pt. belt the jack-knife effect on the hip joint leads to a head impact against the back of the seat ahead (see Figure 12.). When the padding of the seat back is inadequate, this leads to high contact forces, head decelerations and neck bending angles in the derived representative accident characterizations. In the worst-case studies, head decelerations with a HIC > 1000 can be simulated. In order to reduce these loadings to a negligible level, it is necessary to pad the seat backs on their back side in the

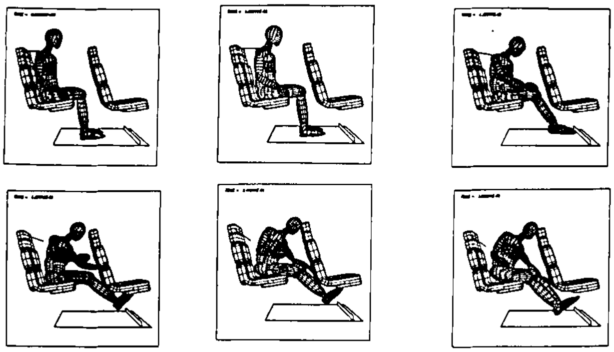
area of the head-rests. The padding should contain sheet metal or foam rubber of high density because in this case the padding thicknesses of 2.5 to 5 cm already present are sufficient for providing protection against head impacts. These measures should be carried out with respect to the specifications defined in the ECE-R 80 concerning occupant safety in frontal impacts so that the level of occupant safety is not decreased by introducing belts as compared with today's standards.



10% belt strain, 60mm belt slack, no belt force limiter

Figure 12. Kinematics of a Hybrid III 50 % male dummy during frontal impact, 2 pt. belt.

When no belt is used, the neck and head strike against the upper edge of the seat back in the row ahead. The loadings are dependent on the construction of the seat back. The best restraint is provided by the 3 point belt, see Figure 13.



10% belt strain, 60mm belt slack, no belt force limiter

Figure 13. Kinematics of a Hybrid III 50 % male dummy during frontal impact, 3 pt. belt.

To serve as an example, the time of the resulting belt forces during the use of a 2 pt. belt is shown in Figure 14.. On the left-hand side the belt slack and on the right-hand side the force limitation are varied. The resulting belt force is approximately 6000 N.

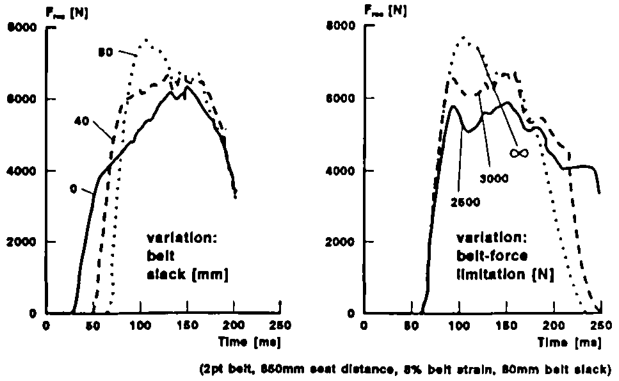


Figure 14. Frontal impact resultant belt force versus time.

Simulation of the overturn

First the overturning of the bus structure is simulated by means of a two-dimensional model so that the characterizations for the acceleration of the occupants and the rotation movement of the bus structure during the overturn process are maintained. The overturning motion was simulated under the following conditions which were defined based on data from the accident assessments:

- overturning motion from a strictly transverse motion of the bus
- starting velocity of 50 km/h
- maximum tilting angle of 98°
- maximum deformations of the side structure of 150 mm during the overturning process.

The differentiated curves of the transverse and vertical accelerations of the bus can be found in the report [14].

On the basis of the accident characterizations obtained from the overturn simulation, it was possible to simulate the occupant kinematics and kinetics during the overturning action for different combinations of dummies with their interactions. To serve as examples, some of the important simulation results are described:

The analyses of motion sequences show (see Figure 15., top) that the occupants not wearing belts are thrown around when the bus overturns. They first move in a lateral direction, then towards the roof; after that the dummies on the offside fall onto the dummies on the impacted side.

- By using 2 pt. belts the occupants are fixed securely on their seats. Only the occupants sitting directly next to the window on the impacted side face the danger of being partially catapulted out of the bus when the upper body is shifted to a horizontal position after a window has been

destroyed. The degree of the horizontal positioning of the upper body and the severity of the head impact against the road surface connected with this are influenced critically by the height of the side panel, see Figure 15., center.

- The 3 pt. belt shows a definite disadvantage as far as ensuring that the bus occupants are fixed securely in their seats is concerned. If one assumes that the shoulder belt is positioned over the shoulder facing the nearest side window, then the offside occupants slide out of the shoulder belts during the overturning process. After a side impact the dummies slide completely out of the belts because of the extreme belt slack resulting from the sliding of the shoulder belt slack through the d-ring (see Figure 15., bottom).
- The resulting belt forces are greater with the 3 pt. belt than with the 2 pt. belt; they are lesser for the occupants on the impacted side than for those on the offside, see Figure 16..
- By using a belt force limiter, the maximum resulting belt force for the offside occupants wearing a 2 pt. belt decreases from just under 14 000 to approximately 7000 N, see Figure 17..
- The simulation of the occupant kinematics of a passenger sitting directly next to the impacting side wall and wearing a 2 pt. belt shows that the height of the side panel has a considerable influence on the motion of the occupant when the side window is destroyed by a side impact. From a side panel height of approximately 800 to 850 mm onwards above the ground the horizontal positioning of the upper body is prevented for the most part by the shoulder resting against the side wall. If the road surface is taken into consideration in the simulations, then the occupant's head and with lower side panel heights the occupant's head and shoulder strike against the street surface. With side panel heights from 800 mm on, the loadings resulting from the head impact are not serious (>100), whereas with lower side panel heights HIC-values which are only slightly under the limit of 1000 (see Figure 18.) can be analysed from the simulations. The restraining effect could also be achieved by fixing a shoulder-rest on the window columns at the corresponding height (see Figure 19).

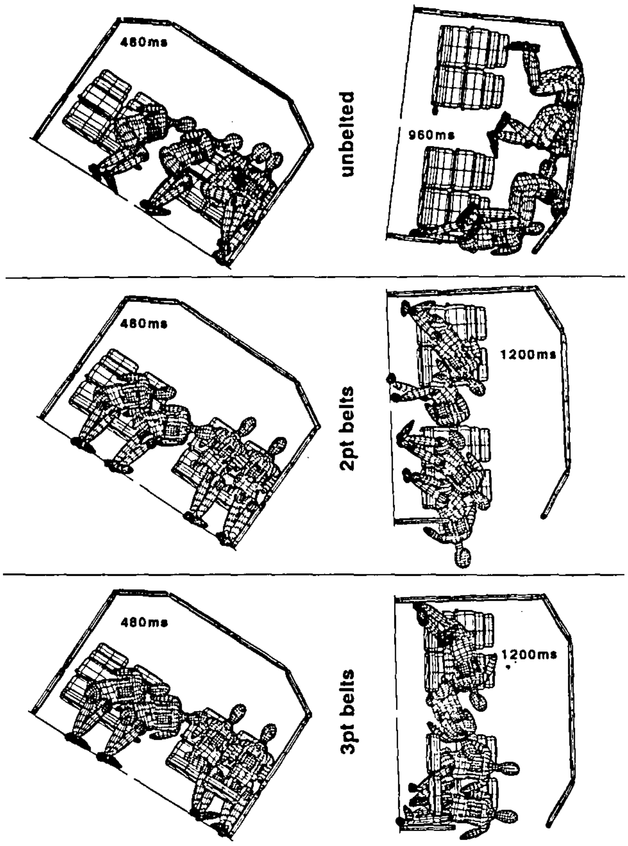


Figure 15. Motion sequence of four dummies Hybrid III 50 % male during overturn.

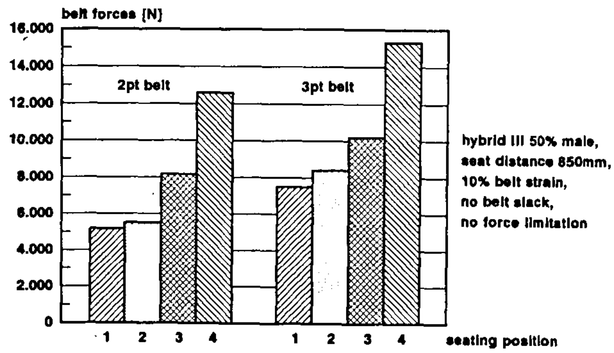


Figure 16. Maximum resultant belt forces during overturn.

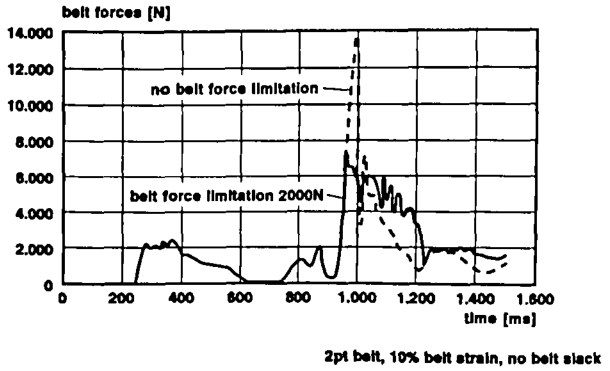


Figure 17. Resultant belt force for the offside occupant verus time.

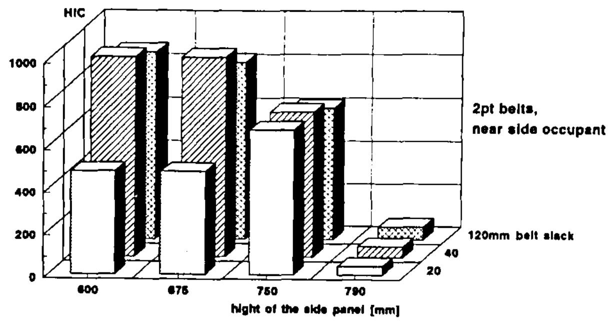


Figure 18. HIC Caused by head impact with road surface influence of side panel.

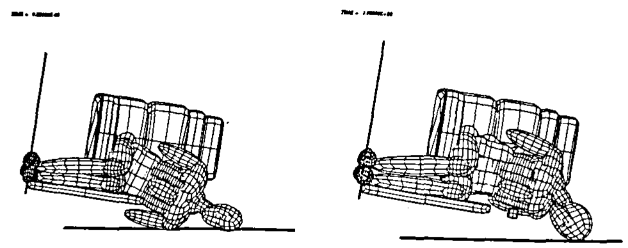


Figure 19. Different head kinematics and head loadings for various heights of side panel (collision type overturn).

CONCLUSION

The accident analysis of severe bus accidents shows the frontal impact, but most of all the overturn/rollover of buses cause severe and fatal injuries to bus occupants. With the aid of occupant simulations for these collision types, to what degree belts can reduce the danger of injury to bus occupants was analysed. The simulations show that passive safety especially in accidents of the collision type overturn/rollover can be considerably improved by belts, with the 2 pt. belt being sufficient for fixing the occupants securely in their seats and even showing advantages in comparison with the 3 pt. belt for guaranteeing that occupants do not slide out of the belts.

As belts help to reduce the danger to occupants in the accident types with the highest number of severely and fatally injured bus occupants, their use in touring coaches can generally be considered an effective measure for improving safety in touring coach transportation. Of course it is not only necessary to install the belts, but also to make their use mandatory because otherwise it cannot be assumed that they will be used by everyone. As an accompanying measure for improvement of occupant safety by introducing the 2 pt. belts, padding the back-side of the seat backs in the area of the head rests and raising the side panels on the side walls or fixing a shoulder-rest to the window columns of the side wall have been found to be advisable. The first measure pertains to the head impact against the seat back which with the 2 pt. belt results from the occupant kinematics during the restraint phase of the frontal impact. The second measure is supposed to protect the occupants sitting directly next to the impacting side wall from having their upper bodies partially catapulted out of the bus in the case of an overturn. In addition, the buses should be furnished with laminated safety glass in some of the side windows. The possibility of quick escape must be maintained. Loss of comfort and the present difficulty of enforcing the use of belts are not acceptable As reasons against making belts obligatory in buses. The disadvantages, that after an overturn occupants wearing belts are left hanging in the air and can scarely free themselves without danger and also cannot be as easily rescued by helpers, are of more import. These disadvantages, however, do not outweigh the advantages gained by requiring the general use of belts in buses.

REFERENCES

[1] Auwärter, C.; Otte, D.; Hackenberg, N.; Lenz, W.; Sarnes, J.; Woschei, K.: Preliminary Investigations of the Level of Active and Passive Security in Touring Coaches - SMARAKD. Technical Final Report. NEOPLAN/SNV/TÜV Rheinland e.V., Cologne, 1990

[2] Scheper, A.: On the Security of Touring Coaches, Accident Data Evaluation. Reports of the Federal Traffic Insitution. People and Safety, Issue M 17, 1992, 52 pages

[3] Langwieder, Kl.: Safety in Touring Coaches - Requirements for People and Technology from the Perspective of Accident Research. 5th Coach Forum of the TÜV Southwest, 1994, 9 - 14

[4] Hammer, G.: Technical Requirements for Coach Safety from the Perspective of the EU and the ECE. 5th Coach Forum of the TÜV Southwest, 1994, 35 - 40

[5] Hamsten, B.: Are Safety Criteria for Structure Stability, Seat Construction and Restraint Systems Still Sufficient for Today? 5th Coach Forum of the TÜV Southwest, 1994, 41 - 45

[6] Breitling, U.: Combined Effect of Construction, Computation and Testing in the Development of Coach Structures with Increased Passive Safety. 5th Coach Forum of the TÜV Southwest, 1994, 46 - 54

[7] Stangl, G.; Hummel, H.: Possibilities for Increasing the Safety of Coaches from the Perspective of the Manufacturer. VDI-Reports 1188 1995, 261 - 274

[8] ECE Regulation R 66: Standardized Specifications for Approval of Motor Coaches with Respect to the Stability of Their Structure. FEE, 13th Supplement, January 1988

[9] ECE Regulation R 80: Standardized Specifications for Approval of Seats in Motor Coaches and of These Vehicles with Repect to the Stability of the Seats and Their Anchoring. FEE, 17th Supplement, March 1990

[10] Langwieder, K.; Danner, M.; Hummel, Th.: Collision Types and Characteristics of Bus Accidents - Their Consequences for the Bus Passengers and the Accident Opponent. Proceedings of the Tenth International Technical Conference on Experimental Safety Vehicles, Oxford, England, July 1985, 585 - 594

[11] Färber, B.; Heinrich, H.C.; Hundhausen, G.; Hütter, G.; Kamm, H.; Mörl, G.; Winkler, W.: Safety in Tourist Coach Transportation. Reports of the Federal Traffic Institution. People and Safety, Issue M 40, 1995, 124 pages

[12] Grandel, J.; Niewöhner, W.: Inner Safety of KOM (Results of an In-Depth Investigation). DEKRA Accident Research, Stuttgart, Final Report, April 1994

[13] Grandel, J.; Muller, C.-F.: Contribution to the Safety of Coaches. DEKRA Accident Research, Stuttgart, 1994, 42 pages

[14] Appel, H.; Rasenack, W.; Rau, H.; Rietz, C.: Requirements for Belts in Touring Coaches. Final Report. Commissioned by: Research Association of Automotive Technology e.V. (FAT). Berlin, 1995, 66 pages plus 33 pages of appendices

Section 5
Invited Speakers Panel

New Vehicles Crashworthiness Rating System

Moderator: James Hackney, United States of America

Activities of the New Car Assessment Program in the United States

James R. Hackney
Charles J. Kahane
Robert Chan
National Highway Traffic Safety Administration
United States

ABSTRACT

In 1978, the National Highway Traffic Safety Administration began assessing the occupant protection capabilities of new cars by conducting high speed frontal barrier crash tests. This New Car Assessment Program has primary goals to provide consumers with a measure of the relative safety potential of automobiles and to establish market forces which encourage vehicle manufacturers to design higher levels of safety into their vehicles.

The New Car Assessment Program crash test conditions closely resemble actual frontal crashes that result in fatalities or serious injuries. In these controlled crash tests, the levels of potential injury are assessed by measurements taken from two anthropomorphic test devices (dummies) that simulate 50th percentile adult males. Biomechanical data have been used to develop injury risk functions which relate the dummy measurements to injury probabilities. Beginning with the model year (MY) 1994 vehicles, the National Highway Traffic Safety Administration adopted the use of these injury risk functions to develop a simplified star rating data format which could provide consumers with easily understandable vehicle safety performance information.

Notable improvements in occupant safety as measured by the dummy responses have occurred during the history of the program. About a one-third reduction in the probability of a life-threatening injury has occurred in the NCAP passenger cars (PCs) as measured by the controlled crash test results. Light trucks, vans, and sport utility vehicles (LTVs) are noted to have injury probabilities higher than those measured in the PCs. However, in recent years, improvements in NCAP LTV performance have led to about a 25 percent reduction in the calculated probability of AIS$\geq$4 injuries.

Studies have established that a significant correlation exists between the serious injury probabilities as predicted by the test scores and actual fatality risks on the road. When dividing the vehicles into "lower risk" and "higher risk" performers as defined by the injury probabilities from the NCAP tests, restrained drivers of the "lower risk" cars are as much as 30 percent less likely to receive fatal injuries when compared to restrained drivers of the "higher risk" cars in severe frontal crashes. These results when compared to the test results from the rapidly increasing number of air bag equipped vehicles indicate that the trend of improving occupant protection in severe frontal crashes is expected to continue.

The upgrade of Federal Motor Vehicle Standard (FMVSS) No. 214, Side Impact Protection, to require a dynamic test provides the opportunity for the expansion of NCAP into side-impact protection. Crash conditions for this expansion have been determined and test results from higher speed crashes have been compared to results from FMVSS No. 214 test results.

In 1995 and 1996, The Insurance Institute for Highway Safety (IIHS) conducted frontal offset crash tests on PCs and LTVs. These data provide the first comparison of an extensive group of U. S. vehicles which have been tested in both full frontal and frontal offset crashes. The results support the position that the full frontal test is a more stringent evaluation of the restraint system performance. However, due to more intrusion, the probability of lower leg injury will be better determined in the offset crashes. By testing in both crash modes, as the Road and Traffic Authority of New South Wales is doing, a more complete assessment of vehicle safety is possible.

Two studies on consumer information have recently been completed. The "NHTSA 1995 Customer Satisfaction Survey" provides national estimates of the public's attitudes, opinions, and behavior relative to traffic safety. The Transportation Research Board's study "Shopping for Safety: Providing Consumer Safety Information," broadly examined motor vehicle consumer needs and methods of communicating this information to the public. NHTSA is closely reviewing these studies relative to NCAP and consumer information activities.

Introduction

With the continued efforts of the National Highway Traffic Safety Administration (NHTSA), automobile manufacturers, consumer groups, and other safety organizations, safety belt use among passenger-vehicle occupants in the United States continues to increase. Usage rates are now approaching 70 percent. The use of safety belts by front-seat occupants greatly reduces the risk of serious and fatal injuries.[1]

To assist consumers in determining which passenger vehicles provide higher levels of occupant protection for those occupants who buckle up, NHTSA began the New Car Assessment Program (NCAP) with the 1979 MY PCs. NCAP represents the first crash test program ever initiated to provide relative crashworthiness information to consumers on potential safety performance of passenger vehicles. In this program, data from high-speed 56.3 kilometers per hour (km/h) frontal crashes are provided to consumers for evaluating the relative safety between different vehicle makes and models. NHTSA has now conducted NCAP crash tests of 410 different makes and models of PCs and 130 LTVs (Note: LTVs include all trucks, buses, and multipurpose vehicles with a gross vehicle weight rating of 8,500 lbs. or less).

Data from the tests are distributed in news releases and are regularly published by a variety of consumer and news media. These NCAP data have encouraged manufacturers to significantly improve the safety performance of their products.[2]

This paper provides:

1) updated information on NCAP,
2) data on the relationship of vehicle crash test performance to actual occupant injuries in real-world crashes,
3) a review of side impact test results,
4) a comparison of NCAP to the offset tests that have been conducted by the Insurance Institute for Highway Safety,
5) a review of the recently completed NHTSA 1995 Customer Satisfaction Survey, and
6) a summary of the recommendations from the Transportation Research Board's Report, "Shopping for a Safety: Providing Consumer Safety Information."

NCAP Crash Conditions

Beginning with MY 1992, all new vehicles (PCs and LTVs) sold in the United States are required to meet a 48.3 km/h frontal barrier safety compliance test standard.[3] NCAP tests, however, are conducted as a consumer information program rather than as safety compliance tests. NCAP tests are conducted at 56.3 km/h (this amounts to a change in velocity, delta V, of approximately 64.4 km/h), 8 km/h over the federal safety requirement. Since kinetic energy is proportional to the square of the velocity, there is 36 percent more kinetic energy in a 56.3-km/h crash than one at 48.3 km/h. This 56.3 km/h crash test is equivalent to a head-on collision between two identical vehicles, each moving at 56.3 km/h. This severe crash test magnifies the differences between vehicles and exposes the vehicles to conditions which are similar to real-world crashes in which a high percentage of the fatal and serious injuries occur to restrained occupants.

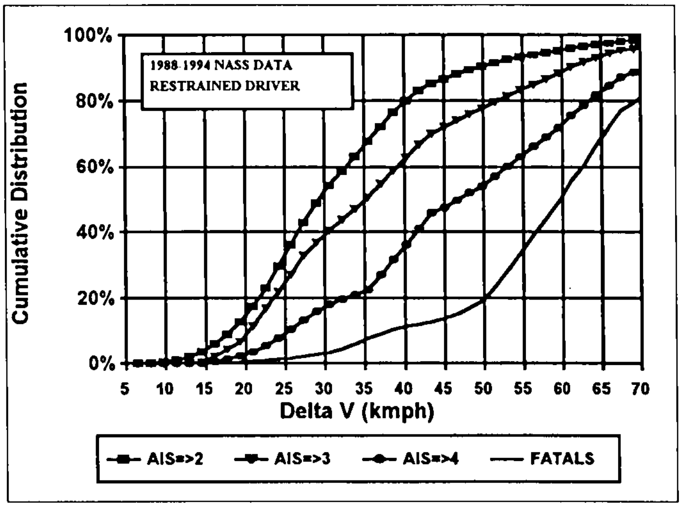


Figure 1. Cumulative Distribution of Injuries and Fatalities for Restrained Drivers in Frontal Crashes.

A subset of non-rollover frontal crash data contained in the National Accident Sampling System's (NASS)[4] files has been used to develop the relationships of delta V to injury and fatalities. These frontal crashes include angled (-30 degrees to +30 degrees) and head-on impacts with both offset and full frontal engagement with PC drivers restrained by available belt systems (no air bag equipped vehicles are included). These data are shown in Figure 1. Curves are given for Abbreviated Injury Scale[5] (AIS)$\geq$2 injuries, AIS$\geq$3 injuries, AIS$\geq$4 injuries, and fatalities. AIS 2 and 3 injuries are moderate to serious but often not life threatening with emergency care. AIS$\geq$4 injuries are severe and life threatening. AIS$\geq$4 injuries to the head may include severe skull fractures and/or brain injury. AIS$\geq$4 injuries to the thorax may include severe damage to the lungs, torn aortas, or massive collapse of the rib structure.

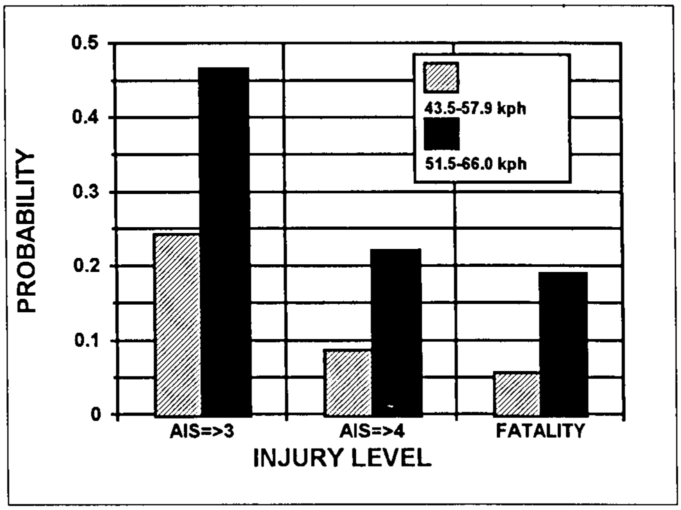


Figure 2. Probabilities of Serious Injury and Fatality for Different Ranges of Delta Vs from 1988-1994 NASS

These NASS data show that approximately 50 percent of the life-threatening injuries and 80 percent of the fatalities of

restrained drivers in frontal collisions occur in crashes with a delta V greater than 48 km/h (which represents the FMVSS No. 208 impact velocity). The NASS data indicate that the fatality and injury rates for restrained, front-seat drivers are several times greater in a crash between 51.5-66.0 km/h delta V than in a crash with a 43.5-57.9 km/h delta V (See Figure 2). These two ranges of delta Vs represent the approximate severity of the NCAP and FMVSS No. 208 crash tests, respectively.

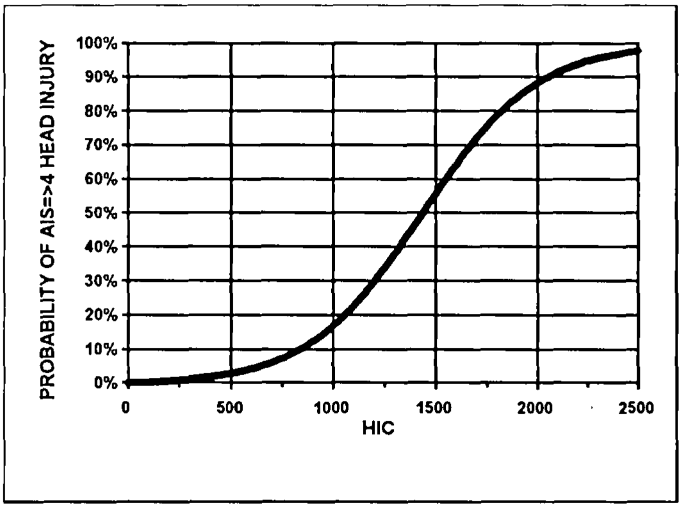


Figure 3. Injury Risk Function Curve Relating HIC to Probability of Injury.

Methods for Assessing Injury in Crash Tests

In the controlled NCAP tests, the levels of potential injury are assessed by measurements taken from two instrumented anthropomorphic test devices (dummies) that simulate 50th percentile adult males. These dummies are located in the driver and front-right passenger seats and are restrained by the vehicle's safety belts and air bags, if available. During the crash, measurements are taken from each dummy's head, chest, and upper legs. The injury potential to the head is measured by a composite of acceleration values known as the Head Injury Criterion or HIC. The injury potential to the chest is measured by a chest deceleration value known as chest G. For the upper legs, the injury potential is measured by compressive forces on each of the femur bones. These numeric values for HIC, chest G, and femur loads can be converted to the probability of injury by using injury risk function curves based on available biomechanical data.

In 1985, Priya Prasad and Harold J. Mertz (Ford Motor Company and General Motors Corp.) presented an injury risk function curve that relates the probability of an AIS≥4 head injury to HIC.[6] In 1990, David Viano and Sudhakar Arepally (General Motors Corp.) expanded the application of this injury risk function curve and also provided the equations to directly calculate the probability of AIS≥4 injury to the head and chest[7] For head injury, the equation;

$$P_{head} = [1+\exp(5.02-0.00351 \times HIC)]^{-1} \quad \ldots (1)$$

relates the probability of an AIS≥4 injury to HIC.
For chest injury, the equation;

$$P_{chest} = [1+\exp(5.55-0.0693 \times Chest\ G)]^{-1} \quad . (2)$$

relates the probability of an AIS≥4 injury to chest Gs.
The injury risk function curves from these equations are shown in Figures 3 and 4.

An injury risk function for femur loads is also presented in Dr. Viano's paper and is given in the following equation;

$$P_{femur} = [1+\exp(7.59-0.00294 \times Femur\ Load)]^{-1} \quad \ldots (3)$$

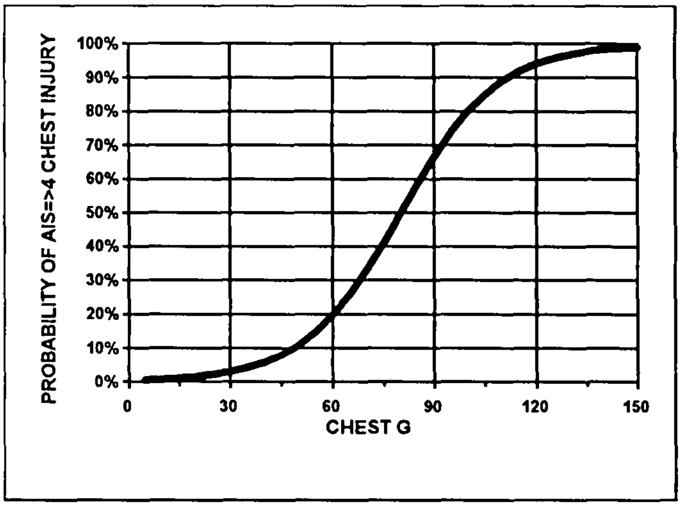


Figure 4. Injury Risk Function Curve Relating Chest G to Probability of Injury.

Femur injury is rarely life-threatening. However, femur and lower limb injuries can be disabling . The injury risk function curve for femur injury is shown in Figure 5.

The injury functions as defined by equations 1, 2, and 3 have been reported previously.[2,6,7,8,9] However, as with any complex biomechanical functions, limitations exist relative to correlations between engineering measures of injury and AIS levels. Research and analysis activities are continuing to

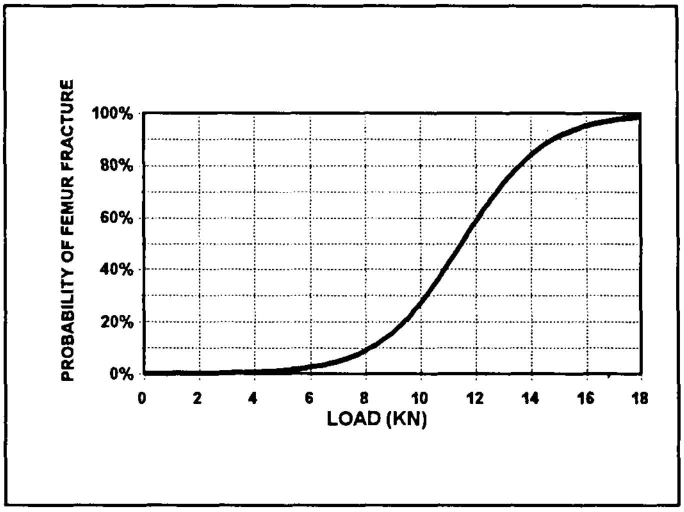


Figure 5. Injury Risk Function Curve Relating Femur Load to Probability of Fracture.

examine existing biomechanical data and to develop additional data which may lead to changes and improvements in methods of

determining injury risk.[10]

NCAP Star Rating System

Beginning with the MY 1994 vehicles, NHTSA adopted the use of the injury risk functions as defined by equations 1 and 2 to develop a simplified NCAP data format.[8] Based on focus group studies, it was decided that a star classification system could better distinguish the safety protection of vehicles and would be more understandable by consumers. Five stars were selected to indicate the lowest probability of an AIS≥4 injury and one star to indicate the highest probability.

NHTSA concluded that a combined effect of injury to the head and chest should be used, since it is likely that an individual who suffers multiple injuries has a higher risk of permanent disability or death.[11] Based on the assumption that head and chest trauma are independent events, a combined probability of an AIS≥4 injury is calculated from equations 1 and 2 as;

$$\text{Combined Probability } (P_{combined}) = P_{head} + P_{chest} - P_{head} \times P_{chest} \quad (4)$$

This equation is applied to the HIC and chest G responses of the driver and passenger dummies in each NCAP test.

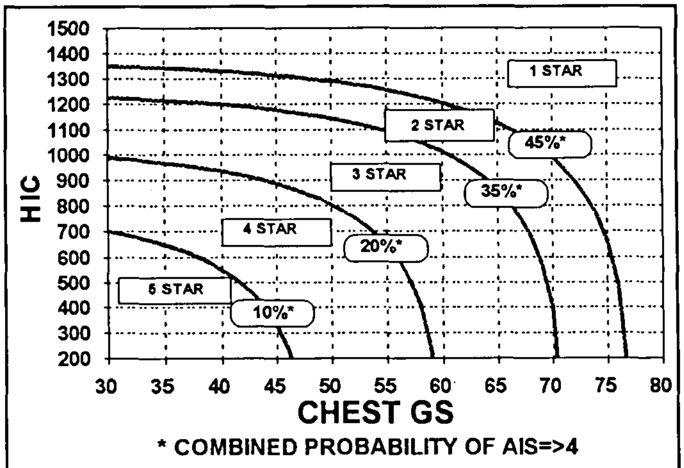


Figure 6. Relationship of Star Rating and Injury Probability to HIC and Chest G.

From these combined probability values, the safety performance is provided for each vehicle that is tested in NCAP with the driver and passenger given;

- five stars for values less than or equal to 10 percent,
- four stars for values greater than 10 percent but less than or equal to 20 percent,
- three stars for values greater than 20 percent but less than or equal to 35 percent,
- two stars for values greater than 35 percent but less than or equal to 45 percent, and
- one star for values greater than 45 percent.

The relationship of the star rating system to injury probability and to the range of HIC and chest G values is shown in Figure 6.

For MY 1996, NCAP results are currently available on 90 vehicles. The star ratings for these makes and models are provided in Appendix A. Data for these new models are released on a regular basis and are available by calling the NHTSA Hotline (800-424-9393). In addition, cooperative efforts with the American Automobile Association and the Federal Trade Commission have led to the development of a brochure "Buying a Safer Car" which contains NCAP results on most of these vehicles. In 1995, 225,000 copies of this brochure with MY 1995 NCAP results were distributed and, in 1996, 400,000 copies have been produced for distribution.

The Effect of NCAP on Crash Test Performance

PCs - Notable improvements in occupant safety as measured by the dummy responses have occurred during the history of the program. Trends as measured by the HIC and Chest Gs are given for the driver and passenger in Figure 7. Average values for each MY and weighted cumulative averages are given. The cumulated averages are weighted by vehicle registrations.[12] Therefore, these values represent the average performance of the fleet of PCs that have been tested in NCAP that are on the road for a given year. After the first year of NCAP testing, this fleet included approximately two million of the PCs on the road. At the conclusion of the MY 1995 NCAP testing, this fleet included over 58 million of the registered PCs. Additional examination of these trends for the driver, based on the probability of AIS≥4 injuries, are shown in Figure 9. The average values for the head injury probability (as defined by equation 1), the chest injury probability (as defined by equation 2), and the joint probability (as defined by equation 4) are given. Significant downward trends are shown. These data indicate that about a one-third reduction in the joint probability of an AIS≥4 injury has occurred in the NCAP PC fleet since MY 1980 as measured by the controlled crash test results.

The average combined probability of an AIS≥4 for the driver in the PC fleets from 1988 through 1993 is 25%. This compares very closely to the 1988 through 1993 NASS data as shown in Figure 2 which indicate about a 22% probability of an AIS≥4 injury for crashes occurring between 51.6 and 66.0 km/h delta Vs.

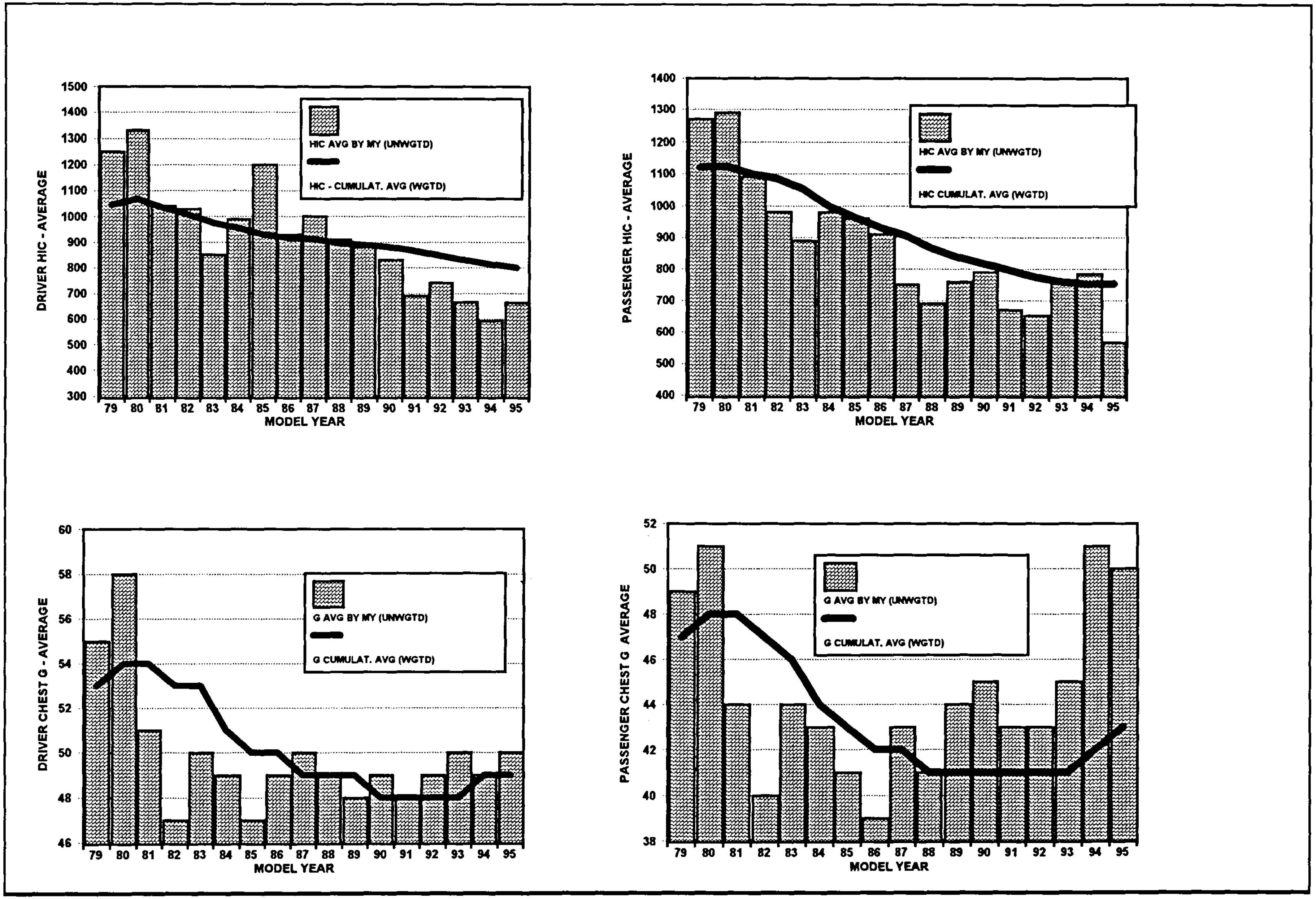


Figure 7. NCAP dummy response trends for PCs

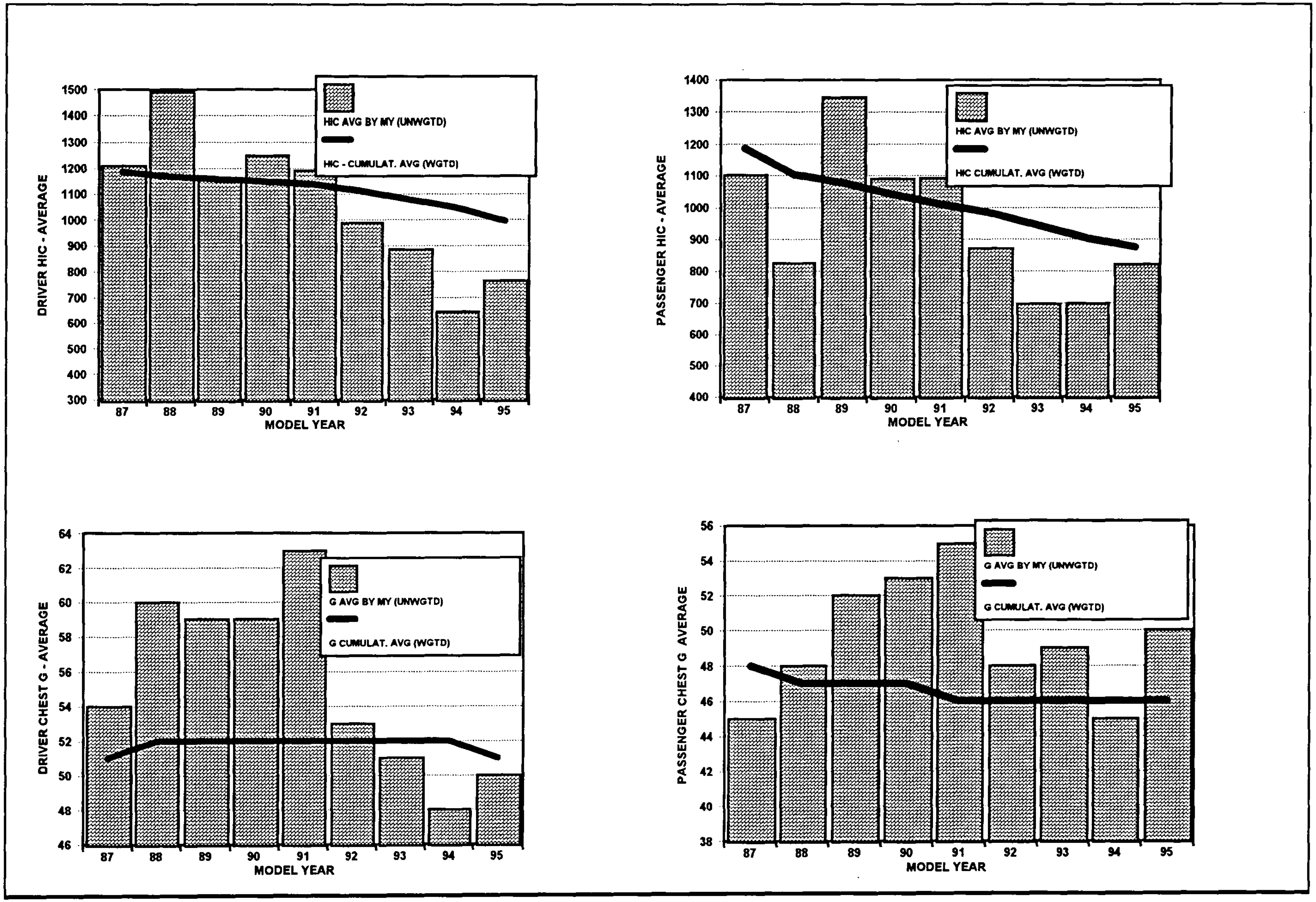


Figure 8. NCAP dummy response trends for LTVs

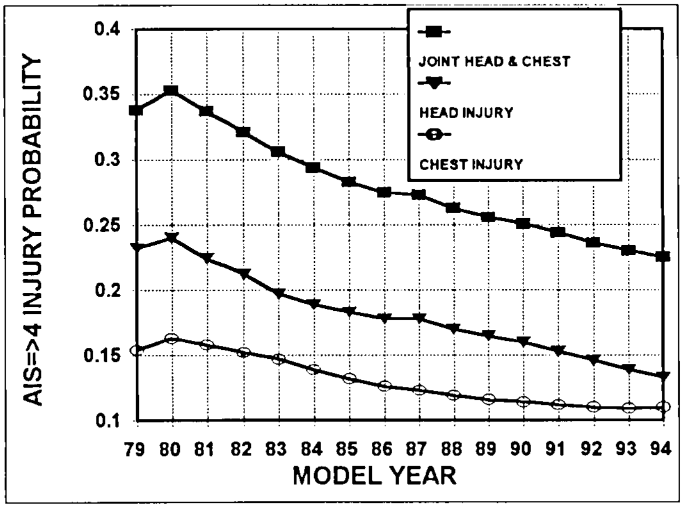


Figure 9. Trends of Improvement in PC Driver Safety as Measured in NCAP.

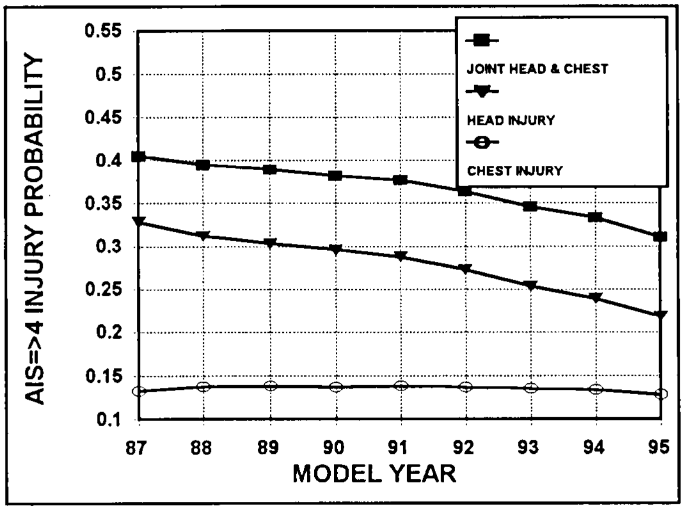


Figure 10. Trends of Improvement in LTV Driver Safety as Measured in NCAP.

<u>LTVs</u> - NHTSA began testing LTVs in MY 1983. Initially, only a few of these types of vehicles were tested. However, as LTVs grew in popularity with consumers, more of the makes and models have been tested. Trends for LTVs as measured by the HIC and chest Gs are given for the driver and passenger in Figure 8. As for PCs, average values for each MY and the weighted cumulative averages are given. Again, these weighted values represent the average performance of the fleet of LTVs that have been tested in NCAP that are on the road for a given year. For MY 1987, this fleet included approximately five million of the LTVs on the road. At the conclusion of the MY 1995 NCAP testing, this fleet included over 20 million of the registered LTVs. The examination of these trends for the driver, based on the probability of AIS≥4 injuries, are shown in Figure 10. In comparing these LTV data to the PCs, it is noted that the LTV injury probabilities as measured in the NCAP are higher than those measured in the PCs. In fact, for the LTV fleet in MY 1987, the joint probability of an AIS≥4 injury for the driver exceeded 40 percent as compared to a probability of 28 percent for the PC driver in that MY. In MY 1995, the LTV probability has dropped to about 31 percent but is still higher than the 23 percent PC value. A more rapid improvement in LTV performance as measured in NCAP has occurred for LTVs beginning with MY 1992. This coincides with the extension of FMVSS No. 208 requirements to the restrained front seat occupants in LTVs. These data indicate that about a one-fourth reduction in the joint probability of an AIS≥4 injury has occurred in the NCAP LTV fleet since MY 1987 as measured by the controlled crash test results.

For PCs, details of improvements to specific vehicle makes and models are given in reference 2. For both PCs and LTVs, the historical trends of each manufacturer relative to performance in NCAP tests through MY 1993 are provided in reference 8.

<u>Lower Extremity Injuries</u> - In the U. S., FMVSS No. 208 requires that all PCs must be equipped with air bags at both the driver and front seat passenger positions in MY 1998 and all LTVs in MY 1999. As seen in Appendix A, manufacturers are already providing these air bags in most PCs and LTVs. This has led to the situation that a higher level of protection is provided for the head and torso than for the lower extremities. That is, due to the protection provided by air bags, occupants in severe frontal collisions who previously may have suffered serious or fatal head or chest injuries are now surviving with only minor upper body injuries, but are experiencing long term disabling lower extremity injuries. This has led NHTSA to assign a higher priority to the study and potential mitigation of these lower extremity injuries. Crash data analysis to evaluate the magnitude of the problem, biomechanical research to assess and develop injury criteria, and vehicle crash testing to determine baseline conditions are being carried out by the agency, manufacturers, and the safety community. To supplement the research data, fully instrumented lower legs are now being used in all NCAP and FMVSS No. 208 tests.

Femur loads have always been measured in NCAP testing. However, it is rare that the femur load exceeds the FMVSS No. 208 requirement of 10,000 newtons (2250 lbs.). A quick review of the NCAP data shows that only 26 times out of over 2,000 measurements have the femur loads exceeded the FMVSS No. 208 level. The average value for the driver femur load in NCAP is about 4,300 newtons (N); for the passenger it is about 3,200 N.

For reference, available upper and lower tibia data that have been collected in NCAP tests during the last few years are provided in Table 1. Of the 37 occupant positions for which these measurements are recorded, 27 tibia moments or loads exceeded the injury assessment reference values as contained in reference 13 (i.e. tibia moment of 225 Nm and tibia compression of 35.9 kN). The Hybrid III lower leg design as specified in FMVSS No. 208 is used in all these tests. These results, along with data from offset tests,may indicate the need for improved protection for lower legs, not only from intruding structure but also from high acceleration levels.

Table 1. MaximumTibia Moments and Forces from NCAP Tests															
MODEL YEAR	VEHICLE	POSITION	LEFT TIBIA					RIGHT TIBIA							
			UPPER		LOWER			UPPER		LOWER					
			MX (Nm)	MY (Nm)	SHEAR (N)	MY (Nm)	AXIAL (N)	MX (Nm)	MY (Nm)	SHEAR (N)	MY (Nm)	AXIAL (N)			
94	NISSAN ALTIMA	DR	67	148	1686	252	3760	124	217	2257	194	9738			
96	PONTIAC GRAND AM	DR	62	163	1578	81	5994	66	170	622	21	7110			
95 .	FORD ESCORT	DR	63	199	1482	141	6014	71	296	2772	287	9901			
95	SATURN SL	DR	39	89	711	85	3198	100	125	2488	541	4805			
95	SUBARU LEGACY	DR	45	77	1126	234	2195	38	185	1513	288	4268			
95	MAZDA MILLENIA	DR	30	70	1004	243	1979	95	218	2072	286	4346			
95	PLYMOUTH NEON	DR	118	298	2274	294	9259	49	150	1999		4733			
95	CHEV MONTE CARLO	DR	17	61	650	53	5042	72	165	1141	37	7192			
95	OLDS AURORA	DR	41	113	962	156	3732	39	179	1514	256	4833			
95	HYUNDAI SONATA	DR	19	64	1727	257	1353	108	245	1975	313	343			
95	HONDA ODYSSEY	DR	64	198	7605	521	7734	87	162	2358	579	4828			
95	NISSAN MAXIMA	DR	64	77	1380	255	2553	143	256	2542	206	12582			
96	TOYOTA CAMRY	DR	49	53	1580	222	1783	62	149	1593	284	4196			
96	NISSAN ALTIMA	DR	143	224	2850	339	6839	88	287	3772	576	9191			
96	AUDI A4	DR	50	76	686	115	859	87	222	1842	264	7924			
96	NISSAN SENTRA	DR	40	114	1923	367	3937	60	219	2584	429	6957			
96	TOYOTA AVALON	DR	31	65	1500	265	2154	65	107	1084	206	4149			
96	DODGE NEON	DR	93	324	2568	201	11135	77	279	2436	352	5805			
96	HYUNDA ACCENT	DR	47	100	3687	591	5620	133	270	2476	144	11892			
96	PONTIAC GRAND AM	PS	93	226	650	165	8238	131	216	1651	130	5462			
96	TOYOTA AVALON	PS	25	126	976	212	4113	43	103	947	296	3085			
96	HYUNDA ACCENT	PS	51	268		55	15810	51	121	2914	561	4489			
96	NISSAN ALTIMA	PS	41	214	1767		4667	70	136	2445	447	3942			
96	NISSAN SENTRA	PS	41	152	2190	440	4294	62	124	1350	201	3829			
94	JEEP WRANGLER	DR	61	69	364	20	1633	52	68	521	74	1113			
95	CHEV S-10	DR	47	115	1200	25	309	111	135	1240	68	5841			
96	TOYOTA TACOMA	DR	79	114	1132	142	2345	62	152	1586	214	4177			
96	CHEV TAHOE	DR	212	206	1002	82	4719	184	139	2043	269	6722			
96	DODGE CARAVAN	DR	110	163	2468		4330	45	166	1655	387	2110			
95	FORD WINDSTAR	DR	28	90	671	30	1574	36	80	763	72	3283			
96	L. ROVER DISCOVERY	DR	210	242	703	35	1024	122	119	988	137	3103			
96	ISUZU RODEO	DR	93	95	1723	247	2107	59		4022		7446			
94	TOYOTA PREVIA	DR	27	110	712	52	1471	40	99	1025	81	1141			
94	CHEV SPORT VAN	DR	71	203	1650	72	5841	88	242	2036	61	9141			
96	CHEV TAHOE	PS	104	50	1185	141	3964	55	112	995	42	2606			
96	TOYOTA TACOMA	PS	60	121	918	45	3580	59	118	983	59				
96	ISUZU RODEO	PS	72	147	1053	94	1925	75	123	898	138	3303			

elationship of NCAP Data to Real-World Occupant Safety

NCAP and NHTSA's major occupant protection crash ındard (FMVSS No. 208) are based on the premise that ıhicles which provide good occupant protection and, therefore, wer probabilities of injury in barrier crash tests will provide ıproved occupant protection in the real world. NHTSA has ıcluded in a recent statistical study of data in Fatal Accident ɛporting System (FARS) that this premise of improved safety ith lower dummy responses is valid in the spectrum of real-ɔrld frontal crashes in which fatal injuries occur.[9] That is, HTSA has found a strong correlation between the NCAP crash test data and the fatality risks of restrained drivers in severe frontal crashes.

Car-to-Car Frontal Head-on Collisions - An extensive statistical study of FARS has been completed and published.[9] This study focuses on head-on collisions between two PCs (Insufficient NCAP and FARS data are available to include LTVs in this study). The goal of the analysis is to determine whether cars with high injury scores in NCAP tests had more fatalities than would be expected, given the weights of the cars, and the age and sex of the occupants involved in the crashes.

In Table 2, a summary of the results of four statistical studies, Cases A, B, C, and D, are given, each of which uses two NCAP parameters, HIC and chest Gs and their injury

probabilities as determined from equations 1 and 2, to distinguish "lower risk" from "higher risk" performance. (See Table 2 for Case definitions and explanations of "lower" and higher risk" performance.) In the detailed technical report, HIC, chest Gs, and femur loads from NCAP test results are used in a variety of approaches. While the analyses using femur loads are not shown here, NHTSA wishes to point out that the detailed technical report does show similarly strong correlations between accident data and various combinations of femur loads with other injury measures. In Table 2, the following data for Cases A, B, C, and D are provided;

- average vehicle weight of car 1 and car 2,
- average drivers' age for car 1 and car 2,
- average drivers' HIC from NCAP,
- average drivers' chest G from NCAP,
- the unadjusted fatality risk reductions for car 1 drivers as compared to car 2 drivers,
- the fatality risk reduction for car 1 drivers as compared to car 2 drivers adjusted by car weight and drivers' ages and sexes, and
- the level of statistical significance (one-sided p for the adjusted fatality risk reduction). A value of p equal to or less than .05 indicates a significant reduction. A value of p less than .01 indicates a high level of statistical significance.

It is interesting to note, in all four cases, the combined injury probabilities as calculated from the average HIC and chest Gs would place the "lower risk" cars in a four star category. In comparison, the "higher risk" performing cars, on the average, would receive one or two star ratings.

In summary, data in Table 2 provide an overview of the car-to-car crash events from FARS. For each of the four cases, there is little difference between the average curb weights for car 1 and car 2, the average drivers' ages are very similar, and, as expected, average injury probabilities, HICs, and chest Gs are very different depending on the definition of "lower risk" and "higher risk" cars. With the small differences in average curb weights and average drivers' ages, the comparison of the reductions in unadjusted and adjusted fatality risks indicates that the findings are consistent (i.e., For Case A through Case D, there is a continuing trend of decreasing fatality risks for the drivers of car 1 for both unadjusted and adjusted data.)

The reductions of fatality risk in Table 2 indicate that by making even a rough cut of NCAP vehicle performance, as in Case A, a positive correlation or trend is found between NCAP results and real-world, head-on collisions. These data provide statistically significant evidence that, when dividing the vehicles into traditional "lower risk" and "higher risk" performers as defined by the injury probabilities (HIC and chest G results) from NCAP tests, strong correlations are shown between NCAP results and real-world crashes. Restrained drivers are at substantially reduced risks of fatality in the "lower risk" car. Depending on the definitions of "lower risk" and "higher risk" cars, the reductions in fatality risks may be as large as 30 percent.

Car-to-Fixed Object Frontal Collisions - Concurrent with the car-to-car analysis, a more generalized study of FARS was conducted to determine if the trend of lower-fatality risks for "lower risk" cars occurred in frontal crashes other than the car-to-car head-on collisions.[8] Remarkable similarity in the results for head-on and fixed-object collisions are found. These comparisons are shown in Figure 11.

In this analysis, the number of restrained drivers killed in single vehicle frontal, fixed-object collisions was obtained from FARS for each PC with applicable NCAP crash-test results. The fatality rates per million vehicle years for the restrained drivers in the "lower risk" and "higher risk" cars as defined in Table 2 in Case B, Case C, and Case D were determined. Since the analysis is now referring to single-car crashes into fixed objects, there is no equivalent Case A. These results are a supplement to the statistical findings from the car-to-car, head-on crash analysis and should be compared only to the unadjusted data of the two-car crash analyses. In Case B, the unadjusted fatality reduction for the lower risk NCAP performers was 20 percent in the head-on collisions and 19 percent in the fixed-object impacts. In Case C, the reductions were 30 and 22 percent. In Case D, where the definitions of a "lower risk" and a "higher risk" car straddled the FMVSS 208 criteria (HIC of 1000 and chest G of 60), the largest relative fatality reduction is found; a reduction of 33 percent in the head-on collisions and 36 percent in the fixed-object crashes.

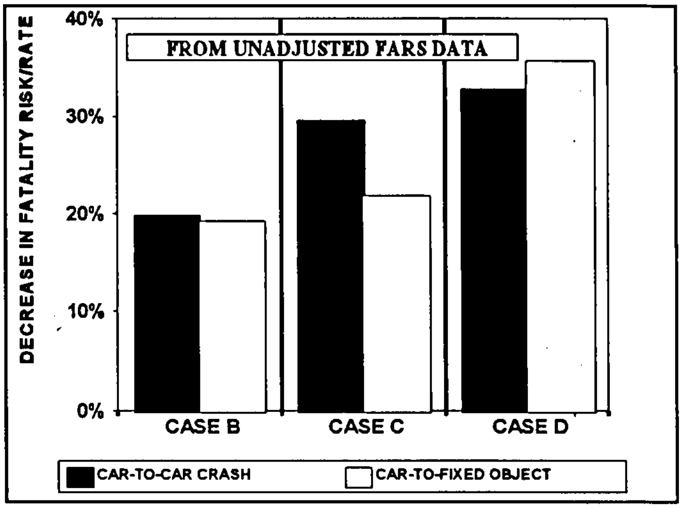


Figure 11. Comparison of the Decrease in Fatality Risks/Rates for "Lower risk" Cars in NCAP in Car-to-Car and Car-to-Fixed Object Collisions.

Table 2. Summary of Real World NCAP Effects Based on FARS Analysis of Car-to-Car Head-on Collisions

Parameter	Car No.	Case A*	Case B*	Case C*	Case D*
Average Vehicle Weight (kg)	1	1282	1324	1334	1335
	2	1271	1256	1256	1252
Average Drivers' Age	1	42.0	43.7	42.2	46.4
	2	42.5	41.1	41.0	43.5
Average Drivers' HICs from NCAP	1	721	747	742	712
	2	1117	1339	1609	1465
Average Drivers' Chest Gs from NCAP	1	45	46	45	43
	2	53	56	55	59
Reduction in Fatality Risk-Car 1 versus Car 2-Unadjusted FARS Data	1	12.7%	19.8%	29.6%	32.8%
Reduction in Fatality Risk-Car 1 versus Car 2-FARS Data Adjusted by Car Weight and Drivers' Ages and Sexes	1	8.7%	13.5%	19.2%	26.7%

* Case Definitions for Table 1.
Case A - Car 1 has a lower life-threatening injury risk to the driver than car 2 in NCAP test. (370 events)

Case B - Car 1 has a head injury probability less than 18.1% (HIC value less than 1001) and a chest injury probability less than 19.9% (chest G less than 61) in the NCAP test. Car 2 has a head injury probability greater than 18.1% (HIC value greater than 1,000) and/or a chest injury probability greater than 19.9% (chest G greater than 60) in the NCAP test. (170 events)

Case C - Car 1 same as Case B. Car 2 has a head injury probability greater than 30.8% (HIC value greater than 1,200) and/or a chest injury probability greater than 33.2% (chest G greater than 70 in the NCAP test. (104 events)

Case D - Car 1 has a head injury probability less than 13.5% (HIC value less than 901) and a chest injury probability less than 15.0% (chest G less than 56) in the NCAP test. Car 2 has a head injury probability greater than 34.7% (HIC value greater than 1,250) and/or a chest injury probability greater than 26.0% (chest G greater than 65) in the NCAP test. (81 events)

In each Case, car 1 is defined as having the "lower risk" performance in NCAP and car 2 is defined as having the "higher risk."

Comparison of NCAP Data Trends to a Generalized Fatality Risk Index from FARS

In addition to the specific statistical analyses for the car-to-car and car-to-fixed object collisions with belted drivers, a generalized analysis of crashworthiness trends over time was also achieved by computing fatality risk indices for cars of different MY groups.[9] For this analysis, the FARS data base consists of all head-on collisions in which the vehicle of interest is a 1979-91 car that matches up with an NCAP test, whose driver wore belts, but the "other" vehicle in the crash can be any 1976-91 car with a belted driver, not necessarily matching with an NCAP test (1189 FARS accident records). The actual and expected fatalities are tallied in the "subject" and "other" vehicles; the fatality risk index is

$$100[(actual_{subject}/actual_{other}) / (expected_{subject}/expected_{other})].$$

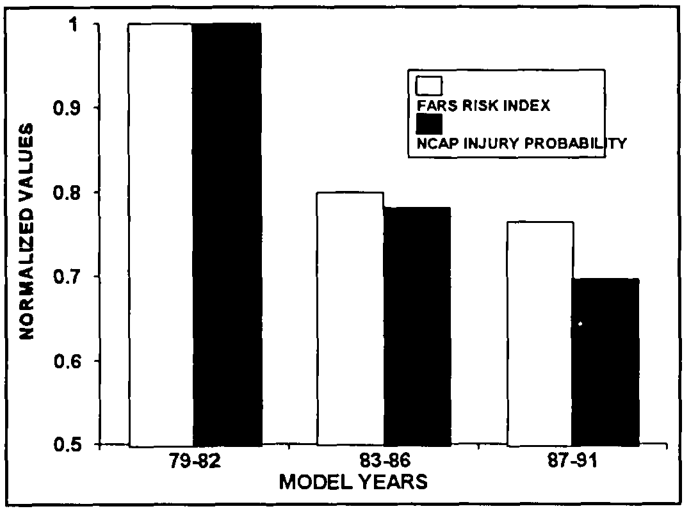


Figure 12. Comparison of Fatality Risk Index from FARS to Injury Probability from NCAP.

With this number of records, the 1979-91 cars can be partitioned into different MY groups and compared to NCAP test results. The initial MYs of NCAP were 1979-82. By 1983-86, manufacturers had leadtime to address major deficiencies in the initial NCAP test results. With the FMVSS No. 208 requirements, the 1987-91 cars were often equipped with air bags or other automatic protection.

In the 280 FARS crashes with a 1979-82 subject vehicle, there were 181 driver fatalities in the subject vehicles, but 166.2 were expected. There were 141 fatalities in the other vehicles (any 1976-91 car with a belted driver), but 154 were expected. The fatality risk index for 1979-82 cars is

$$Index_{79\text{-}82} = 100\,(181/166.2) / (141/154) = 119.0$$

The FARS fatality risk index for the 452 1983-86 cars is just 95.0, and the risk index for the 457 1987-91 cars drops to 90.9 (a risk index of 100 corresponds to the "average" 1976-91 car on the road with a belted driver). The net fatality reduction from 1979-82 to 1991 is a statistically significant 24 percent, with 20 percent of this reduction occurring from 1979-82 to 1983-86.

By using the combined probability function (equation 4), average AIS≥4 injury probabilities can be determined from the NCAP test results for groupings of the same MYs. Trends in the actual fatality risk and the average values of NCAP injury probabilities are almost identical. The risk index decreased from 119 in MYs 1979-82 to 95 in 1983-86, to 91 in 1987-91, a large reduction followed by a much smaller reduction. In parallel, the NCAP combined injury probability improved from an average of 32% in 1979-82 to 25% in 1983-86, with an additional, smaller reduction to 22% in 1987-91. Normalized comparisons of these trends are shown in Figure 12. These data explicitly show that improved safety performance as measured in NCAP coincides with reductions in fatality risks in the real world.

NCAP Expansion into Side Impact Crash Testing

The upgrade of FMVSS No. 214, Side Impact Protection, to require a dynamic test provides the basis for the expansion of NCAP into side-impact protection. The initiation of such a program has the potential for improving occupant protection significantly above that required in FMVSS No. 214 if the vehicle manufacturers which have been responsive to the frontal NCAP test results are equally responsive to such a program in side-impact testing. As in the frontal NCAP, a side-impact NCAP will provide NHTSA with an engineering data base which can be used to inform consumers of relative vehicle crashworthiness performance. That data base can also serve as a basis for further research and additional vehicle safety evaluation.

NHTSA has completed several steps to establish the requirements and procedures for the new program. These include:

1. The determination of a reasonable crash severity level. FMVSS No. 214 requires a 30/15 crash condition (the striking vehicle traveling at 30 mph (48 km/h) and the struck vehicle at 15 mph (24 km/h) with a striking vehicle mass of 3,065 pounds).

2. The examination and analysis of results from the higher severity crash tests to assure that testing, instrumentation, and test device performance are consistent.

NHTSA held a public hearing to discuss these steps in January 1991. Responses from that public hearing were considered in the project activities.

In FY 1992 and 1993, NHTSA received Congressional approval and budgeting to investigate the development of a side-impact NCAP.

The scope of this developmental program included;

1. Testing 11 PCs to the conditions proposed by FMVSS No. 214.

2. Testing 11 PCs to higher severity side-impact crash conditions (increased closing velocity).

3. Evaluating the data from these 22 tests to determine the

feasibility for initiating a side-impact protection NCAP.

The completion of these activities has provided the agency with the information necessary for expanding NCAP into side-impact crash protection.

Program Results - The following activities were completed:

1. Eleven MY 1992 and 1993 PCs were selected for testing in the developmental program. The manufacturers provided input in this selection process which indicated that many of these vehicles were expected to perform reasonably well in the side-impact test in the 30/15 crash configuration.
2. Based on examination of NASS data, a 34/17 impact

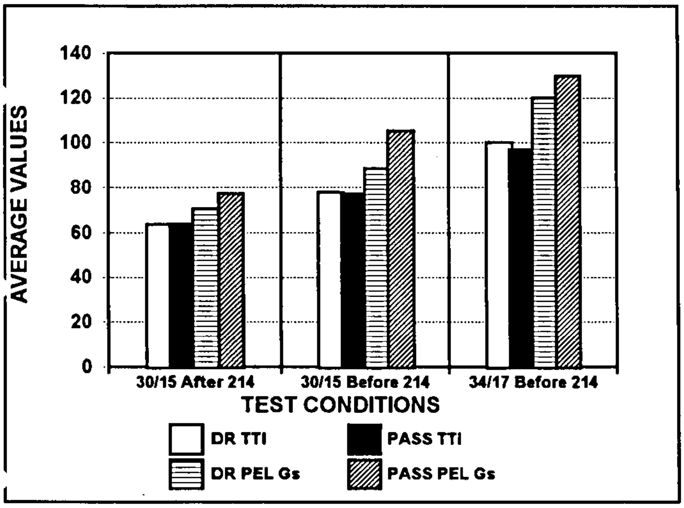


Figure 13. Comparison of PC Performance - Before and After FMVSS No. 214

condition (the striking vehicle traveling at 34 mph (54 km/h) and the struck vehicle at 17 mph (27 km/h)) was chosen as the initial higher speed crash condition.

3. Tests at the 30/15 compliance crash configuration and at the 34/17 selected higher speed crash configuration have been completed on all vehicles.

Table 3 contains the available dummy response data from these tests.

The following are observations relative to the performance of the side impact dummy (SID) in the tests and the test results;

a. SID performance-No problems were encountered with the dummies. Calibration of the dummies was routine and critical components of the dummies were not damaged in any of the tests.

b. Test results-Data from the two test conditions show consistent trends of higher responses in the more severe crashes. From these data, the 34/17 crash condition appears to be a reasonable level for a consumer program in side impact protection.

Since the completion of this program, the agency has conducted FMVSS No. 214 compliance tests on MY 1994 and 1995 PCs. Comparison of the results of the tests from the demonstration program to the compliance test results gives an indication of the level of improvements in occupant protection that has occurred after enactment of FMVSS No. 214. In Figure 13, the average values for the thoracic trauma index (TTI) and pelvis Gs from the 11 vehicles in the demonstration test are compared to the 1994 and 1995 compliance test average values. (Note: the passenger is located in the nearside, rear seating position.) In Figure 14, the thoracic injury probabilities are compared for these vehicles. Reductions of approximately 20 percent are seen for TTI and pelvis Gs when comparing pre-214

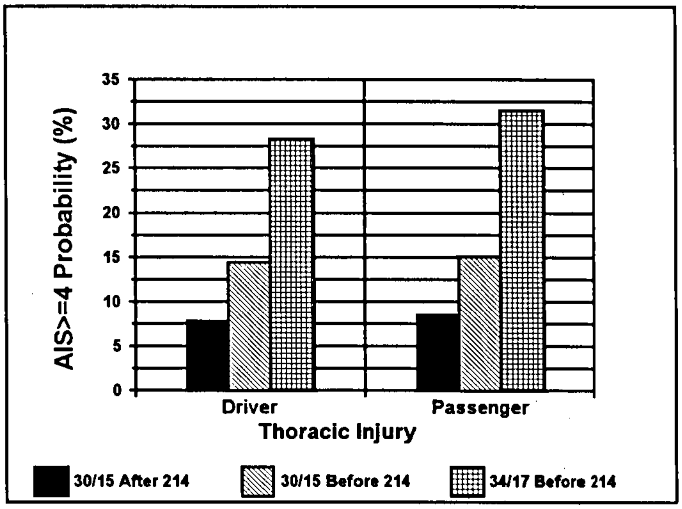


Figure 14. Comparison of Average Injury Probabilities in Side impact Tests - Before and After FMVSS No. 214

averages to post-214 averages in the compliance test conditions. This translates into about a 50 percent reduction in the probability of AIS≥4 thoracic injury.[14]

As noted in these figures, the proposed more severe NCAP test condition results in much higher average dummy responses and injury probabilities than the 30/15 test results,with average injury probabilities near 30 percent in the more severe condition. It is expected that a side impact NCAP will provide to consumers some clear differences in side impact protection for different vehicles and will create market incentives for additional enhancements in safety, including a more rapid introduction of inflatable side impact protection devices. In the fiscal year 1997 budget submitted to Congress, the Department of Transportation requested funds for expanding NCAP into side impact protection.

Table 3. Test Results from the Developmental Side Impact New Car Assessment Program

Vehicle	Test Condition	Injury Measures			
		TTI		Pelvic G	
		Driver	Passenger	Driver	Passenger
Dodge Intrepid	30/15	78	108	74	120
Dodge Intrepid	34/17	93	134	117	147
Volvo 940	30/15	60	47	59	88
Volvo 940	34/17	93	57	66	116
Ford Crown Victoria	30/15	41	No Data	56	No data
Ford Crown Victoria	34/17	70	50	92	92
Nissan Sentra	30/15	91	87	101	173
Nissan Sentra	34/17	100	137	128	218
Honda Accord	30/15	85	64	89	108
Honda Accord	34/17	106	76	103	151
Toyota Corolla	30/15	93	86	114	150
Toyota Corolla	34/17	101	100	134	147
Acura Legend	30/15	71	57	56	98
Acura Legend	34/17	94	48	87	83
Ford Probe	30/15	81	62	116	67
Ford Probe	34/17	124	129	176	83
Oldsmobile Achieva	30/15	107	104	99	113
Oldsmobile Achieva	34/17	121	123	134	167
Honda Civic	30/15	85	94	138	89
Honda Civic	34/17	114	126	169	144
Chevrolet Lumina	30/15	64	86	71	48
Chevrolet Lumina	34/17	85	96	113	77

Offset Crash Testing for Vehicle Rating and Consumer Information

In 1994, the Road and Traffic Authority (RTA) of New South Wales, along with sponsors throughout Australia, advanced the state-of-the art in NCAP testing with the addition of frontal offset crash testing to complement their full frontal testing program.[15] Details of these tests are provided in other reports at this conference. In 1995 and 1996, the Insurance Institute for Highway Safety (IIHS) completed similar frontal

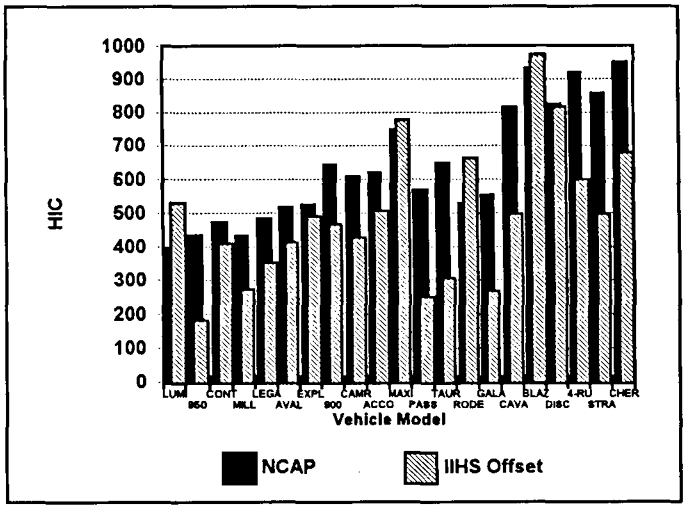


Figure 15. Comparison of NCAP and IIHS Offset Test Results - HIC Values

offset tests on 22 popular passenger vehicles in the U. S. fleet. IIHS provided the agency with tabulated data from 21 of these offset crash tests. These tests were conducted at a speed of 65 km/h into a fixed deformable barrier with a 40 percent overlap with the front of the vehicle.

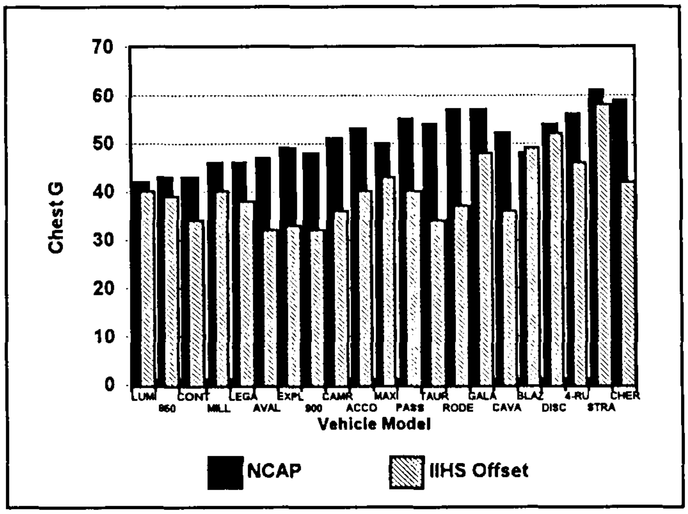


Figure 16. Comparison of NCAP and IIHS Offset Test Results - Chest Gs

Essentially identical vehicles have been crashed in NCAP. The tested vehicles included the; Chevrolet Lumina, Volvo 850, Ford Contour, Mazda Millenia, Subaru Legacy, Toyota Avalon, Ford Explorer, Saab 900, Toyota Camry, Honda Accord, Nissan Maxima, Volkswagen Passat, Ford Taurus, Isuzu Rodeo, Mitsubishi Galant, Chevrolet Cavalier, Chevrolet Blazer, Land Rover Discovery, Toyota 4-Runner, Dodge Stratus (Chrysler Cirrus for IIHS), and Jeep Grand Cherokee. In Figure 15, the driver HIC values from NCAP and the offset tests are compared. The NCAP values exceed the offset test values in 17 of the 21 tests, with no values exceeding 1000. In Figure 16, the chest Gs are compared. The NCAP values exceed the offset test values for all vehicles except the Blazer. Only one chest G value exceeded 60. In Figure 17, the maximum driver femur loads are compared. In 15 of the 21 vehicles, NCAP femur loads are higher than those in the offset tests. None of these data indicate a high probability of femur fracture.

In Figure 18, the maximum tibia moments are compared. These data were recorded on only 8 of the NCAP vehicles. The tibia moments are generally higher for the offset tests. However, in the available NCAP tests, all eight moments exceeded the injury assessment value of 225 Nm. It should be noted that in some of the NCAP tests the data were clipped at approximately 280 Nm and that in both the IIHS and the NCAP

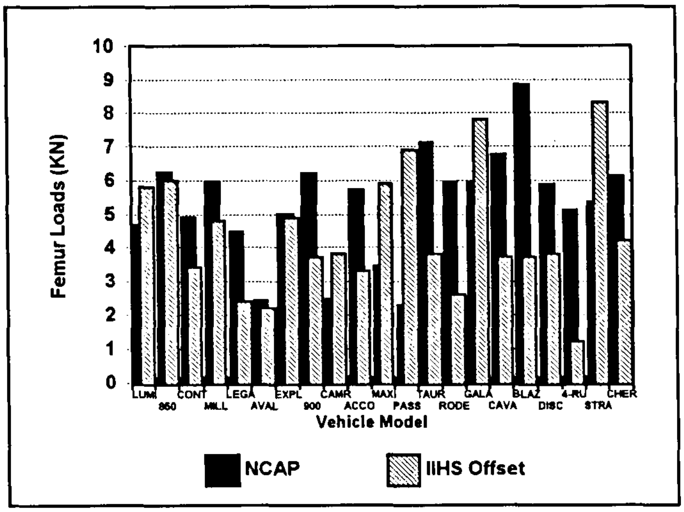


Figure 17. Comparison of NCAP and IIHS Offset Test Results - Maximum Femur Loads

tests the tibia data may be contaminated due to metal to metal contact that occurs in the ankle of the Hybrid III dummy.

In Figure 19, the average values are compared. (Note: Average femur loads have been multiplied by a factor of 100 to provide a reasonable scale for this graph.) All NCAP averages are larger than those from the IIHS offset tests. (Note: The NCAP tibia averages are based only on the eight tests in which data were available.)

In Table 4, NCAP "star ratings" for the combined test results as well as for each test condition are presented. The combined ratings are based on the same weighting factor as used

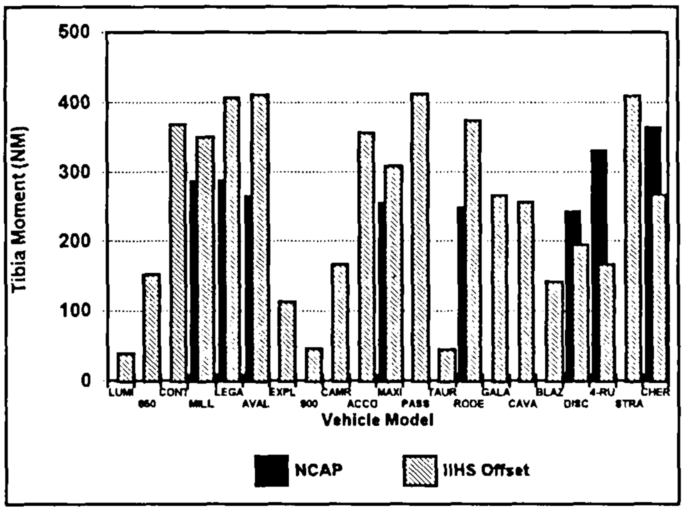


Figure 18. Comparison of NCAP and IIHS Offset Test Results - Maximum Tibia Moments

by RTA (60% full frontal and 40% offset). The star ratings for the femur fracture are based on the injury function curve as shown in Figure 5 and on the same levels of injury probabilities as used for the head and chest.

For protection from severe head and chest injury, in the combined NCAP and offset ratings, the driver receives five stars in six of the vehicles, four stars in 10 of the vehicles, and three stars in five vehicles. In the NCAP ratings, three drivers receive five stars, 12 receive four stars, and six receive three stars. In the IIHS offset tests, thirteen drivers receive five stars, five receive four stars, and three receive three stars. For protection from femur fractures, all drivers (and passengers for NCAP) receive five stars except for one four star rating in NCAP and one in the offset tests.

In Figures 20 and 21, the head and chest injury and femur fracture probabilities which provide the basis for the star ratings in Table 4 are compared for the two test conditions.

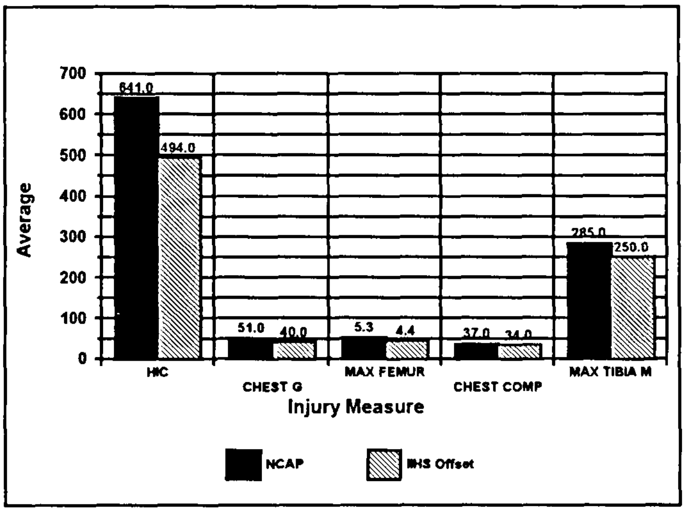


Figure 19. Comparison of NCAP and IIHS Offset Test Results - Average Values

(Note: In Figures 15 through 21 and in Table 4, the vehicles have been sorted to reflect the lowest to highest NCAP injury probability as shown in Figure 20.)

These data provide the first comparison of an extensive group of U. S. vehicles which have been tested in both full frontal and frontal offset crashes. The results support the position that the full frontal test is a more stringent evaluation of the restraint system performance (i.e., head and chest responses are higher than in the offset tests). However, due to more intrusion, the probability of lower leg injury will be better determined in the offset crashes. By testing in both crash modes,

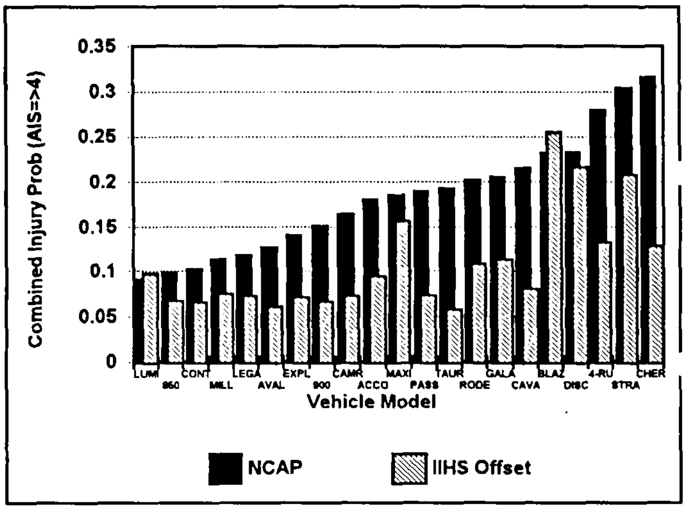


Figure 20. Comparison of NCAP and IIHS Offset Test Results - Combined Head and Chest Injury Probability

as RTA is doing, a more complete assessment of vehicle safety is possible. In the fiscal year 1997 budget submitted to Congress, the Department of Transportation requested funds for expanding NCAP into frontal offset crash testing.

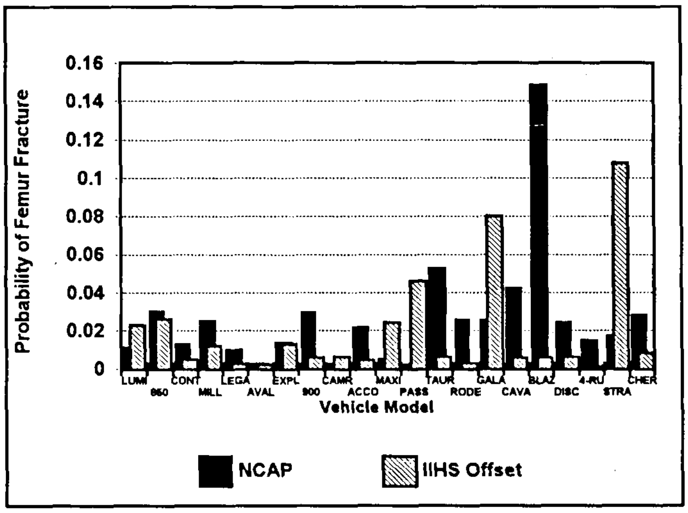


Figure 21. Comparison of NCAP and IIHS Offset Test Results - Femur Fracture Probability

Table 4. Star Ratings for NCAP and IIHS Testing

TEST RESULTS BASED ON CRASH TESTS		PROTECTION FROM SEVERE HEAD & CHEST INJURY			PROTECTION FROM FEMUR FRACTURE		
		COMBINED FRONT & OFFSET RATING	RATING FRONTAL CRASH	RATING OFFSET CRASH	COMBINED FRONT & OFFSET RATING	RATING FRONTAL CRASH	RATING OFFSET CRASH
CHEVROLET LUMINA.	DRIVER	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
VOLVO 850	DRIVER	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
FORD CONTOUR	DRIVER	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
MAZDA MILLENIA	DRIVER	★★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★★	ND	ND	★★★★★	ND
SUBARU LEGACY	DRIVER	★★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
TOYOTA AVALON	DRIVER	★★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
FORD EXPLORER	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
SAAB 900	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
TOYOTA CAMRY	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	★★★★★	ND
HONDA ACCORD	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	★★★★★	ND
NISSAN MAXIMA	DRIVER	★★★★	★★★★	★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	★★★★★	ND
VOLKSWAGEN PASSAT	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
FORD TAURUS	DRIVER	★★★★	★★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
ISUZU RODEO	DRIVER	★★★★	★★★★	★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	★★★★★	ND
MITSUBISHI GALANT	DRIVER	★★★★	★★★★	★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	★★★★★	ND
CHEVROLET CAVALIER	DRIVER	★★★★	★★★	★★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	★★★★★	ND
CHEVROLET BLAZER	DRIVER	★★★	★★★	★★★	★★★★★	★★★★	★★★★★
	PASSENGER	ND	★	ND	ND	★★★★★	ND
LAND ROVER DISCOVERY	DRIVER	★★★	★★★	★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	ND	ND
TOYOTA 4-RUNNER	DRIVER	★★★	★★★	★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★	ND	ND	ND	ND
DODGE STRATUS	DRIVER	★★★	★★★	★★★	★★★★★	★★★★★	★★★★
	PASSENGER	ND	ND	ND	ND	ND	ND
JEEP CHEROKEE	DRIVER	★★★	★★★	★★★★	★★★★★	★★★★★	★★★★★
	PASSENGER	ND	★★★★	ND	ND	ND	ND

Will the Trend of Improvements in Safety Continue? - Expectations of Air Bag Equipped PCs as Measured in NCAP

NCAP has been successful as shown by the above data and by the reduced fatality rates on the U. S. roadways. The expansion of new car assessments throughout the world, an increasingly knowledgeable consumer, additional safety standards, such as the recent increased requirements of FMVSS No. 201, should lead to more improvements is occupant safety.

Data from NCAP also support the probability of continuing safety improvements. Since 1987, 115 PCs with driver air bags have been tested in NCAP. The average probability of an AIS$\geq$4 injury to the driver in these vehicles is 16.8% (unweighted) with an average HIC of 617 and an average chest G of 49. For PCs tested before 1987, this average injury probability is 37.5% (unweighted). These results when compared to the statistical analyses above indicate that modern vehicles, equipped with air bags, will provide much improved protection for belt restrained occupants in severe frontal crashes. On the average, the drivers of these PCs will receive four star ratings in NCAP. The trend of improving occupant protection in severe frontal crashes is, therefore, expected to continue.

The range of safety performance for air bag equipped PCs is substantial, with a minimum injury probability of about 5% and a maximum of near 40%. Twenty-five models of the 115 PCs with driver air bag registered a driver injury probability of less than 11%. These twenty-five models were produced by six different automobile manufacturers. Therefore, it has been clearly illustrated that significant reductions in occupant loadings and potential injuries are still feasible with present state-of-the-art technology. With the federal requirement that all passenger vehicles be equipped with both driver and passenger air bags in the next few years, manufacturers should be (and hopefully are) striving to optimize safety designs to reach these lower injury probabilities as well as to address any adverse effects of air bag deployments.[16]

Recent Studies on Consumer Information

1995 Consumer Satisfaction Survey - In February 1996, NHTSA completed a "1995 Customer Satisfaction Survey" to obtain information about the kind and quality of services the public wants from the Federal government related to traffic safety and their level of satisfaction with existing services.[17] Data collection involved interviews with approximately 4,000 respondents randomly selected to represent the non-institutionalized population, age 16 and older, of the U. S. Because the sample is statistically representative, the results comprise national estimates of the public's attitudes, opinions, and behavior.

The following are some of the questions and responses that are directly related to the public perceptions, knowledge, and interest in vehicle crashworthiness.

Question: Compared to ten years ago, do you think motor vehicles are safer now, more dangerous now, or are they about as safe now as then? More than 59 percent believe that vehicles are safer today, because of air bags, better manufacturing, seat belts, and braking systems. 21 percent responded that vehicle safety is about the same today as 10 years ago.

Question: If you were buying a new motor vehicle, how important would you rank the safety of the vehicle in your purchase decision? Very important, somewhat important, or not too important. Seventy-five percent ranked it very important and 20 percent ranked safety as somewhat important.

Question: What kinds of safety information, if any, would you want to know before buying a new car? Whether the vehicle has air bags ranked first at 54 percent, with antilock brakes at 27 percent followed by seatbelts, crashworthiness, and safety record at about 20 percent each. The weight of the vehicle received only a 2 percent response. Seventy-six percent felt that such information would not be difficult to obtain and that primary sources would be auto dealers and consumer reports, with only 2 percent recognizing the Federal government as a primary source.

Question: Aside from size, how much difference is there between motor vehicles in their ability to protect passengers in a crash? Thirty-eight percent believe there is a lot and 37 percent believes there is some. Twenty-three percent consider consumer reports as the best source of these data, with 11 percent relying on auto dealers and 10 percent on auto manufacturers. Six percent considered Federal agencies as the best source.

Question: Have you seen or heard of the ratings of motor vehicles on their ability to protect passengers in a crash? Fifty-eight answered yes to this question. Fifty-one percent of these indicated that they had heard about crash ratings on TV, 30 percent magazines, 21 percent consumer reports, 15 percent news papers, with 1 percent government.

Question: Who conducts the crash tests on which those ratings are based? Forty-five percent didn't know or did not answer, 21 percent thought it was the manufacturers, 16 percent believed it was the government, and 9 percent consumer groups.

Question: How do you feel about the crash testing of motor vehicles by the government to determine how well they protect passengers in crash? Fifty-one percent strongly favor this and 31 percent somewhat favor. Fourteen percent somewhat or strongly oppose.

Question: Do you think that the government should set the standards for how well motor vehicles protect passengers in a crash or should those standards be left to the manufacturers? Sixty-seven percent want the government to set the standards with 27 percent selecting the manufacturers.

Question: Do you think that there is anything that automobile manufacturers should do to reduce the number of serious injuries in motor vehicle accidents? Fifty-one percent answered yes, 37 percent no. Of those who answered yes, 53 percent believe manufacturers should improve quality of design/construction for safety, 21 percent believe that manufacturers should include more/better safety features.

From these responses and others in the survey, two points are clear 1) consumers are very interested in auto safety and information about auto safety and 2) the government does not appear to be very efficient in informing the public about

available information.

Shopping for Safety - Providing Consumer Automotive Safety Information - In March 1996, the Transportation Research Board, National Research Council completed Special Report 248, "Shopping for Safety - Providing Consumer Automotive Safety Information" by the National Academy of Sciences Committee for study of consumer automotive safety information.[18] The following is the first paragraph of the preface of this report which explains the purpose of the study.

Mindful of growing consumer interest in motor vehicle safety features and the federal role in providing consumer automotive safety information, Congress requested an independent study of consumer information needs by the National Academy of Sciences. The Conference Committee Report authorizing the study recognized that the National Highway Traffic Safety Administration (NHTSA) already provides information to consumers on the crashworthiness of vehicles in frontal collisions. However, the information is limited in scope and does not provide a comprehensive assessment of a vehicle's likely overall safety performance. Hence the request for a study, sponsored by NHTSA, that would broadly examine motor vehicle consumer safety information needs and the most cost-effective methods of communicating this information to the public.

A section of the executive summary which provides the findings and recommendations of the committee is given below.

Findings On the basis of a review of knowledge about vehicle safety characteristics, crash likelihood, and injury causation as well as the information currently available to consumers, the committee reached the following conclusions:

o Considerable information about vehicle safety characteristics and features is available to consumers, but it is not always timely, accessible, or in a form that readily supports comparison shopping.

o Several steps could be taken in the short term to address these limitations (see recommendations).

o In the long term, summary measures of vehicle safety would help consumers incorporate safety in new vehicle purchase decisions.

o At present, development of a defensible summary measure of *vehicle crashworthiness is* feasible only if current knowledge is supplemented with expert judgment. The uncertainties of present knowledge preclude development of a measure constructed strictly on scientific grounds, but, in the committee's judgment, the relation between vehicle characteristics and occupant protection is sufficiently strong that a useful measure of crashworthiness can be developed if expert judgment is used and the uncertainties are acknowledged. The most reliable estimates can probably be achieved if experts begin with information about the relation between crashworthiness and vehicle weight and size, and then use analysis combined with their expert professional judgment to incorporate results from crash tests, highway crash statistics, and a variety of other factors, such as the presence or absence of specific design features. Over time the estimates can be improved by development of more field-relevant crash tests and test criteria, more reliable test dummies, and collection of more comparable and consistent field accident data.

o The state of knowledge is not well enough advanced, even with expert judgment, to develop a corresponding summary measure for *crash avoidance*. A major problem is the limited role that vehicle characteristics (as opposed to driving behavior) currently play in predicting crash likelihood. However, with many vehicle technology improvements (e.g., collision avoidance systems) in development, crash avoidance features may play a larger role in the future, and continuing attention to this area is merited.

Recommendations On the basis of these findings, the committee recommends the following measures to improve the provision of automotive safety information to consumers.

Improvements to Existing Information In the short term, the following measures would improve the automotive safety information available to consumers:

o Consumers could be provided with more explicit information on

--The importance of vehicle size and weight in crash outcomes,

--The benefits of proper use of vehicle safety features such as occupant restraint systems and antilock brakes,

--The frequency of crash types for which crash test results are available, and

--The uncertainties associated with crash test results.

o The reliability of crash test results should be established and the sources of variance identified.

o The presentation and dissemination of existing vehicle safety information could be improved by increasing awareness that the information is available and by making it more accessible.

Development of Summary Measures In the longer term, new summary measures could be developed to provide consumers with comparative safety information on overall vehicle performance that is more helpful than current data in making purchase decisions. The following recommendations indicate how development of summary measures could be accomplished:

o From the consumers' perspective, one overall measure that combines the relative importance of vehicle crashworthiness and crash avoidance features would be ideal. However, for the foreseeable future, summary measures of crashworthiness and crash avoidance should be presented separately because of differences in the current level of knowledge and in the roles of the vehicle and the driver in the two areas. An effort to develop a

summary measure of crashworthiness should go forward, incorporating defensible information supplemented with the professional judgment of automotive experts, statisticians, and decision analysts and reflecting the range of uncertainty associated with those judgments. For now, a checklist of safety features related to crash avoidance rather than a summary measure is recommended.

o Because consumers differ in the amount of detail they want and can manage, communication of new vehicle safety measures can best be accomplished through a hierarchically organized approach. The most highly summarized information should be provided on a vehicle label that includes a simple graphical display of comparative crashworthiness performance and a checklist of crash avoidance features. Product labels, such as the energy efficiency label for major appliances and the fuel economy label on passenger vehicles, provide model formats that consumers have found useful and easy to understand. Because of the amount of information already provided on vehicle window stickers--price, fuel economy, vehicle features--a separate label is desirable for all vehicle safety-related information. It may be necessary to display the summary safety information in some other prominent location because of limitations on window space for some vehicles and concerns about visibility in driving test vehicles. An accompanying brochure would contain more detailed explanations of the summary measures, the assumptions used in their calculation, and their key components such as vehicle size and weight. A handbook would provide complete comparisons among vehicles. These materials should be developed, tested, and refined with groups of typical users.

o A multichannel approach is recommended for dissemination of vehicle safety information. Consumers need safety information to assist decision making well before they reach the dealer, and product labels are more effective if they are part of an overall communications strategy. A mix of dissemination outlets is suggested, including NHTSA's safety hotline and the Internet, insurance industry and automobile club mailings, and reprints in consumer journals. Development of a segment for driver education courses on purchasing a safe car, and of course public service advertising, should help increase awareness of the label and backup materials.

Before these steps are taken, preliminary research into consumer decision making and safety information requirements should be undertaken by NHTSA. Such research should address

o How consumers conceptualize automotive safety,

o How consumers apply safety information in selecting among vehicle types and specific models, and

o How automotive safety information can best be communicated and disseminated to consumers.

Development of a Process To Stimulate Better Consumer Safety Information and Safer Cars Finally, there are a number of organizational considerations that must be addressed in any effort to develop the measures outlined.

Development of summary measures of vehicle safety for consumers should not be viewed as an end in itself but rather as part of a continuing long-term process to yield both better consumer information and safer cars. The Secretary of the Department of Transportation (DOT) should encourage automobile manufacturers and the insurance industry, among others, to join NHTSA in a voluntary effort to achieve these goals. Congress should initiate the process with a formal request and appropriate funding, charging DOT to ensure the development by 2000 of reliable summary vehicle safety measures and a mechanism for continuing improvements. The secretary would issue a progress report to Congress in 18 months and determine the most appropriate organizational structure to carry the program forward. If for any reason the voluntary process reaches a stalemate, legislative action would be necessary.

Two organizational approaches to oversee the process were identified as most desirable: (a) establishment of a federal advisory committee and (b) creation of a public private Automotive Safety Institute (ASI). The functions of the two organizations would be the same--development of improved vehicle safety information, including summary safety measures, and dissemination strategies. They would also develop a program of long-term applied research leading to advances in crash testing, design procedures, and vehicle technologies to yield better safety measures and safer automobile designs. With a NHTSA-appointed advisory committee, the process could start quickly with a modest annual investment of $1 million to $2 million and NHTSA staff support. The ASI approach, which would involve a partnership between NHTSA, the automobile manufacturers selling in the U.S. market, and the insurance industry, probably offers the best chance of achieving a sustained long-term program. However, a new institute would be more difficult to establish and could cost more. Under either alternative, a fully operational program of research and vehicle testing and design initiatives would require annual resources of $10 million to $20 million or more, most of which could be expected to come from participating industries.

The NHTSA will closely review this report in the next few months and will provide comments to Congress and TRB relative to the report findings and recommendations.

Summary

From MY 1979 through MY 1995, approximately 540 different passenger vehicle makes and models have been tested in NCAP. Since MY 1979, average MY HIC values for PCs decreased from near 1300 to about 600 and the probabilities of life-threatening head and chest injuries for the tested fleet dropped by more than 30 percent. In comparison, since MY 1987, average HICs for LTVs decreased from about 1200 to approximately 800 with the probabilities of life-threatening head and chest injuries for the tested fleet having dropped by about 25 percent.

Data analyses confirmed that NCAP crash conditions and crash severities are similar to many real world crashes and

that PCs that performed well in NCAP also provide higher levels of protection in actual severe crashes. In PCs that perform well as defined by the injury probabilities from the NCAP tests, restrained drivers are as much as 30 percent less likely to receive fatal injuries in severe frontal crashes when compared to restrained drivers of vehicles that perform poorly in NCAP. A fatality risk index, determined from FARS data, decreased by 24 percent for MY 87-91 PCs as compared to MY 79-82 PCs. These data explicitly show that improved safety performance as measured in NCAP coincides with reductions in fatality risks in the real world.

The upgrade of FMVSS No. 214, Side Impact Protection, to require a dynamic test provides the basis for expansion of NCAP into side-impact protection. Testing that establishes potential crash conditions for such a program has been completed. Comparison of the results of the tests from the demonstration program to the compliance test results gives an indication of the level of improvements in occupant protection that has occurred after enactment of FMVSS No. 214. Reductions of approximately 20 percent are seen for TTI and pelvis Gs when comparing pre-214 averages to post-214 averages in the compliance test conditions. This translates into about a 50 percent reduction in the probability of AIS≥4 thoracic injury. The proposed 34/17 NCAP test condition results in much higher average dummy responses and injury probabilities than the 30/15 test results, with average injury probabilities near 30 percent in the more severe condition. It is expected that a side impact NCAP will provide to consumers some clear differences in side impact protection for different vehicles and will create market incentives for additional enhancements in safety, including a more rapid introduction of inflatable side impact protection devices.

In 1995 and 1996, IIHS conducted frontal offset crash tests on PCs and LTVs. These tests were conducted at a speed of 65 km/h into a fixed deformable barrier with a 40 percent overlap with the front of the vehicle. Essentially identical vehicles have been crashed in NCAP. These data provide the first comparison of an extensive group of U. S. vehicles which have been tested in both full frontal and frontal offset crashes. The results support the position that the full frontal test is a more stringent evaluation of the restraint system performance. However, due to more intrusion, the probability of lower leg injury will be better determined in the offset crashes. By testing in both crash modes, as the Road and Traffic Authority of New South Wales is doing, a more complete assessment of vehicle safety is possible.

Two studies on consumer information have recently been completed. The "NHTSA 1995 Customer Satisfaction Survey" provides national estimates of the public's attitudes, opinions, and behavior relative to traffic safety. The Transportation Research Board's study "Shopping for Safety: Providing Consumer Safety Information," broadly examined motor vehicle consumer needs and methods of communicating this information to the public. NHTSA will closely review these studies relative to NCAP and consumer information activities.

References:

1. CDC. *Increased Safety-Belt Use - U. S.*, 1991. MMWR 1992;41:421-3.

2. Hackney, J. R., *The Effects of FMVSS No. 208 and NCAP on Safety as Determined from Crash Test Results*, Proceedings of the Thirteenth International Conference on Experimental Safety Vehicles, November 1991, Paris, France.

3. *Federal Register* 49 (17 July 1984): 28962. Also, *Code of Federal Regulations*, Title 49, Part 571.208, General Printing Office, Washington, 1992.

4. *National Accident Sampling System 1986*, Report No. DOT HS 807 296, National Highway Traffic Safety Administration, Washington, 1988.

5. *The Abbreviated Injury Scale (AIS) - 1990 Revision*, American Association for Automotive Medicine, Des Plaines, IL, 1990.3 .

6. Prasad, Priya, and Mertz, Harold J., *The Position of the United States Delegation to the ISO Working Group 6 on the Use of HIC in the Automobile Environment*, Society of Automotive Engineers Paper No. 851246, 1985.

7. Viano, D. C., and Arepally, S., *Assessing the Safety Performance of Occupant Restraint Systems,* In Proceeding of the 34th Stapp Car Crash Conference, pp. 301-327, SAE Technical Paper #902328, Society of Automotive Engineers, Warrendale, PA 1990.

8. *New Car Assessment Program: Response to the NCAP FY 1992 Congressional Requirements*, Report to the Congress, National Highway Traffic Safety Administration, Washington, 1993.

9. Kahane, Charles J., *Correlation of NCAP Performance with Fatality Risk in Actual Head-On Collisions*, Report No. DOT HS 808 061, National Highway Traffic Safety Administration, Washington, 1994.

10. Hertz, Ellen, *A Note on the Head Injury Criterion (HIC) as a Predictor of the Risk of Skull Fracture*, 37th Annual Proceedings of the Association for the Advancement of Automobile Medicine, November 4-6, 1993, San Antonio, Texas.

11. Eppinger, Rolf H., and Partyka, Susan C., *Estimating Fatality Reductions Associated with Safety Improvements*, Proceedings of the Eighth International Conference on Experimental Safety Vehicles, October 1980, Wolfsburg, Germany.

12. *National Vehicle Population Profile*, R. L. Polk, Detroit, Annual Publication.

13. Mertz, H. J., *Anthropomorphic Test Devices - Hybrid*

III - The First Human-like Crash Test Dummy, SAE Pt-44, Society of Automotive Engineers, 1994, Warrendale, PA.

14. Morgan, R. M. , Marcus, J. H., and Eppinger, R. H., *Side-Impact - The Biofidelity of NHTSA's Proposed ATD and Efficacy of TTI*, In Proceeding of the 30th Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA 1986.

15. Griffiths, Michael, Etal., *Australia's New Car Assessment Program*, Proceedings of the Fourteenth International Technical Conference on Enhanced Safety of Vehicles, May 1994, Munich, Germany.

16. *Federal Register* Vol. 60 No. 217, 9 November 1995, Pgs. 56554-56559, 49 CFR Part 571 (Docket No. 74-14; Notice 97).

17. National Highway Traffic Safety Administration, *1995 Customer Satisfaction Survey*, Conducted by Schulman, Ponca, and Bucuvalas, Inc., February 1996.

18. Special Report 248, *Shopping for Safety, Providing Consumer Automotive Safety Information*, Committee for Study of Consumer Automotive Safety Information, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C. 1996.

Appendix A

Activities of the New Car Assessment Program in the United States

New Car Assessment Crash Test Results for Model Year 1996 Passenger Vehicles

New Car Assessment Program

How To Use This Chart

Vehicles should be compared against other vehicles in the same weight class. If a light vehicle collides head-on with a heavier vehicle at 35 mph, the occupants in the lighter vehicle could experience a greater chance of injury than the results of this test indicate.

Vehicles are classified by the estimated chance of life-threatening head and chest injury for the driver or passenger, and receive a one to five star rating, with five stars ★ ★ ★ ★ ★ indicating the best head and chest protection.

Thigh injury, although rarely life threatening, is also measured in the tests. Such injury can be disabling and, if a high likelihood of thigh injury occurs in the tests, it is indicated in the charts by an asterisk (*).

1996 MINI PASSENGER CARS
(1500 - 1999 lbs. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
GEO METRO 4-DR. SEDAN	1986 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	

APRIL 1996

1996 LIGHT PASSENGER CARS
(2000 - 2499 lbs. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
FORD ASPIRE 4-DR. HB	2086 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
HONDA CIVIC 4-DR SEDAN	2337 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
HYUNDAI ACCENT 4-DR. SEDAN	2261 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★	✓	
MAZDA MX-5 2-DR CONVERTIBLE	2312 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
MAZDA PROTEGE 4-DR. SEDAN	2429 lbs.	DRIVER	★★★	✓	
		PASSENGER	NO DATA	✓	
MITSUBISHI MIRAGE 2-DR SEDAN	2196 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
NISSAN SENTRA 4-DR. SEDAN	2454 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
SATURN SL 4-DR. SEDAN	2332 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
TOYOTA TERCEL 4-DR. SEDAN	2176 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★	✓	

1996 COMPACT PASSENGER CARS
(2500 - 2999 lbs. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
ACURA INTEGRA 4-DR. SEDAN	2709 lbs	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
CHEVROLET CAVALIER 4-DR. SEDAN	2731 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
CHEVROLET CORSICA 4-DR. SEDAN	2741 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★		✓
DODGE AVENGER 2-DR.	2952 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
DODGE NEON 4-DR. SEDAN	2547 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
FORD ESCORT 4-DR. SEDAN	2509 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
FORD PROBE 2-DR.	2773 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★	✓	
HONDA ACCORD 4-DR. SEDAN	2901 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
HYUNDAI SONATA 4-DR. SEDAN	2761 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★	✓	
MAZDA 626 DX 4-DR. SEDAN	2762 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
MITSUBISHI ECLIPSE 2-DR.	2853 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	

1996 COMPACT PASSENGER CARS
(2500 - 2999 lbs. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
MITSUBISHI GALANT 4-DR. SEDAN	2832 lbs.	DRIVER	NO DATA	✓	
		PASSENGER	★★★★	✓	
NISSAN 240 SX 2-DR.	2765 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★	✓	
NISSAN ALTIMA 4-DR. SEDAN	2941 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
NISSAN MAXIMA 4-DR. SEDAN	2970 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
PONTIAC GRAND AM 4-DR SEDAN	2987 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
SUBARU IMPREZA 4-DR SEDAN	2769 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
SUBARU LEGACY 4-DR. SEDAN	2654 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
TOYOTA CAMRY 2-DR.	2992 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
TOYOTA COROLLA 4-DR. SEDAN	2553 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
VOLKSWAGEN JETTA III 4-DR. SEDAN	2725 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	

1996 MEDIUM PASSENGER CARS
(3000 - 3499 LBS. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
ACURA TL 4-DR SEDAN	3285 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
AUDI A4 4-DR. SEDAN	3096 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
AUDI A6 4-DR. SEDAN	3373 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
BMW 328i 4-DR. SEDAN	3234 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
BUICK CENTURY 4-DR. SEDAN	3049 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★		✓
CHEVROLET CAMARO 2-DR. HB.	3408 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
CHEVROLET LUMINA 4-DR. SEDAN	3344 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★	✓	
CHEVROLET MONTE CARLO 2-DR.	3284 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
DODGE INTREPID 4-DR. SEDAN	3254 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
DODGE STRATUS 4-DR. SEDAN	3144 lbs.	DRIVER	★★★	✓	
		PASSENGER	NO DATA	✓	
FORD CONTOUR 4-DR. SEDAN	3020 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★	✓	
FORD MUSTANG 2-DR.	3119 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
FORD MUSTANG 2-DR CONVERTIBLE	3317 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	

1996 MEDIUM PASSENGER CARS
(3000 - 3499 LBS. Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
FORD TAURUS 4-DR. SEDAN	3358 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
FORD THUNDERBIRD 2-DR.	3460 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
HONDA ODYSSEY 4-DR. WAGON	3459 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
LEXUS ES 300 4-DR SEDAN	3393 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★	✓	
MAZDA MILLENIA 4-DR. SEDAN	3150 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
MERCEDES-BENZ C220 4-DR. SEDAN	3190lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
PONTIAC GRAND PRIX 2-DR.	3210 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
SAAB 900 4-DR. HB	3064 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
TOYOTA AVALON 4-DR. SEDAN	3290 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★	✓	
TOYOTA CAMRY 4-DR. SEDAN	3128 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
VOLKSWAGEN PASSAT 4-DR. SEDAN	3124 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
VOLVO 850 4-DR. SEDAN	3241lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★	✓	

1996 HEAVY PASSENGER CARS
(3500 lbs. & over Curb Weight)

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
CHEVROLET CAPRICE 4-DR. SEDAN	4177 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★	✓	
CHRYSLER NEW YORKER 4-DR. SEDAN	3589 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
FORD CROWN VICTORIA 4-DR SEDAN	3849 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
INFINITI J30 4-DR. SEDAN	3640 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
LEXUS GS300 4-DR. SEDAN	3765 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
OLDSMOBILE AURORA 4-DR. SEDAN	3993 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
PONTIAC BONNEVILLE 4-DR. SEDAN	3558 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★	✓	

1996 SPORT UTILITY VEHICLES

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
CHEVROLET S-10 BLAZER 4-DR. 4x4	4156 lbs.	DRIVER	★★★	✓	
		PASSENGER	★		✓
CHEVROLET TAHOE 4-DR. 4x4	5276 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★		✓
FORD BRONCO 2-DR. 4x4	4783 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★		✓
FORD EXPLORER 4-DR. 4x4	4242 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★	✓	
GEO TRACKER 2-DR 4X4	2501 lbs.	DRIVER	★★	✓	
		PASSENGER	★★★	✓	
ISUZU RODEO 4-DR. 4X4	4105 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
JEEP CHEROKEE 4-DR.	2983 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★		✓
JEEP WRANGLER YJ 4-DR.	2896 lbs.	DRIVER	★★		✓
		PASSENGER	★★★★		✓
LAND ROVER DISCOVERY 4-DR 4X4	4486 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
TOYOTA 4-RUNNER 4-DR 4X4	4179 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	

1996 LIGHT TRUCKS

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
CHEVROLET S-10 PU 2-DR.	3091 lbs.	DRIVER	★★★	✓	
		PASSENGER	★		✓
DODGE DAKOTA PU 2-DR.	3924 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★		✓
DODGE RAM 1500 PU 2-DR.	4469 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	NO DATA		✓
FORD F150 PU 2-DR.	4444 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★		✓
FORD RANGER PU 2-DR.	3245 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★		✓
MITSUBISHI PU 2-DR.	2731 lbs.	DRIVER	★★★		✓
		PASSENGER	★★★		✓
TOYOTA T100 PU 2-DR.	3382 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★★★		✓
TOYOTA TACOMA PU 2-DR.	2560 lbs.	DRIVER	★★	✓	
		PASSENGER	★★★		✓

1996 VANS

TEST RESULTS BASED ON 35 MPH FRONTAL CRASH			RATING	BELTS & AIR BAG	BELTS
CHEVROLET ASTRO VAN	4415 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★	✓	
DODGE GRAND CARAVAN VAN	4000 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★	✓	
DODGE RAM B250 VAN*	4056 lbs.	DRIVER	★★★	✓	
		PASSENGER	★★★★		✓
FORD AEROSTAR VAN	3670 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★		✓
FORD ECONOLINE VAN	5166 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★		✓
FORD WINDSTAR VAN	3801 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★★★	✓	
MERCURY VILLAGER VAN	3862 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	
PONTIAC TRANS SPORT VAN	3708 lbs.	DRIVER	★★★★★	✓	
		PASSENGER	★★★		✓
TOYOTA PREVIA VAN	3644 lbs.	DRIVER	★★★★	✓	
		PASSENGER	★★★	✓	

*HIGH LIKELIHOOD OF DRIVER LEFT THIGH INJURY

NEW VEHICLE CRASHWORTHINESS EVALUATIONS BY THE INSURANCE INSTITUTE FOR HIGHWAY SAFETY

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ABSTRACT

In 1995, the Insurance Institute for Highway Safety began a program of crash testing to evaluate important aspects of crashworthiness of new passenger vehicles. The major component of the evaluation is a 40 mi/h frontal offset crash test of each vehicle into a deformable barrier. The crashworthiness of each vehicle in the frontal offset test is based on criteria assessing structural performance, injury measures obtained from a 50th percentile male Hybrid III dummy, and restraint performance and dummy kinematics. These tests are designed to complement the U.S. government's 35 mi/h full-width barrier testing in the New Car Assessment Program (NCAP). Good performance in both tests should be the goal for frontal crashworthiness designs. The results obtained from 16 midsize four-door passenger cars and 6 midsize utility vehicles indicate large differences in performance among the vehicles in each group. Several of the cars with good performance in offset tests also performed well in NCAP tests demonstrating that the two tests need not produce design conflicts.

Since the late 1970s, the New Car Assessment Program (NCAP) of the National Highway Traffic Safety Administration (NHTSA) has compared frontal crashworthiness among new passenger vehicles based on a full-width frontal crash test (NHTSA, 1970). This program, which involves 35 mi/h crash tests into a full-width rigid barrier, has been successful in providing consumers with comparative vehicle information. The public response to the information provided by this program has contributed to automobile manufacturer's improvements in passenger vehicle restraint system performance (Hackney, 1993). The very success of this program means that the remaining differences in performance among most new cars in the U.S. market in full-width tests are likely to be small. This does not mean that important crashworthiness differences among vehicles no longer exist; however, additional crash test configurations are more likely than full-width barrier tests to highlight these differences among new cars. One such test is the frontal offset crash.

Full-width and offset tests complement each other. Because full-width barrier crashes distribute crash forces across the full-width of a vehicle, the integrity of the occupant compartment should be maintained in all but very high speed tests. The principal value of full-width tests is that, because they produce high occupant compartment decelerations, they are especially demanding of restraint systems. In offset tests, only part of a vehicle's front-end hits the barrier and a smaller area of the structure must manage the crash forces. The front-end on the struck side crushes more than in a full-width test, and occupant compartment deformation is more likely. Thus, the two tests complement each other — full-width tests are especially demanding of restraints but not so much so of structure, while the reverse is true of offsets.

In the Institute's 40 mi/h (64 km/h) offset test, 40 percent of the total width of each vehicle strikes a barrier on the driver's side. The barrier's deformable face is made of crushable aluminum honeycomb, which absorbs some of the vehicle's kinetic energy and makes the forces in the test similar to those involved in a frontal offset crash between two vehicles of the same weight, each traveling a little less than 40 mi/h (64 km/h). The test results, like full-width crash test results, can be compared only among vehicles of similar weight. A separate paper presented at this conference shows how this particular test speed relates to real-world crash severities (O'Neill et al., 1996). The results of that study suggest that a 40 percent offset test into a deformable barrier at 64 km/h represents a real-world crash severity below which about 75 percent of all Maximum Abbreviated Injury Score 3 or greater injuries and slightly less than half of all fatal injuries to

passenger car occupants occur in frontal offset crashes in the United States. Another consideration in the choice of 40 mi/h (64 km/h) as the test speed is that the European Experimental Vehicle Committee Work Group 11 was considering a similar test at 60 km/h (37 mi/hr) as a recommended possible minimum standard for new cars in the European Union (Lowne, 1995).

CRASHWORTHINESS EVALUATION CRITERIA

Each vehicle in the Institute's Crashworthiness Evaluations receives a good, acceptable, marginal, or poor overall crashworthiness rating, based primarily on its performance in the offset test. However, other available information is considered as well, such as the NCAP crash test results and on-the-road crash experience. In addition, the Institute separately assesses whether head restraints have adequate geometry to protect occupants from neck injury in rear-end collisions, and it conducts 5 mi/h (8 km/h) crash tests to assess the ability of the design to prevent damage in low speed crashes.

To receive a good overall rating in the Institute's evaluations, a vehicle must do well in the offset test and cannot have unacceptable results in NCAP crash tests or on-the-road crash experience. Head restraint and bumper evaluations currently contribute less to the overall ratings, but they do influence the rankings of vehicles with otherwise similar performance.

Evaluations of Offset Test Performance

Three aspects of performance are considered in the evaluation of each vehicle in the offset test: structural performance (how well the front-end crush zone manages crash energy to limit damage to the occupant compartment), injury measures from an instrumented dummy in the driver seat, and restraint system performance and dummy kinematics (IIHS, 1995a).

Structure. Because the offset test is a demanding test of structural design, the performance of the vehicle in maintaining occupant compartment integrity is a major factor in its evaluation. This assessment begins with various measurements indicating the amount and pattern of deformation of the occupant compartment in the offset test. Measurements of the precrash and postcrash positions of several points on the instrument panel and in the footwell area are taken (IIHS, 1995b; 1996). In addition, movement of the steering column and closure of the driver door opening is measured. Table 1 indicates the points where measurements are made and the range of intrusion at these points in the Institute's tests of 16 midsize, four-door cars and six midsize utility vehicles.

As shown in Table 1, occupant compartment deformation varies considerably among vehicles within a class. Deformation is so great in some cases that intruding structure threatens not only lower extremities but also the head, neck, and torso. These vehicles receive poor structural ratings. There are no vehicles tested thus far with no occupant compartment deformation, but there are several cars and utility vehicles in which intrusion is minimal. In these vehicles, the injury threat to the driver appears largely based on occupant compartment deceleration with little complication from intruding structure. These vehicles are given good structural ratings.

Between these extremes are vehicles that show relatively large intrusion in some areas but not others. When a large amount of intrusion is limited to one or two areas with less intrusion in most areas, the vehicle generally receives an acceptable rating; if there are more areas with large intrusion than small, then the vehicle would typically receive a marginal rating. In addition, some vehicles whose measurements place them among other vehicles with acceptable structure receive only marginal ratings because of the pattern of deformation. For example, otherwise acceptable levels of intrusion would be downrated to marginal if the footwell deformation resulted in entrapment of the foot or leg of the dummy. Thus, though the structural evaluation begins with empirical measurement, there is an element of expert judgment, as well.

Distinctions among levels of intrusion are further assessed by the use of statistical cluster analyses. A requirement of the structural ratings is that vehicles receiving the same rating should cluster together in this analysis, unless there are sound reasons based on other test information that lead to assignment to a different rating.

Injury Measures. Injury measures obtained from an instrumented 50th percentile male Hybrid III dummy in the driver seat are used to determine the likelihood that an occupant would have sustained significant injury to various body regions. Twenty-eight different measures are recorded by the driver dummy in each of the Institute's frontal offset crash tests:

- the acceleration of the center of gravity of the head in three directions
- the axial force, the anterior-posterior force, and the anterior-posterior bending moment acting at the connection between the dummy's head and neck
- acceleration of the dummy's spine in three directions
- compression of the dummy's chest
- axial force on each femur
- tibia-femur displacement
- two transverse bending moments at either end of the tibia (lower leg)
- axial force in each tibia
- acceleration of each foot in two directions

Table 1
Minimum and Maximum Intrusion Measurements: 1995-96 Crashworthiness Evaluations

	Longitudinal				Lateral				Vertical				Resultant			
	Passenger Cars		Utility Vehicles		Passenger Cars		Utility Vehicles		Passenger Cars		Utility Vehicles		Passenger Cars		Utility Vehicles	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Selected Locations:																
L. lower instrument panel	4	21	3	21	0	6	0	5	0	11	2	12	5	21	7	24
R. lower insturment panel	3	20	4	19	0	6	0	5	0	8	2	11	4	20	5	21
Steering column	1	17	−1	16	0	9	0	5	−1	13	5	16	3	19	8	18
Brake pedal	7	36	7	29	0	10	1	7	0	10	1	6	8	36	8	29
Left toepan	9	39	15	35	0	10	−2	7	−1	13	2	9	10	39	16	35
Center toepan	13	39	16	31	1	11	2	9	0	14	−1	8	14	39	20	33
Right toepan	12	35	14	30	0	15	0	9	1	9	0	7	14	35	16	32
Footrest	7	34	14	38	0	10	1	−6	0	13	0	8	8	34	16	39

The 28 measurements are grouped into four body regions: head and neck, chest, left leg and foot, and right leg and foot. Six injury parameters are used to judge protection for the head and neck, four parameters make up the evaluation for the chest, and nine parameters are used to evaluate protection for each leg and foot.

Each body region receives an injury protection score of good, acceptable, marginal, or poor, based on the injury parameters for that region. For any body region to receive a good rating, the scores for all injury parameters in that region must indicate good results. If any parameter indicates only acceptable results, then the rating of that body region is acceptable. If any parameter has a marginal rating, then the rating of that body region is marginal. Thus, the overall injury rating for any body region is the lowest rating scored for an injury parameter within that region.

Table 2 and Figure 1 divide possible scores for each injury parameter into good, acceptable, marginal, and poor ranges. These ranges are based on current biomechanical information about human injury mechanisms (Mertz, 1994a; Mertz, 1994b; Begeman and Prasad, 1990; Begeman et al., 1993; Mertz and Patrick, 1971; Parenteau, 1995; Welbourne, 1994; Zeidler, 1984). Often, but not always, the border between acceptable and marginal ratings for a given injury parameter corresponds to a published threshold for significant injury related to that parameter. Acceptable ratings correspond to scores just below the injury threshold, and good ratings correspond to scores

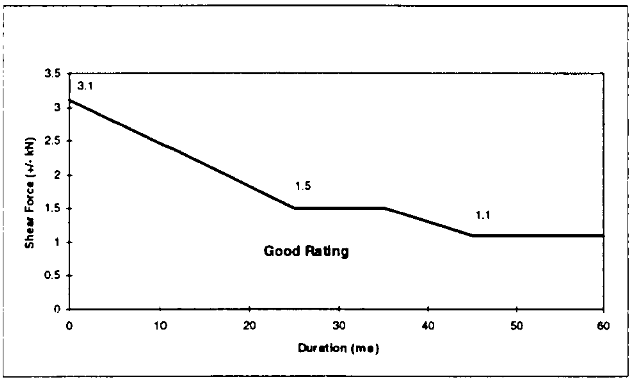
Table 2
Injury Parameter[1] Scores Associated with Good, Acceptable, Marginal, and Poor Performance - IIHS 1996

INJURY MEASURE	Good Performance	Acceptable Performance	Marginal Performance	Poor Performance
HEAD AND NECK				
HIC	< 750	750-899	900-999	≥ 1000
Head acceleration peak g	The head injury rating based on HIC is lowered one category if g ≥ 70 corresponds to contact with hard surface			
Neck shear	*See Figure 1 - Evaluation of Neck Shear*			
Neck tension	*See Figure 1 - Evaluation of Neck Tension*			
Neck compression	*See Figure 1 - Evaluation of Neck Compression*			
Neck flexion[2]	< 90 Nm	90-139 Nm	140-189 Nm	≥ 190 Nm
Neck extension[2]	< 40 Nm	40-56 Nm	57-73 Nm	≥ 74 Nm
CHEST				
Chest acceleration 3 ms	< 60 g	60-74 g	75-89 g	≥ 90 g
Chest compression	< 50 mm	50-59 mm	60-74 mm	≥ 75 mm
Viscous criterion	< 0.7 m/s	0.7-0.9 m/s	1.0-1.2 m/s	≥ 1.3 m/s
LEG AND FOOT				
Femur axial force	*See Figure 1 - Evaluation for Axial Femur Force*			
Tibia-femur displacement	< 12 mm	12-14 mm	15-17 mm	≥ 18 mm
Tibia Index Upper or Lower	< 0.8	0.8-0.9	1.0-1.1	≥ 1.2
Tibia axial force	< 4.0 kN	4.0-5.9 kN	6.0-7.9 kN	≥ 8.0 kN
Foot acceleration	< 150 g	150-199 g	200-259 g	≥ 260 g
Lower tibia bending moment	< 160 Nm	≥ 160 Nm		

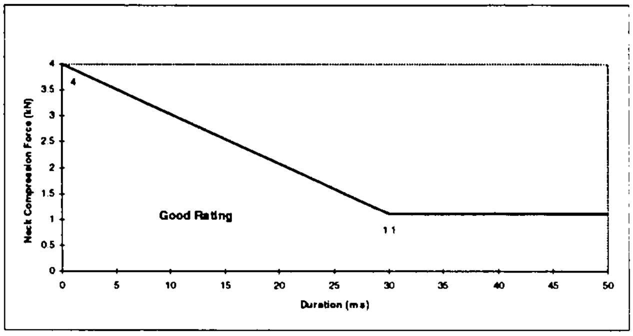
[1] Note that all injury parameter measures are rounded to the same precision as the tabled values before rating.
[2] The occipital moment for neck flexion and neck extension, calculated from the forces and moments measured by the Hybrid III upper neck load cell, should only be compared against the values indicated in this table when film analysis can verify the dummy's neck Is flexed forward or extended rearward, respectively.

Figure 1
Parameters for Significant Injury

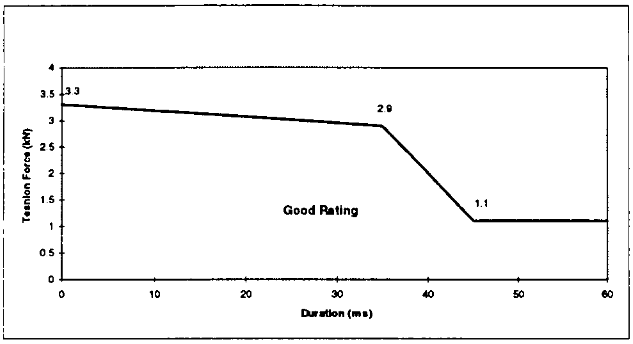
Neck Shear (+/-) Magnitude-Duration Limit for Significant



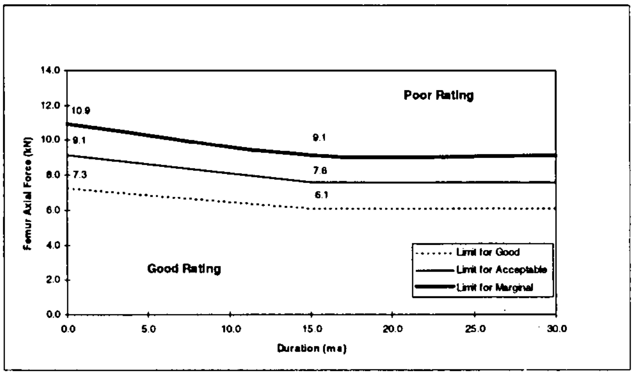
Neck Compression Force Duration-Magnitude Limit for Significant Injury



Neck Tension Magnitude-Duration Limit for Significant Injury



Injury Ratings for Femur Axial Force



further below the threshold. Similarly, marginal ratings correspond to ratings just above published injury thresholds, and poor ratings correspond to scores further above. For example, Mertz (1994a; 1994b) indicated that a tibia index of 1.0 is a threshold for tibia fracture. Accordingly, in the Institute evaluations, scores more than 20 percent less than 1.0 are rated good, and scores at least 20 percent higher are rated poor. Scores just below or just above the published threshold are rated acceptable and marginal, respectively. It is important to remember in reading Table 2 that crashes are very complex events. It is not possible for an injury coding scheme to foresee all the possible combinations of outcomes that could suggest injury risk in a crash.

Therefore, the information in Table 2 should be interpreted as providing guidelines for evaluating the dummy measurements, which are always subject to modification based on the circumstances of the particular crash test and on new biomechanical information about injury tolerance.

Restraints and Dummy Kinematics. A full-frontal, flat barrier crash provides the most severe test of the ability of restraint systems to manage the kinetic energy of an occupant, keeping forces experienced by the occupant to survivable levels. However, the rotation and lateral translation of the occupant compartment that occur during an offset crash place demands on the restraint system, and in particular, how it interacts with other parts of the

vehicle, that are not assessed in full-frontal crash tests. Significant injury risk can result from undesirable dummy kinematics — for example, partial ejection from the occupant compartment — in the absence of high injury measures.

Ideally, an occupant should load the seat belt and air bag and then rebound back into a normal seated position during an offset crash, just as typically occurs in a full-frontal crash. The air bag should stay between the occupant and hard surfaces to the front of the occupant. The restraint system, including the seat belt, the seat itself, and the door, should keep the position of the occupant predictable relative to the occupant compartment; in particular, the restraint system should not allow the head and torso to lag far behind as the vehicle begins to rotate.

The degree to which restraint systems meet this description determines whether vehicles receive a good, acceptable, marginal, or poor rating for restraints and dummy kinematics. The primary concern in this assessment is the motion of the dummy, but clear failures of the restraint system can result in lower ratings, as well. For example, it is unacceptable for the door to open in a crash, even if other aspects of the restraint system work well. In addition, the dummy's lower extremities should not contact stiff structures on the way to, or inside, the knee bolster. These assessments are made by studying high speed film of the offset crash test taken by cameras positioned at several different angles as well as postcrash examination of the vehicle interior and dummy.

This is the most subjective of the Institute's crashworthiness evaluation procedures, but differences among vehicles thus far have been reasonably clear-cut. Some cars have kept dummy motion in the offset crash virtually the same as in a frontal crash, and these cars receive a good rating. Other cars have major problems, with the dummy rolling left, off the air bag, as the seat tilts and the door bows outward; in the worst cases, the head may leave the occupant compartment through the window or strike the door window frame hard as the torso leans toward the driver door. These cars receive marginal or poor scores for restraints/occupant kinematics. Cars with somewhat less than optimal kinematics but in which the occupant motion does not appear to bring the head or torso near to potentially injurious contact may be rated as acceptable.

Other Crash Tests and On Road Crash Experience. Although performance in the offset test is the primary determinant of the Institute's crashworthiness evaluations, other crash test information and on-road injury and fatality experience are considered as well. For example, dummy measurements from the NCAP tests are rated according to the same rules as the offset test (Table 2) when that information is available. Similarly, a vehicle's overall rating could be lowered if its on-road crash experience indicated high fatality or injury rates.

Head Restraints

Although there are no widely used criteria to determine acceptable head restraint geometry, at a meeting in 1994 in Lyon, France, an international ad hoc group for neck protection in rear-end impacts recommended that head restraints have a minimum height corresponding to the top of the head of the 50th percentile adult male seated in the car seat. The Lyon group also generally agreed that the backset (the distance from the back of an occupant's head to the front of the restraint) should be as small as possible. Backsets greater than 10 cm have been associated with increased symptoms of neck injury in rear-impact crashes (Ollson et al., 1990). To prevent neck injury, head restraints must be positioned behind and close enough to the backs of most people's heads to limit relative movement of the head and torso in rear-end collisions.

Details of the head restraint measurement procedure are available elsewhere and are briefly summarized below (Estep, Lund, and Vann, 1995). Head restraints were rated as good, marginal, or poor based on two measurements: head restraint height (the distance down from the top of an occupant's head to the top of the restraint) and head restraint backset. Measurements of head restraint height and backset were made with a standard H-point machine fitted with a special device that represents the head of an average size male. A head restraint received a poor rating unless it was about as high

Figure 2: Head Restraint Geometric Zones

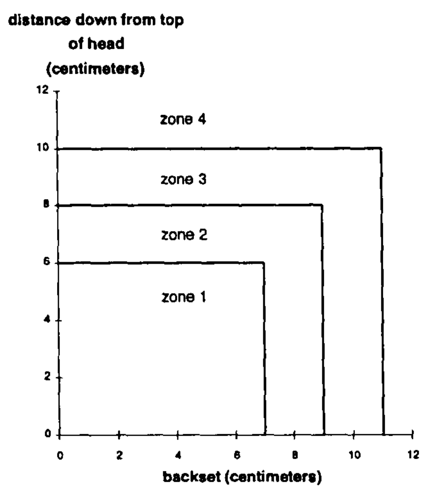


Figure 3
Crashworthiness: Midsize 4-Door Cars

Midsize 4-Door Cars	Overall Evaluation	Frontal Offset Crash Test Performance: Structure	Restraints & Dummy Kinematics	Injury Measures: Head/Neck	Chest	Leg/Foot, Left	Leg/Foot, Right	Head Restraint Design	Bumper Performance (see note)
FORD TAURUS 1996 Models	G	G	G	G	G	G	G	P	G
CHEVROLET LUMINA 1995-96 Models	G	G	G	G	G	G	G	P	M
FORD TAURUS 1992-95 Models	G	G	G	A	G	G	G	P	M
VOLVO 850 1993-96 Models	G	A	G	G	G	G	G	G	M
TOYOTA CAMRY 1992-96 Models	A	A	G	A	G	A	G	M	M
SUBARU LEGACY 1995-96 Models	A	A	G	G	G	P	G	M	A
HONDA ACCORD 1994-96 Models	A	A	G	G	G	P	A	P	A
MAZDA MILLENIA 1995-96 Models	A	M	G	G	G	P	G	P	M
TOYOTA AVALON 1995-96 Models	M	M	G	G	G	P	A	P	P
SAAB 900 1995-96 Models	M	P	M	G	G	G	A	A	A
FORD CONTOUR 1995-96 Models	P	M	G	G	G	P	P	M	P
VOLKSWAGEN PASSAT 1995-96 Models	P	M	P	G	G	P	G	P	M
CHEVROLET CAVALIER 1995-96 Models	P	P	P	A	G	P	G	P	A
MITSUBISHI GALANT 1994-96 Models	P	P	P	G	G	P	A	P	P
CHRYSLER CIRRUS 1995-96 Models	P	P	M	G	G	P	P	P	M
NISSAN MAXIMA 1995-96 Models	P	A	P	M	G	P	P	M	P

LEGEND

- G GOOD
- A ACCEPTABLE
- M MARGINAL
- P POOR

as the center of gravity of the head (or higher) of an average size male, which is about 9 cm below the top of the head, and was no more than about 10 cm from the back of the head.

Four geometric zones were specified based on head restraint height and head restraint backset (Figure 2). Each zone represents progressively worse geometry. The border values for height (6,8,10 cm) and for backset (7,9,11 cm) were included with the lower zone. A restraint was rated as good if its geometry put it in zone 1 without adjustment; acceptable if it was zone 2 without adjustment or in zone 1 with adjustment that locks in place; or marginal if it was zone 3 without adjustment or if it was in zone 2 with locking adjustment; and poor if its geometry put it in zone 3 with adjustment or zone 4 regardless of adjustment. The lower ratings for the adjustable-locking restraints reflect the fact that most occupants do not adjust the head restraints (Viano and Gargan, 1995).

Bumpers

Performance is assessed using the costs of repairing the vehicle damage that occurred in four crash tests at 5 mi/h — front and rear into full width barrier, front into angle barrier, and rear into pole. Details of the bumper test procedure are available in, for example, the Institute's1993 technical report on low speed damage (IIHS, 1993).

RESULTS OF IIHS CRASHWORTHINESS EVALUATIONS

The Institute has conducted crashworthiness evaluations of 22 vehicles in two market classes: four-door midsize cars (16 vehicles) and four-door, midsize utility vehicles (6 vehicles). The results reveal a wide range of performance in all three aspects of offset crash

Figure 4
Crashworthiness: Midsize Utility Vehicles

Midsize Utility Vehicles	Overall Evaluation	Frontal Offset Crash Test Performance: Structure	Restraints & Dummy Kinematics	Injury Measures: Head/Neck	Chest	Leg/Foot, Left	Leg/Foot, Right	Head Restraint Design	Bumper Performance
TOYOTA 4RUNNER 1996 Models	A	G	G	G	G	G	A	P	P
LAND ROVER DISCOVERY 1994-96 Models	A	A	G	A	G	G	A	M	P
FORD EXPLORER 1995-96 Models	A	A	P	A	G	G	G	P	P
JEEP GRAND CHEROKEE 1993-96 Models	M	A	G	G	G	P	P	P	P
ISUZU RODEO/ HONDA PASSPORT 1996 Models	P	P	M	G	G	P	P	P	P
CHEVROLET BLAZER/ GMC JIMMY/OLDSMOBILE BRAVADA 1995-96 Models	P	P	P	P	G	G	A	P	P

LEGEND
G GOOD
A ACCEPTABLE
M MARGINAL
P POOR

protection: structural integrity, dummy injury measures, and restraints and dummy kinematics (see Figures 3 and 4). Within both vehicle classes, ratings ranged from good to poor in each of these areas.

This range of performance is noteworthy because it further confirms that the test speed chosen for the crashworthiness evaluations is reasonable. The separate results indicating that many serious injuries and fatalities are occurring in real-world crashes of greater or equivalent severity to the 40 mi/h offset deformable barrier test means that improved protection up to and including this severity is desirable. These crash test results show that several cars and utility vehicles are already capable of providing good protection in such crashes, while a number provide relatively poor protection and need improvement.

It is also noteworthy that NCAP test results affected some of the overall evaluations of the utility vehicles. Most notable was the Toyota 4Runner, which would have received a good overall rating except for a marginal HIC (over 900) in the 35 mi/h barrier test. None of the midsize cars tested by the Institute had NCAP test results that resulted in their evaluation being downrated. This difference suggests that restraint systems in utility vehicles have not yet been optimized to the same extent as in cars, perhaps because of different crash pulse characteristics of the two classes of vehicles. In any case, the difference shows the need for both full width barrier and offset barrier tests, the first to assure that restraint systems are adequate to handle high deceleration crashes and the second to assure that occupant compartment integrity is maintained when only part of the front end is engaged in the crash.

REFERENCES

Begeman, Paul C.; and Prasad, Priya. 1990. Human ankle impact response in dorsiflexion. *Thirty-fourth Stapp Car Crash Conference Proceedings.* Warrendale, PA: Society of Automotive Engineers.

Begeman, Paul; Balakrishnan, Pradeep; Levine, Robert; and King, Albert. 1993. Dynamic human ankle response to inversion and eversion. *Thirty-sixth Stapp Car Crash Conference Proceedings.* Warrendale, PA: Society of Automotive Engineers.

Estep, C., Lund, A., and Vann, D. 1995 Measurement and Evaluation of Head Restraints in 1995 Vehicles. Arlington, VA.: Insurance Institute for Highway Safety.

Hackney, J.R. 1993. The effects of FMVSS No. 208 and NCAP on safety as determined from crash tests results. *Proceedings of the 13th International Technical Conference on Experimental Safety Vehicles.* Washington, DC: U.S. Department of Transportation; 993-1021.

Insurance Institute for Highway Safety. 1993. Low-Speed Crash Tests: 1993 Midsize Four-Door Passenger Cars. Arlington, VA: Insurance Institute for Highway Safety.

Insurance Institute for Highway Safety. 1995a. Crahsworthiness Evaluations (Various Models). Arlington, VA: Insurance Institute for Highway Safety.

Insurance Institute for Highway Safety. 1995b. Offset Crash Protocol, Version I. 1995. Arlington, VA: Insurance Institute for Highway Safety.

Insurance Institute for Highway Safety. 1996. Offset Crash Protocol, Version II. 1996. Arlington, VA: Insurance Institute for Highway Safety.

Lowne, R.W. 1995. EEVC Working Group II Report on the Development of a Front Impact Test Procedure. Proceedings of the 14th International Technical Conference on Enhanced Safety of Vehicles. Washington DC: US Dept. of Transportation.

Mertz, H.J. 1994a. Injury assessment values used to evaluate Hybrid III response measurements. *The First Human-Life Crash Test Dummy.* Warrendale, PA: Society of Automobile Engineers, 407-422.

Mertz, H.J. 1994b. Anthpromorphic test devices. *The First Human-Life Crash Test Dummy* Warrendale, PA: Society of Automobile Engineers, 387-405.

Mertz H.J. and Patrick, L.M. 1971. Strength and response of the human neck (71085). *Biomechanics of Impact Injury and Injury Tolerances of the Head-Neck Complex.* Warrendale, PA: Society of Automobile Engineers, 821-846.

National Highway Traffic Safety Administration. 1970. Occupant crash protection in passenger cars, multipurpose passenger veicles, trucks, and buses. *Federal Register.* Vol. 35, No. 214: 16927-16931.

Ollsen, I., Bunketorp, O., Carlsson, G., Gustagfsson, C., Planath, I., Norin, H., and Yslander L. 1990 An in-depth study of neck injuries in rear end collisions. *Proceedings of the 1990 International IRCOBI Conference on the Biomechanics of Impacts.* Lyon, France; 269-280.

O'Neill, B., Preuss, C.A., Nolan, J.P. 1996. Relationships between computed delta Vs and impact speeds for offset tests. *Presented at the 15th International Technical Conference on the Enhanced Safety of Vehicles.* Melboune, Australia.

Parenteau, Chantal S. 1995. Foot-ankle injury: Epidemiology and method to investigate joint biomechanics. Gothenburg, Sweden: Chalmers University of Technology.

Viano, D. and Gargan, M.F. 1995 Headrest position during normal driving: Implication to neck injury risks in rear crashes. *39th Proceedings of the AAAM Conference.* Des Plains, IL: AAAM, 215-230.

Welbourne, E.R. 1994. Vehicle performance requirements for head injury protection: A comparison of the Head Injury Criterion with an 80 g limit on resultant acceleration. Technical Memorandum. Ottowa, Ontario: Transport Canada, Vehicle System Division.

Zeidler, Falk. 1984. The significance of lower limb injuries of belted drivers. *Journal of Orthopedics* [German].

CONSUMER CRASH TEST PROGRAMS
INTERNATIONAL HARMONISATION AND SCOPE FOR INJURY REDUCTION

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INTRODUCTION

There are now five published papers in international conference proceedings, which describe the origins and various aspects of the Australian New Car Assessment Program (ANCAP),

• Australia's New Car Assessment Program – Michael Griffiths – ESV, Munich, 1994

• Consumer Needs in Vehicle Crash Rating Systems – Lauchlan McIntosh – ESV, Melbourne, 1996

• The development of Result Presentation in Australia's New Car Assessment Program – Richard Stolinsky – ESV, Melbourne, 1996

• Correlation of the Australian New Car Assessment Program with Real Crash Data – Stewart Newstead – ESV, Melbourne, 1996

• Australian NCAP Results Reviewed – Carleen Reilly-Jones – ESV, Melbourne, 1996.

This is not intended to be a technical paper. The primary purpose of this paper is to look at:-

– the potential for international harmonisation of consumer crash test programs,

– the degree of harmonisation adopted by ANCAP,

– and the scope for improvement, that may go unrealised, if a country does not have a consumer crash test program.

INTERNATIONAL HARMONISATION

The Australian New Car Assessment Program's (ANCAP) method, in terms of test procedures, has generally been to adopt established protocols, where possible to build upon those, and to maintain sufficient flexibility to keep test procedures up to date with the latest developments.

On this basis, ANCAP adopted the US NCAP full-frontal tests, which had been used since 1978, with the additional proviso that only Hybrid-3 dummies could be used. This was in contrast to the US program where the manufacturer could choose either a Hybrid-2 or Hybrid-3 dummy for his vehicle, depending on which gave him the most favourable result.

ANCAP had decided from the start that it was to be a two test program with a full frontal and an offset test. The dilemma was which offset test. At that time 'Automotor und Sport' (German motoring magazine) were using a 50% rigid barrier with a 15° inclination and anti-slide bars, whereas it was known that the European Experimental Vehicle Committee (EEVC) was working towards an offset test with a crushable face, to better replicate an offset head on impact between two vehicles. ANCAP adopted the EEVC 40% offset, Mark One barrier, and test protocol. ANCAP subsequently progressively incorporated barrier changes. ANCAP initially conducted the test at 60 km/hr. However this was recently changed to 64 km/hr, to maintain uniformity with the Insurance Institute of Highway Safety and UK Department of Transport consumer crash test programs.

ANCAP adapted the NHTSA protocol for establishing a single index rating system for each vehicle, with the difference that whereas the NHTSA system effectively rounded off the number to get a star rating, ANCAP published a single index number which was based on a combination of the head and chest measurements for the full frontal and offset impacts, with a separate number being derived for the driver and passenger position in each vehicle model.

In 1995 the Insurance Institute of Highway Safety released its evaluations with additional information on the performance of the vehicle structure, head restraint systems, etc. ANCAP was impressed with the broader information available in the IIHS presentations, and in March 1996, ANCAP brochure included information on other factors such as vehicle structure, restraint performance and head restraints.

The head restraint assessment was directly adopted from Insurance Institute of Highway Safety using a rig developed for Transport Canada. ANCAP procedures adopted are hence identical to those already in use in North America.

The IIHS results presentation reports on the different aspects of a vehicle's overall performance, including structure, restraints, etc. and then proceeds to take all these factors into account in their awarding of 'a best pick'. ANCAP agrees that this approach basically gives consumers what they need, which is a simple guide to the overall best safety buys. However, ANCAP wants to be able to recognise the best performance of currently available vehicles, yet have scope to further recognise better performing vehicles in the future. At this stage, it is likely that ANCAP may move to a similar 'best pick'

system to IIHS, but probably build on it, to give different levels of 'best picks' with perhaps some 'Olympic Medal' modelling of progressive awards of bronze, silver and gold. This will allow us to acknowledge adequate performance, and yet leave scope for improvement.

The ANCAP was one of the co-initiators of international meetings of all those organisations conducting, sponsoring or considering, consumer crash ratings.

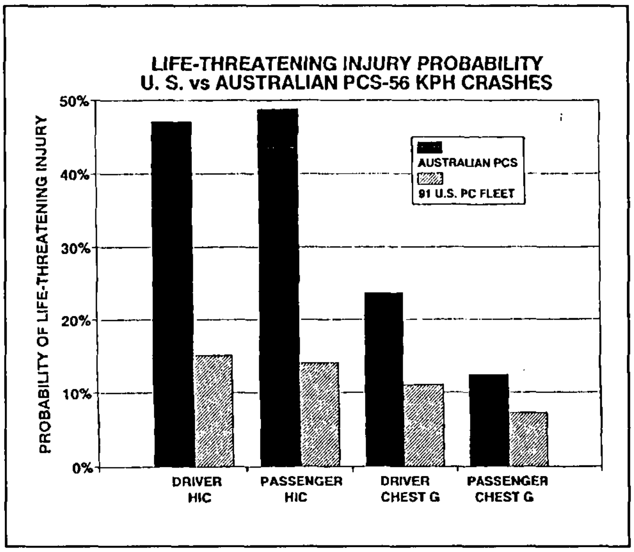
Previous meetings have been held in Brunnen, Switzerland in September 1995, adjacent to the IRCOBI annual conference, hosted by European Transport Safety Council. The next meeting was held in San Diego, US, in November 1995, adjacent to the annual STAPP conference, hosted by the Insurance Institute of Highway Safety. I am viewing this session here today, albeit a lot more formal, as an extension of these discussions.

One of the potential benefits of internationally uniform consumer crash tests methods is the exchange of results. In that regard ANCAP is very close to making a decision to incorporate some overseas offset crash test results of right hand drive versions of vehicles sold on the Australian market. This will of course represent a significant cost saving to ANCAP and allow it to increase the number of other vehicles that it tests.

COMPARISONS

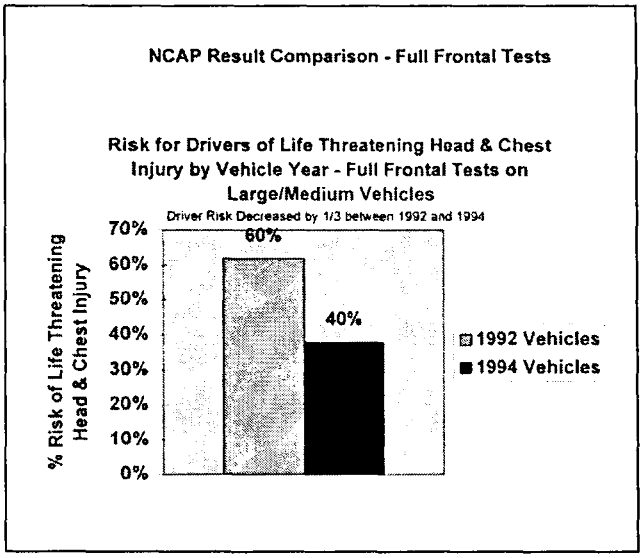
Since the Australian Program commenced publishing results in 1993, we have had the opportunity to retest upgraded models of some of the vehicles from the original round of testing. The apparent improvements in performance are very encouraging, with a 30% reduction in the probability of receiving serious injury for both drivers and passengers. This is illustrated in the barcharts below.

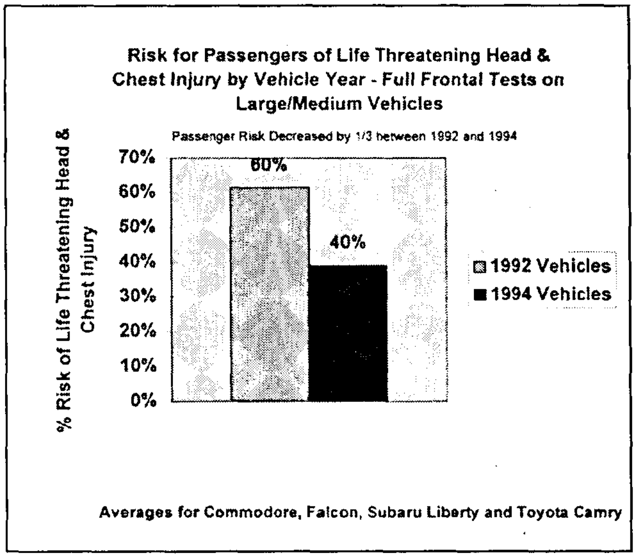
A comparison of ANCAP tests to USNCAP tests was conducted by James Hackney from NHTSA. He reported that the probability of receiving a serious head injury in the Australian vehicles was in the order of three times higher than that for the equivalent US vehicles. This was a very contentious result, and continues to be hotly contested by some in Australia.

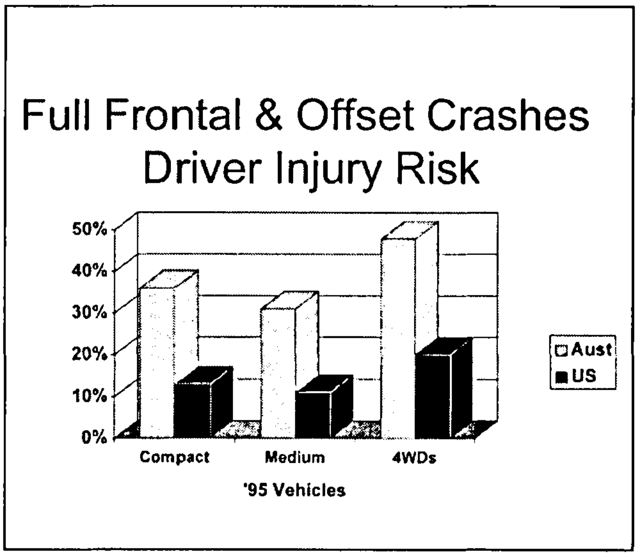


Nevertheless, whatever the actual size of the difference between the Australian fleet and the North American fleet, the available evidence continues to strongly support the proposition, that the differences are still significant, and although worthwhile improvements have been observed, this difference may still be in the order of serious injury twice as likely to occur in crashes at these speeds. [Ref. Reilly ESV96-S1-O-12]

These differences are not the result of some kind of statistical analysis of a macro database, where there might







be a variation in how things were coded, that might lead to discrepancies. Instead these comparisons were based on discrete numbers of equivalent vehicles. More recently we were able to directly compare the test results on the Toyota Camry and the Ford Mondeo. The US version of the vehicles performed better in the crash tests, in both the full frontal and offset crash tests. Unfortunately ANCAP hasn't had the resources available to fully investigate why these differences occur.

However in some cases information has been available to indicate why the Australian version may not perform as well as the US version. Some examples are:-

– Following commencement of ANCAP the Honda Civic in Australia incorporated lower elongation seatbelt webbing, web clamps, five mile per hour bumpers, and better availability of airbags.

– After an average, but by no means worst performance in the first round of ANCAP, Subaru Australia reportedly told their Japanese supplier, that in future they would require the North American safety package on vehicles sold into the Australian market. The considerably improved crash test performance of the subsequent models of Subaru Liberty are strong evidence that this occurred. Subaru has reproduced these ANCAP results in its inhouse publications and makes the ANCAP brochures available at its distributors.

– Daewoo Australia has shown strong interest in the ANCAP programme. It purchased the ANCAP tested vehicles and shipped them back to its Korean head office for inspection by its Korean engineers. It has reported that it is putting its next model prototypes of vehicles through the full ANCAP test program as part of future model development.

In most, but not all cases, there is a significant difference between the public views on NCAP of many of the larger car companies' spokespersons, compared to the private views of their engineers. Several companies' engineers have privately reported that they had previously attempted to persuade their overseas head office to supply them with the full North American safety package to the vehicles destined for Australia, however the response had been 'What reason was there to do this, as the buyers wouldn't really know the difference'. The engineers reported that the ANCAP program provided a reason for these companies to fit the full safety package into vehicles destined for the Australian market.

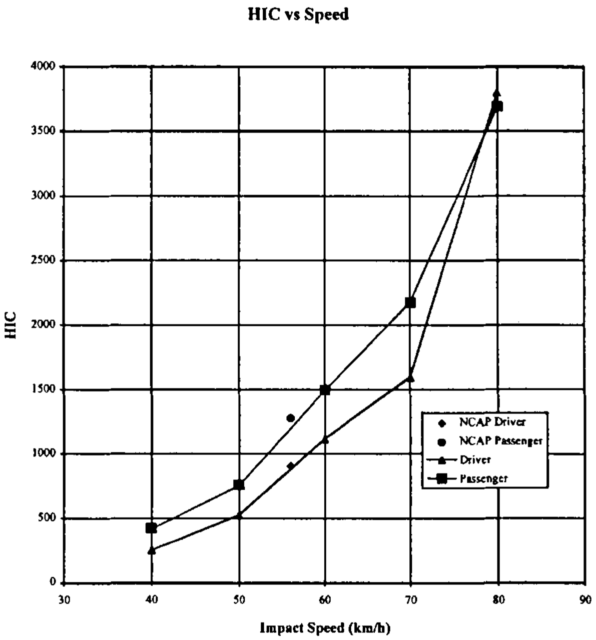
CORRELATION WITH REAL WORLD CRASHES

ESV proceedings contain a paper on correlation of ANCAP test results and real world crash outcomes. [Ref. Newstead ESV96-S9-O-14].

In that paper you will note that there is a strong correlation between the offset test results and the injury outcome performance of vehicles in real world frontal crashes. This correlation is maintained at a significant level even for all crashes. The correlation for the full frontal test is nowhere near as strong, and the combination of the full frontal test and the offset test does not enhance the correlation with real world outcomes.

Clearly this outcome will be very influential in ANCAP's decision making process, as to when to drop the full frontal tests and include a side impact test.

Although discussions are by no means finalised, ANCAP's general consensus seems to be, that the side impact test will be based on the European one, probably identical to the current consumer crash test being conducted by the UK Department of Transport.



There is some reticence to drop the full frontal test, while some popular vehicles sold in Australia are still performing so poorly in it. Alternatives under discussion are:-

– Drop the routine conduct of the full frontal test on each vehicle, but maintain it as a 'Audit' part of a program, to be conducted when there are suspicions that a vehicle might be delivering significantly worse than average performance in such a test.

– Access and publish the results of the mandatory 48 km/hr full frontal test (This is identical to FMVSS208 with the exception that only Hybrid 3 dummies can be used, and the dummies are restrained by the available seatbelts).

Information that counts against the usefulness of the latter approach was uncovered in a recent RTA crash test program. A popular Australian sedan was crashed at 40, 50, 60, 70, and 80km/hr. At 50km/hr the HIC's for the driver and passenger were low at 520 and 750 respectively, leading to an expectation that at the higher speed of 60km/hr the head impacts would still be in the acceptable range of below 1000. However the HIC's at 60km/hr were 1120 and 1490 respectively, indicating that the vehicle may have been tuned to give a peak performance at the regulatory crash test speed of 48 km/hr. When the vehicle is crashed at 56km/hr, HIC performance has deteriorated to approximately 900 and 1300 respectively. Without an NCAP test at 56km/hr, this rapidly deteriorating performance of the restraint systems would not have been detected.

Of further interest, is that the addition of a passenger's side airbag did not appear to offer a significant improvement in performance at any speed, indicating that the passenger's side airbag may not have been developed to extend the speed range of enhanced protection.

OCCUPATIONAL HEALTH AND SAFETY OBLIGATIONS AND FLEET BUYERS.

The original target audience of the ANCAP information was private car buyers, however it later occurred to the ANCAP group that it might get better results if they targeted fleet buyers. More than 50% of new vehicle sales are to fleets. ANCAP only had to influence a smaller number of fleet managers to achieve an equivalent shift in vehicle purchasing.

Additional benefits of targeting fleet managers are :-

– Fleet vehicles are generally resold in one to two years, thus offering the onselling of safer vehicles to private buyers at more affordable prices

– Fleet buyers work for employers who have obligations under The Occupational Health & Safety Act to provide a safe workplace. A fleet work car constitutes a workplace.

To communicate this information to fleet buyers, ANCAP stakeholders RTA NSW, NRMA, and RACV, presented their inaugural fleet managers' seminar on safe vehicle selection in late 1994. The success of that seminar led to invitations to present the safe vehicle selection component at most future commercial fleet managers' seminars in NSW and Victoria. To date the Australian NCAP travelling team have presented six seminars to fleet managers and are achieving strong support from the two magazines aimed at fleet managers in Australia. Part of the presentation package is from a senior lawyer in a prestigious law firm. The lawyer details very tough criminal sanctions available in the Occupational & Safety Act. The message is clearly that the employer has an obligation to provide a safe workplace, and that the Australian New Car Assessment Program provides independent information on the relative safety of the alternative workplaces/vehicles.

DESIRABLE DEVELOPMENTS

Clearly the better the biofidelity of the available dummies, then the more reliable will be the outcome of the crash test assessments. In this regard ANCAP is keen to see a uniform injury criteria for lower legs.

Many attempts have been made to make assessments of injury causing potential of intrusion into the footspace. Some have attempted to seek correlation between change in volume, rearward displacement of the firewall, acceleration of the firewall, and accelerations and forces on the dummy lower legs. However in all of these assessments the positioning of the feet has proven to be critical, minor changes in foot positioning appear to have the potential to give major changes in observed injury criteria outcomes. The good news is that energy absorbing padding of the firewall has been reported to consistently result in reductions of forces on the lower leg, where ever it is placed.

IIHS has introduced comparative observations of the performance of the vehicle structure and ANCAP has subsequently included similar observations. It is desirable to increase the scientific content of these evaluations. This will require protocols that might be uniform internationally.

Another issue is the representativeness of the size of the test dummies. A more rigorous, very well funded program, would probably conduct an assessment for each seating position using a 5, 50 and 95 percentile test dummy to ensure a broader evaluation of the overall safety offered in that seating position, to at least 90% of the potential occupants of that position. This use of such a broader range of test dummies would also be more likely to cover the worst case safety evaluation of that seating position.

Some UK based advocates say that any fair consumer

evaluation should always be a worst case one. That is the tester should look at the various known characteristics of the vehicle and seating position, then use a test dummy and appropriate seating geometry to test the vehicle for the likely worst case. This concept probably merits further discussion.

POSSIBLE INJURY REDUCTION

A general review of the most recent test results of the ANCAP programme and the performance of vehicles in the US IIHS Offset Tests, and US NHTSA full frontal tests, indicate that all vehicles ought to be able to achieve, in the next few years, a driver rating of not more than 20% likelihood of receiving serious injury, and a passenger rating of not more than 15% likelihood of receiving serious injury. Many moderately priced vehicles have demonstrated that this can be accompanied by good structural performance without gross intrusion into the occupant compartment space.

In a fairly rough comparison (certainly not a scientific evaluation) between the ANCAP test results and driver protection rating results, it appears these ANCAP performances of 20% and 15% are roughly equivalent to a Driver Protection Rating of 1.4. That is there is a 1.4% chance of a driver receiving serious injury in any crash reported to police, ie generally towaway or any casualty. The current average of all vehicles on the Driver Protection Rating Analysis is 2.6. The potential for improvement then is to reduce the overall average for all light vehicles from 2.6 to 1.4 which translates to a 46% reduction in the likelihood of serious injury in all crashes.

1994 Road Safety Statistics for NSW recorded 382 fatalities and 4076 serious casualties for light passenger vehicles involved in crashes. A 46% reduction would mean a drop to around 206 fatalities, and a fall in serious casualties to approximately 2200. This is a reduction of approximately 180 fatalities and 1900 serious casualties each year! Just how quickly this benefit might be realised is dependent upon how quickly the changes are made to the vehicles (potentially 1-2 years), and how quickly they infiltrate the crash exposed vehicle population (potentially 2-10 years).

The potential of such gains, accompanied by the reduced polluting emissions of newer vehicles, may well justify a strong Government incentives program for older vehicle replacement.

I acknowledge that these projections appear to be too good to be true, however they are consistent with previous views published by the European Transport Safety Council and Swedish road safety researchers.

Who says there are no more 'road safety silver bullets', the evidence may be to the contrary!

CONSUMER NEEDS IN VEHICLE CRASH RATING SYSTEMS

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ABSTRACT

Consumers and fleet purchasers have shown that they want intelligent but simply expressed information on vehicle safety. Much of this material is not available from the vehicle manufacturers and as a result the information must come from developing consumer safety interest groups. Needs of consumers are discussed together with the extent that international consumer groups are able to provide the required safety information .

INTRODUCTION

Every year more than 2000 people die on Australian roads. Thousands are injured and many suffer debilitating injury that will remain with them for the rest of their lives. Road accidents are a major cause of death amongst young people. The human suffering is immeasurable, but the financial loss to Australia can be quantified and is put at more than $6 billion dollars every year.

This is not an Australian problem, it is a problem in every motorised country and community across the world. Users or consumers of transport systems urgently need something done to reduce the pain and cost.

Fatality rates vary across Australia, varying from 9.4 per 100,000 population in Victoria to 26.2 in the Northern Territory, with an Australian average around 11.2 (1995). Serious injury accidents occur ten times more frequently than fatal accidents so the chances of a road user being involved in some sort of serious accident are ten times greater than the fatality rate. Injury accidents are in addition to fatal and serious injury accidents and they occur at four times the rate of serious injury accidents.

AUSTRALIAN DATA	1995 Rate/100,000 population
Fatals	11.2
Serious Injuries	approx 122
Injuries	approx 500

Consumer Needs in Vehicle Purchases

From 1987 to 1993 the Australian Automobile Association (AAA) commissioned Woolcott Research to evaluate motorists concerns. The safety of vehicles emerged as a consistent concern during the national tracking study. In 1993 survey respondents were asked for the three most important factors when buying a new car. Reliability, fuel economy and safety factors emerged as most important.

In 1995 AAA commissioned a more extensive survey of motorists priorities and attitudes using focus groups and telephone polling of 2211 motorists. Safety was consistently identified by motorists as a key issue. Of all the issues rated, safety and roadworthiness emerged at the top, together with the personal importance motorists attached to their own cars. When motorists were asked to nominate their main concerns about cars, safety came at the top of the list.

Some motorists were reluctant to acknowledge the disadvantages of older cars with 37% believing older cars to be safer and better built while 34% thought older cars were less safe, unroadworthy, had fewer safety features and inferior handling.

In line with motorists concerns there was very strong support for motoring organisations to be involved in special car safety and crash tests.

Since NCAP commenced publishing consumer crash test results in Australia in 1993 there has been a increasing demand by private and government fleet operators, and private buyers to consider the data when selecting vehicles.

Very little factual data on crashworthiness is published by the manufacturers in publicly available material.

With the competitive vehicle market that exists in nearly all world markets a problem for the consumer test organisations is to ensure that the availability of safety information keeps pace with the changing models available across a vehicle range.

Manufacturers in Australia have made many changes to models and repeat crash test results have shown that many have achieved improved NCAP injury results, justifying the retest of the model. Unfortunately some of the poorer performing vehicles continued to duplicate the poor results of the earlier test.

Fleet managers have been critical of the results available to them from time to time as a new model is not available with crash test results. The safety of the vehicle must then be based on old model data which may not represent the new vehicle.

One of the factors fleet managers stress is the need for relevant crash test results at an early stage in the

manufacturing cycle of the vehicle under consideration. In Australia this places strains on the resources available to NCAP and we have not been able to always meet the fleet managers expectations.

What Safety Information is Available to Australian Consumers?

For popular new vehicles NCAP full frontal and offset crash test results are published.

Legislated tests to determine that the vehicle meets Australian Design Rule (ADR) requirements remain confidential to the manufacturer and the Federal Office of Road Safety who administer the ADR system. No results are publicly available.

Insurance records of vehicle safety records are published in a Driver Protection Rating publication to allow consumers to determine the record of safety of a particular model. These records always lag the purchasers decision to acquire new vehicles, but are of assistance in used car purchasing decisions.

Published records of overseas NCAP or Crash Test results may be available for some models marketed in Australia, but care has to be taken to ensure the model was representative of the model that was tested.

Some manufactures do use overseas crash test results to promote the vehicles safety in Australia and the new release of the E class Mercedes is a typical example.

The Australian press release noted
" The unique bodywork and structure and Mercedes-designed restraint systems, combine to make the new E-class the world's safest car-according to Germany's authoritative Auto Motor and Sport magazine's rigorous crash test program.

"The independent project, designed and supervised by the national magazine, showed the new E-class as the safest ever in a history of more than 60 crash experiments."

Not quoted however were any of the Mercedes test results. A left hand drive E-series vehicle damaged in the crash test was brought to Australia for exhibition at the recent Melbourne Motor Show.

Ford Australia has recently launched the Taurus with a statement on the safety of the vehicle, which points out that: " Not surprisingly, Taurus scored highest in a recent US crashworthiness test against 16 other cars".

Unfortunately, the consumer is left with no specific data or realistic comparisons against which sixteen other cars the Taurus was tested.

The reluctance of manufacturers to quote their own factual test results shows the problems facing consumers requiring useful safety material.

Most vehicle manufacturers and suppliers appear to have similar policies and avoid publishing factual data unless prescribed by legislation. It may be the only way that safety legislators can move in the future is to legislate for publication of the crash safety material that is necessary for consumers to make an educated choice.

Safety is not the only factor. Details of emissions and recyclable material used in the construction of the vehicle are other areas where specific information is not available to the consumer.

Australian vehicle manufacturers have noted in advertising material and in new car brochures that their vehicles meet or exceed various safety regulations. But they have not published test results which would allow consumers to know if the vehicle just met the minimum standard or if it was best in its class.

Side impact data has been required under the ADR system since 1976 but some manufacturers are now advertising that their vehicle meets the new side impact test required in the United States in 1997. No data is presented to give the consumer any information on the result of the test. Consumers may also be confused between the two different standards if the material is presented without sufficient facts to make it clear about which specific standard the advertising refers to.

What Information Should be Available to Consumers to make a Safer Selection?

Australian NCAP remains the only detailed crash test results available to the Australian consumer.

In Australia the results of the frontal crash test for ADR 69 (similar to FMVSS 208) are not available to the public as they are in the United States. There appears to be no reason why this information is withheld in Australia.

As frontal crash test results account for almost 60 percent of the serious injury and fatal vehicle crashes, other information should also be included for consumers to make a educated vehicle selection. The United Kingdom Department of Transport is testing a range of vehicles where the results will include side impact test results and pedestrian impact injury data. This will be a significant step forward in consumer available safety information.

Australian NCAP will be monitoring these tests closely to see the results and will gauge consumer reaction to better safety information.

International Action

There is an awareness that road safety actions taken in one community can be beneficial to others. To improve

the situation for road users, the needs of all consumers must be taken into account, for example in the consideration of traffic calming measures. These must be adapted to the community needs and therefore different actions will be taken across a large population area.

This also applies to different actions across different national boundaries.

Driver training and re-education is another area where intensive action is taken in one community, with little action in another adjacent community defined by State or national boundaries.

Vehicle safety measures in Australia have been controlled by the Australian Design Rules requirements that require manufacturers to meet minimum design standards for registered vehicles sold across Australia.

Traditionally, most road safety programs are driven by governments from advice from road safety transport departments and motoring associations that represent the needs of the motorist. Legislation is written, debated upon and eventually becomes law to produce action that may take place several years after the need for it has arisen.

The problem is more difficult when crossing international boundaries such as those that exist in Europe, Asia, South Africa and the Americans.

In Europe progress is being directed to:

- Harmonisation of technical requirements
- Education of drivers to improve behaviour
- Advertising material and codes of practice

Consumers are being advised that "world cars" are being made. The abovementioned examples by Mercedes and Ford demonstrate the advertising encouragement for such belief, even though the vehicles are made to different specification and may well have different characteristics.

What Is Wrong with Legislated Safety Levels?

If legislated safety levels were satisfactory then we would have road crash serious injury levels and fatality levels that were the lowest in the world in Australia. We have not reached that level and therefore must continue to improve the safety level of the vehicles that are available to the Australian consumers.

It is more complicated as we have a variable vehicle fleet age in terms of safety features as many of the Australian fleet vehicles were built before safety requirements were introduced. Registration records show that we have an ageing fleet with the average age of all registered vehicles approaching ten years. New vehicles were only required to meet Australian Design Rule 69 (similar to FMVSS 208) from July 1995, so many Australian consumers may wait another decade before they see the benefit of this legislated requirement.

The ANOP Survey also demonstrated the confusion of car owners relating to the safety of older vehicles.

Retrofit of Safety Equipment to Older Vehicles

Consumers may not be prepared to wait for known safety requirements and there is a challenge for the automotive industry to find knew ways to retrofit safety equipment into older vehicles. Governments must also consider the impediments in taxes on safety items which discourage rapid community acceptance.

Everyone must be more active in making sure the consumer is aware of the safety level of the vehicle and to be able to upgrade where necessary.

Legislators must find ways to ensure the consumers are not disadvantaged for the long life of today's motor vehicles when it comes to safety features.

Some legal protection for manufacturers may be necessary to ensure they are not unnecessarily charged with not providing safety equipment when a consumer elects to choose not to use it or to purchase safety improvements as optional items.

This conference has a focus on the enhanced safety of vehicles and there is every reason to believe that it is possible to enhance the safety of existing vehicles without having to completely replace the vehicle with a new model.

The Australian Automobile Association would support moves for upgrades to the existing fleet to give the owners of older vehicles the opportunity to improve the vehicle without the costly step of new vehicle replacement.

Some action is already available in this area with European vehicle manufacturers such as BMW and Renault offering retrofit factory fitted airbags to older model vehicles that were supplied from the factory without this safety feature.

The Need for International Standardisation in Safety Publications

It could be confusing to consumers if every crash testing group published results in a different format, and to different procedures. Fortunately there is general consensus by the present consumer testing groups to move towards similar formats and test protocols for frontal crash tests so as to make the task controllable. As examples the international groups are:

UNITED STATES

- NHTSA
  Commenced in 1978 full frontal crash test results at 35 mph (56 kph) with a star rating. For comparison 30mph (48 kph) full frontal crash test results from the FMVSS 208 tests are also available.
- Insurance Institute for Highway Safety (IIHS)
  Commenced in 1995 publishing 40mph (64.4kph) 40 percent overlap into a deformable barrier with slotted bumper.

EUROPE

Germany - Four motoring clubs, ADAC, ANWB, TCS & OAMTC, together with the motoring magazine Autobilt have been crash testing vehicles since 1986.

Other crash tests have been undertaken and published by the magazine Auto Motor und Sport.

United Kingdom - Commenced crash testing in 1995 with an offset test at 64 kph into a deformable barrier and added side impact tests to the European procedure plus pedestrian impact tests. Yet to publish the results for consumer use.

Crashed vehicles from consumer tests in Europe have been displayed publicly at Frankfurt and London Motor Shows.

AUSTRALIA

- Commenced testing and publishing full frontal crash tests in 1993 and in 1994 added a second test vehicle with a 40 percent offset test into a deformable barrier at 60 kph. Late in 1995 increased the offset test speed to 64 kph to harmonise with England and the United States.

There is a degree of consistency in the international tests and it is hoped that the testing methods and protocols will continue to develop with a view to the transfer use of the data in other international markets.

While vehicles are generally never symmetrical about the centerline the use of Left Hand Drive Crash test results in Right Hand Drive markets is not generally directly applicable. Hence care should be exercised in interpreting the results when a vehicle is tested in one drive configuration, and the vehicle is to be used in another drive market. The degree of interchange is greater with rear wheel drive vehicles but this class is becoming less common.

A preliminary review of international results is however encouraging as a good vehicle in one market has been shown in tests to be a good vehicle in other markets, provided the safety equipment levels were similar.

CONCLUSIONS

Consumers have a keen interest in and have a right to know the relative safety level of vehicles in the marketplace. While the manufacturers have been reluctant in the past to distribute factual safety information on vehicles, road safety and consumer groups have taken on the role. The need for uniform test protocols is essential in the international world in which motor vehicles are marketed. From a slow start in the United States in 1978 consumer safety testing and reporting is gaining momentum internationally. In the future it is expected that the range of information available to the consumer will expand to include side impact crash test results and pedestrian collision vehicle friendliness. Consumers, manufacturers and governments have to be more active in working together to use, develop and remove impediments to safer vehicles to reduce the suffering from road accidents.

Experimental Program of Automotive Safety Assessment and Publication Activity in Japan

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ABSTRACT

This program is designed to gather information concerning the safety of automobiles and to provide this information to consumers on a regular basis to encourage them to select safer automobiles. The experimental program was designed to study problems concerning active safety and passive safety for five years. Concerning passive safety, full-frontal crash test was proved to be useful from the stand point of repeatability, discrimination, usefulness and internationality in the assessment of crash safety. As the result of this experimental program, the brochure titled *Automobile Safety Information* was published in Mar. 1996 as a trial.

BACKGROUND

The number of traffic accidents in Japan has been increasing annually in recent years. In 1988, the number of traffic deaths rose above 10,000 for the first time since 1976, and it has remained at that level ever since.

In response to this situation, the Ministry of Transport published an action plan in March 1990 aimed at advancing automobile safety measures. Part of this plan called for examining the prospects for providing safety information to automobile users. The 5th Basic Traffic Safety Plan, adopted in March 1991 established a program to provide information on automobile technical safety and promote more widespread use of safer automobiles according to their mode of use.

Since the provision of information on automobile safety represented a new strategy for accident prevention in Japan, it was necessary to examine the program's effectiveness. It was consequently decided to conduct it initially as an experimental program at the National Organization for Automotive Safety (OSA) beginning in 1991 to determine the information parameters to be provided and the procedures for testing the automobiles, provided advice and instruction by experts committee. The 6th Basic Traffic Safety Plan, adopted in March 1996 endorsed this program to be implemented by OSA.

As the result of five years examination, OSA, under the guidance of Japanese Ministry of Transport (MOT), experimentally published *Automobile Safety Information* in Mar. 1996 which included the results of full-frontal crash test with eight passenger cars in the market.

OBJECTIVES

Automobiles supplied to consumers of course conform to safety standards. A comparison of automobile models shows differences, however, in installation and performance conditions concerning safety equipment. Consumers sense that this is the case, but they lack accurate knowledge of specific differences.

Adopting an official position of neutrality, the program is designed to gather information comparing the safety of each model and to provide this information to consumers on a regular basis to encourage them to select safer automobiles. This is expected at the same time to encourage research and development efforts by automobile manufacturers concerning the construction and equipment of safer cars. As a result, besides helping to prevent accidents, this will minimize injury to occupants and pedestrians when accidents do occur.

PROVISION OF THE INFORMATION

In Mar. 1996, OSA published a brochure titled *Automobile Safety Information* as a result of five years experimental program as a trial.

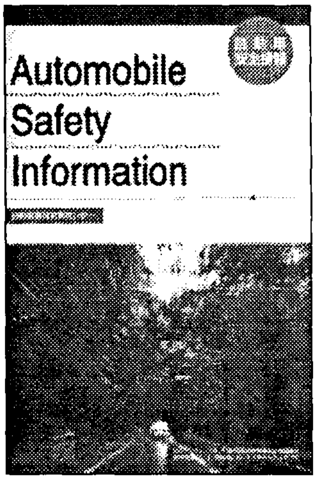

Figure 1. Published brochure titled *Automobile Safety Information.*

Contents of *Automobile Safety Information* are as follows.

Part 1:
Enlightenment of the correct usage and the effect of a seat belt as one of the most basic safety devices

Figure 2. Examples of Enlightenment of the correct usage of a seat belt in Part 1 of the brochure.

Part 2:
Introduction of the conditions of installation of safety devices ,which are normally, optionally or not installed in domestic passenger cars currently on the market

Model	Grade	Air Bag		ABS	Adjustable Belt Anchor	High-Mounted Stop Lamp
		driver	passenger			
AAA		○	○	○	◎	◎
BBB	CCC	◎	×	×	◎	◎
	DDD	◎	○	×	◎	◎

◎=normally installed ○=optionally installed ×=not installed

Figure 3. Presentation format for conditions of installation of safety devices in Part 2 of the brochure.

Part 3:
The result of braking performance test and full frontal crash test conducted on eight 4-door sedan with 1,500cc displacement engine which were selected from domestic passenger cars.

15,000 copies were printed and distributed to consumers through branch offices of OSA and local agencies of the MOT. Same contents are also introduced on OSA's home page on the Internet.(http://www.osa.go.jp/)

PRESTUDY OF CRASH TEST PROCEDURE

Prior to the evaluation test, Prestudy was carried out for deciding crash test procedure.(1)

Results of Actual Accidents Analysis

The evaluation method should reflect the actual conditions of traffic accidents in Japan. The results of actual accidents analysis on the basis of materials are as follows.

(1) The number of automobile occupants is on the increase in deaths due to traffic accidents in recent years.

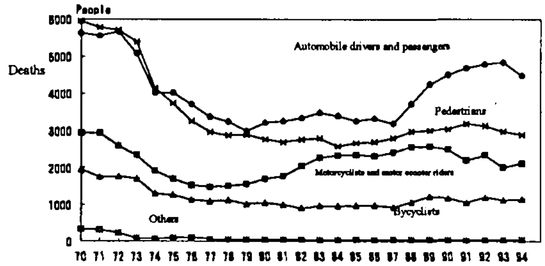

Figure 4. Trends in number of traffic accident fatalities according to victim situation. (2)

(2) Many of these deaths of automobile occupants were due to frontal crashes.

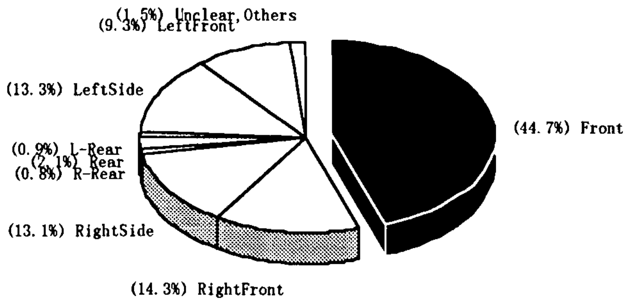

Figure 5. Distribution of traffic accident fatalities in ordinary passenger cars by Area of impact in Japan. (2)

(3) Of these frontal crashes, the most common types were full-frontal and driver's seat offset crashes, both of which accounted for about 30% of the Total.

Table 1.
Damage to automobiles in front-end crashes[3]

Part damaged	Percentage of vehicles
Entire front end	29.8%
Right two-thirds	25.5%
Left two-thirds	11.0%
Right one-third	21.2%
Center one-third	3.2%
Left one-third	9.3%
Total	100%

(4) 95% of all traffic accidents occur at a speed of 50km/h or below.

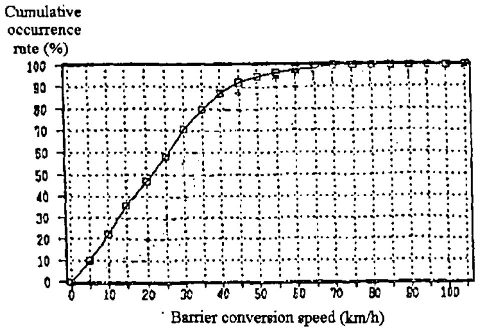

Figure 6. Cumulative occurrence rate of automobile accidents and barrier conversion speed (frontal).[3]

Necessary Conditions For Evaluation Method

Because the preparation of crash test needs considerable terms and costs, following conditions are required for evaluation test.
(1)Repeatability of test parameters - Test parameters are required to demonstrate the features in a single test.
(2)Discrimination among test parameters - Test parameters are required to discriminate among differences between features.
(3)Usefulness of test parameters - Test parameters are required to be the appropriate for evaluation and comprehensive.
(4)Simplicity of test methods - Test methods are required to be carried out easily.
(5)Internationality of test method - Test methods are required to be harmonized with overseas trends.
(6)Effectiveness of test methods in improving automobiles - The test method should be selected considering characteristics of method to improve automobile safety.

Operation of crash test for examination

Because 50-60km/h full-frontal and offset crash test seemed to be appropriate for evaluation for reasons mentioned above, 56km/h full- frontal, 50km/h offset and 50 km/h full- frontal (according to Japanese safety regulations as references) were carried out by using 22cars (2 models of 11cars).

Main specification of test vehicles are shown in table 3.

Table 2.
Main specifications of test vehicles

Specifications		Car A	Car B
Overall length		4270mm	4090mm
Overall height		1380mm	1380mm
Overall width		1680mm	1590mm
Vehicle weight		990kg	890kg
Body	Body style	4-door sedan	4-door sedan
	Drive train	FF	FF
Engine displacement		1498cc	1493cc
Seat belts		3-point ELR	3-point ELR
Air bags		None	None
Year first sold in Japan		1991	1989

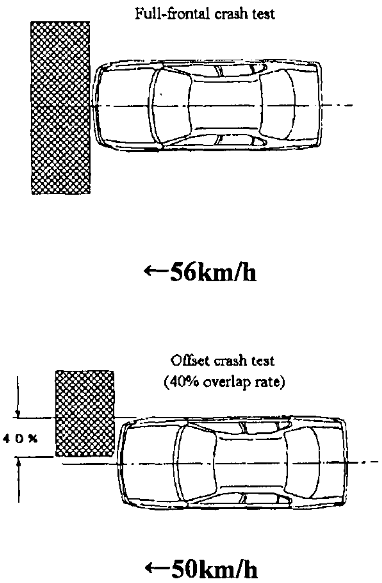

Figure 7. Crash test methods.

Examined Test Parameters

10 measurement parameters for dummy (Hybrid III) injury criteria and 10 measurement parameters for car body deformation are examined for deciding appropriate test parameter.

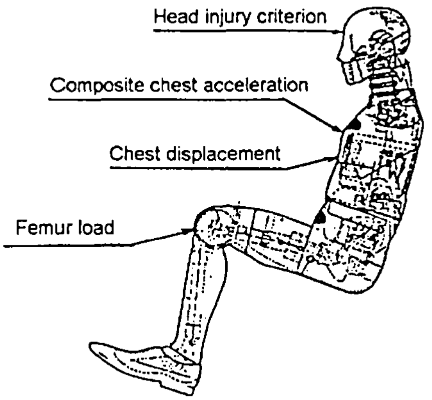

Figure 8. Measurement parameters for dummy injury criterion.

Table 3.
Measurement parameters for car body deformation.

Around doors	Pillar A
	Door striker
Inside passenger compartment	Dashboard
	Steering column
	Firewall (Driver's side) (Passenger's side)
Car body front end and engine compartment	Front bumper
	Engine block
Undercarriage	Transmission
	Frame

Results

Extract of the results of full-frontal crash tests is as follows.

HIC(driver) - Tests conducted on the five A cars produced consistent injury criteria scores. Although the HIC scores for the five B cars were somewhat more widely dispersed, they were still nearly consistent. The results for the A car and B car in the 56km/h and 50km/h full-frontal crash test were similar, and a difference between the two car types was revealed.

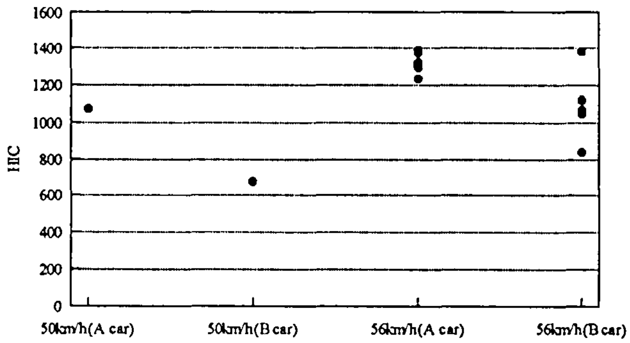

Figure 9. HIC(driver).

Chest Displacement (driver) - Consistent chest displacement results were obtained for both cars. Although consistent data were obtained, no differences were shown between the 56km/h and 50km/h full-frontal crash tests or between the results for the two car types.

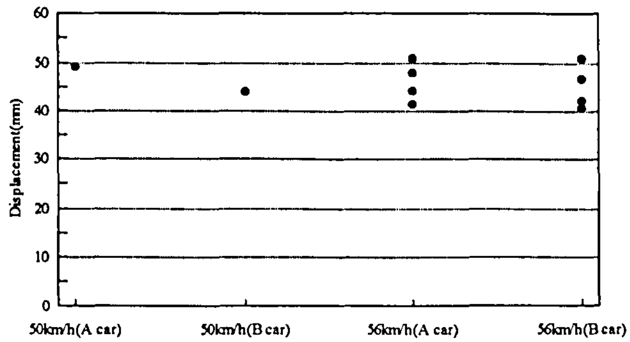

Figure 10. Chest Displacement (driver).

Femur Load (driver's right leg) - The right leg femur load results obtained for the five A cars were nearly consistent. The results for the five B cars showed a wide disparity. A difference was thus shown between the A cars and B cars.

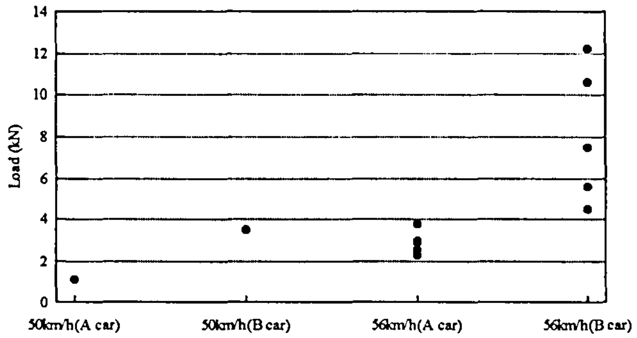

Figure 11. Femur Load (driver's right leg)

Amount of Rearward Door Striker Movement - The results obtained for the five A cars were widely dispersed. The results for the five B cars were also widely dispersed. Although the door striker moved forward in the case of A cars and rearward in the case of B cars, there was scarcely any difference between the two car types in terms of the actual amount of movement.

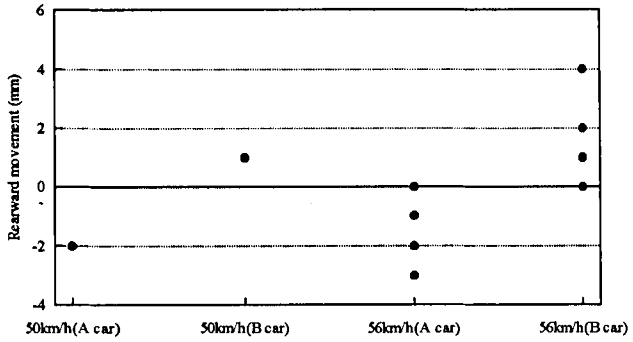

Figure 12. Amount of Rearward Door Striker Movement

Amount of Rearward Steering Column Movement - The results obtained for the five A cars were nearly consistent. The rearward movement in the five B cars was also consistent. There was thus a clear difference between the two car types, with the B cars showing greater rearward movement.

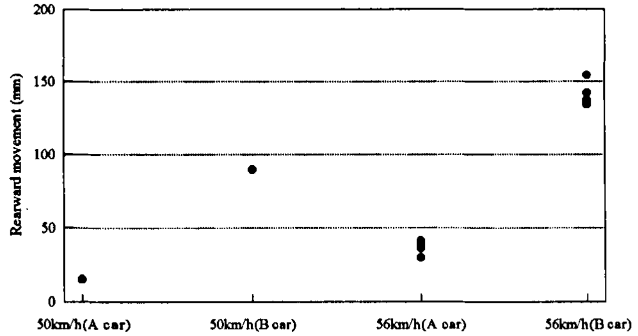

Figure 13. Amount of Rearward Steering Column Movement

Amount of Rearward Dashboard Movement - The results obtained for both car types in the test, were nearly consistent. There was thus a clear difference between the two car types, with the B cars exhibiting greater rearward dashboard movement.

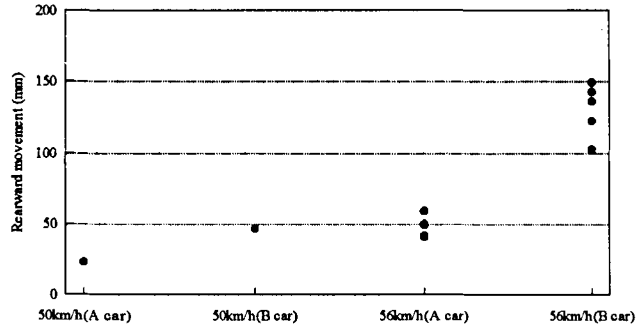

Figure 14. Amount of Rearward Dashboard Movement

Conclusion

As the result of examination, full-frontal crash test method was proved to be appropriate for evaluation by reason that there was no problem in its implementation, its international position was clearly established by actual result of NCAP in the U.S. etc. and it could be expected to lead to improvements in restraint systems and car body structures. Two information parameters were proved to be appropriate for dummy injury criteria, HIC and composite chest acceleration. As concerns car body deformation, the parameters of rearward steering column movement and rearward dashboard movement were proved to be appropriate for being offered on the particular occasion in which a considerable loss of survival space was appeared.

CRASH TEST FOR EVALUATION IN FY1995

Test Method

As the result of prestudy, full frontal crash test at 55km/h into a rigid barrier using Hybrid III dummies (AM50) was adopted in this program for evaluation. Test method was adjusted to that of Japanese safety regulation except the speed at the time of collision .The speed at the time of collision was modified as 55km/h, which is 10% faster (21% increasing of kinetic energy) than the speed specified in Japanese safety regulations (50km/h).

Test Parameter

Head Injury Criteria(HIC) and Composite Chest Acceleration of driver and front seat passenger were adopted as test parameters. The parameters of rearward steering column movement and rearward dashboard movement were offered when a considerable loss of survival space was appeared.

Test Vehicles

Eight passenger cars of 4-door sedan with 1,500cc displacement engine, which were the best sellers of each domestic car manufacturers in this category, were selected as test vehicles in order to cover the car sales share as much as possible. Safety devices which were able to equip optionally were all installed, encouraging the purchaser to select safer vehicle.

Evaluation Method

Injury Risk - Because the purpose of this program was to introduce the test results to general vehicle

purchasers, an unique simplified method in four degrees was adopted to evaluated injury risk of driver and front seat passenger in this program as follows.

A: There is little possibility of serious damage to both head and chest.
B: There is slight possibility of serious damage either to head or chest.
C: There is slight possibility of serious damage to both head and chest.
D: There is possibility of serious damage to head and/or chest.

Result of Crashworthiness Test for Frontal Collision(55km/h)	
Injury Risk	
Driver	Front Seat Passenger
[A] [B] [C] [D]	[A] [B] [C] [D]

Figure 15. Presentation format for injury risk in Part 3 of the brochure.

The categorization for four degrees were based on particular values of HIC(1000), composite chest acceleration (60G-3ms) and dispersions of each.

At the same time , the detail data of each tests were provided to the specialists who have enough knowledge to analyze it according to their request.

Other Evaluation Factor - Conditions of dummies while colliding and broken/deformed vehicles, availability of door opening and rescue/remove of dummies and fuel leakage after collision were also mentioned.

Attention to compare the results

The results of the crash test can be compared with each other only in case of the vehicles whose weights are in a same degree.

Therefore, attention was expressed in published brochure.

Test Results

Concerning the injury criteria, five of eight cars were evaluated as **A** for both driver and front seat passenger, and three cars were evaluated as **A** for driver and **B** for front seat passenger.

No remarkable result was obtained for the evaluation factor other than injury criteria.

FUTURE PLAN

In spite of the publication of "*Automobile Safety Information(Mar. 1996)*" was a trial, the response from the consumers and mass-media was strong enough to encourage the enforcement of the program. It seems to reflect the increase of the interest of the consumers concerning the safety of the automobiles.

This Automotive Safety Assessment and Publication program is now planed to be annual enterprise after additional examination about the implementation of the program.

REFERENCES

(1)Naito,M, "008 Experimental Program of Automotive Safety Assessment Activity in Japan",IPC-8, Yokohama Japan, Nov. 1995.
(2)Institute for Traffic Accident Research and Data Analysis "Analysis of Automobile Driver and Passenger Deaths and Injuries(1994)"
(3)Japanese Ministry of Transport "Survey and Analysis of Automobile Structure and Equipment(1991)"

United Kingdom - New Car Assessment Programme (UK-NCAP)

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ABSTRACT

The United Kingdom is carrying out a study into the feasibility of using the European Experimental Vehicles Committee (EEVC) test procedures for frontal and side impact and pedestrian protection to provide consumer safety information. The first group of tests has just been completed and the assessment is now being made. The study will consider the validity of using data from crash tests to provide reliable, objective consumer information.

The ways in which crash test data might be assessed and supplied to the consumer, in a understandable format, is being studied and the need for such programmes to be extended more widely and harmonisation is discussed.

INTRODUCTION

The realisation that safety is becoming increasingly important to consumers has led car manufacturers to add safety features to their cars and to promote them in their marketing campaigns. Although consumers are increasingly requesting information about safety, it is difficult to provide them with the information they need to help with their choice of car. With all manufacturers making similar claims for their products, consumers find it difficult to judge the level of protection offered by different car models.

In the USA, NCAP has led to improved frontal impact protection for cars sold there. But these improvements have frequently not been incorporated in the same car models sold in Europe, or some other parts of the world. This was detected in Australia, by their NCAP and it brought about a change to some of the cars imported there.

On behalf of the UK Department of Transport, the Transport Research Laboratory has embarked on research into the feasibility of adopting a New Car Assessment Programme for the UK. Like programmes carried out elsewhere, UK-NCAP research is aimed at providing reliable, objective safety information to help consumers choose their cars. The results of the UK-NCAP will be published, but the identification of the car models will depend upon the Department of Transport's view about the ability of the programme to provide a fair and meaningful comparison of the different car models.

TYPES OF CONSUMER INFORMATION

Three types of car safety consumer information exist. Each has its advantages and disadvantages. Expert examination can provide information about the presence and quality of safety features, fitted to the car, and it can identify likely hazards, which accident experience has shown to cause injuries. The inspection can be carried out at the time the car is first sold and the reasons behind a car's rating can be detailed. However, inspection schemes cannot show how the car actually performs in accidents and the assessment of how a car's structure will perform is difficult.

The second method relies on accident data to provide information about how the car actually performs in accidents, in comparison with others. Unfortunately, such analyses cannot be carried out until the car has been in use long enough for sufficient accident cases to be available. It has the advantage of showing how well the car actually performs in the wide variety of accidents which occur, but it does not show why a car performs as it does. For analyses of this type to be valid the influence of other factors, such as driver behaviour, must be removed.

The third source of information is from full scale or component crash tests. These can be carried out as soon as the car is introduced to the market and have the benefit of showing why the car performs as it does, in the crash configurations used. The more representative the tests are of how cars have to perform in accidents, the better the test results will indicate the cars' true safety performance. Information from the test can be used, by the car designer, to identify how the car needs to be improved.

Information from these different methods compliment each other, they can all inform the consumer and the car manufacturer. There is good evidence that the manufacturers respond to consumer information by improving their cars and that this is reflected in road accident casualties.

Consumer information crash testing was started in the USA, with their New Car Assessment Programme (NCAP). More recently, NCAP programmes have been developed in Australia and Japan. In Germany, Auto Motor und Sport magazine and the ADAC have both developed

test programmes, as have the Insurance Institute for Highway Safety, in the USA. In Europe, the consumer organisations have their programme. Its start was helped by TRL, with funding from the Department of Transport.

AIMS OF THE UK-NCAP

The UK-NCAP research will study the feasibility of providing reliable, objective, and meaningful consumer information, from full scale frontal and side impact crash tests and component tests for pedestrian protection. It is intended that this should provide consumers with safety information which can help in their choice of car. This should also influence manufacturers to improve the safety of the cars they sell. Such information should compliment the comprehensive information already available to consumers about performance, fuel consumption and reliability.

Already, we know that manufacturers are being influenced by the programme, with some of them improving their cars in anticipation of being tested. The programme should provide manufacturers with a continuing incentive to improve the safety of their cars, beyond the base level required by legislation. It should also provide support to safety engineers, when they need to justify the use of resources to improve safety, in competition with the demands of others wishing to fund the development of other aspects of car design. For those manufacturers who wish to emphasise safety, it will provide recognition of their efforts. With all manufacturers making similar claims for their cars, there is no other means by which a manufacturer can show the results of particularly good work.

In addition to these direct benefits, the programme will help to provide information for the reviews of the new European directives for frontal and side impact. It should also help to support the move for a directive for pedestrian protection.

CONSUMER INFORMATION AND LEGISLATION

In Europe, past improvements in vehicle safety have been brought about by legislation or by the manufacturers' voluntary efforts. However, relying on legislation or manufacturers' initiatives will not lead to a high standard of safety. The test procedures, developed for legislation by the EEVC, are amongst the best available. They have been researched and validated more than earlier test procedures and this process has taken many years to complete. During this time, few manufacturers have taken the opportunity to use the procedures to develop their cars. They normally wait until legislation is imminent, before trying to meet the requirements. Manufacturers committed to improving safety could have built to the new requirements much earlier.

Relying on legislation, with infrequent updates, means that safety improvements will always lag well behind current knowledge. Legislation brings about a step change at the time of its introduction, after which, there is no further requirement to improve. Furthermore, the requirements have to be sufficiently easy, for all manufacturers to be able to meet them from the introduction date.

As consumer information tests have no pass/fail criteria, higher standards can be set and manufacturers are encouraged to make continuing improvement, as their knowledge develops. There is no compulsion for manufacturers to improve their cars, but market forces encourage this. Those improvements made can be timed to suit the manufacturer's design schedules.

CHOICE OF TEST PROCEDURES

For this research, it was decided that each of the most important accident types should be addressed. This was the same reason behind the EEVC's development of test procedures for frontal and side impact and pedestrian protection. Each of these test procedures were designed to influence car design, so that a large proportion of accidents would benefit from their effect.

Car occupant frontal impact is the major road accident problem, and for car occupants, side impact is the second priority. In the UK, pedestrian protection is second only in importance to that of car occupants. It will become increasingly important elsewhere, as car occupant casualties rates fall. The major source of pedestrian injuries comes from being hit by the front of cars. The EEVC procedure addresses such accidents.

For frontal impact, a test speed of 64 km/h was chosen. This choice was based on accident evidence, which indicated that protection against fatal and serious injuries was necessary in accidents with a velocity change of 64 km/h and over. With the deformable barrier absorbing some of the impact energy, the test speed of 64 km/h is actually equivalent to a lower velocity change in a car to car impact. Comparative tests, with one modern car, showed that testing at 64 km/h was less severe than a car to car crash at 56 km/h. Even so, a test at 64 km/h is still quite severe.

The severity of the side impact test not been increased, above that proposed for legislation. Side impacts are complex and no research is yet available to show how adequate protection can be provided at higher speeds or with an increased barrier ground clearance.

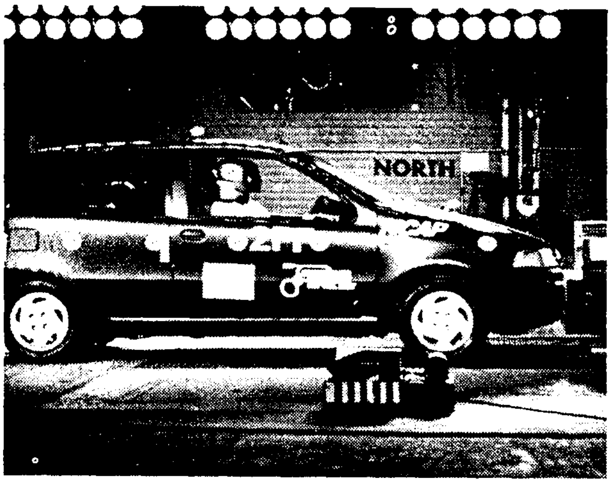

Figure 1. Frontal Impact Test.

Figure 2. Side Impact Test

For pedestrian protection, legislation has still to be formulated and few car manufacturers have started to work with the proposed EEVC procedure. This is designed to protect at up to 40 km/h. At higher speeds, the pedestrian tends to be thrown over the car, receiving more severe injuries from hitting the ground, so improving the car for such speeds may be of limited value.

In the frontal and side impact tests, a child restraint is being fitted. This does not affect other aspects of the tests but should encourage car manufacturers to pay greater attention to the quality of child restraint provision. The child restraint used is the one recommended by the manufacturer, currently, for a three year old child. Already, it has been found that a recommended restraint could not be fitted properly in the car. An assessment is also being made of the vertical and horizontal adjustment of the head restraints.

In summary, the test procedures used in the first group of UK-NCAP tests are:

Frontal Impact

Forty percent overlap impact into an EEVC deformable barrier at 64 km/h (Figure 1)
Two Hybrid III dummies with enhanced instrumented legs and 45° ankles, in the front seats
An un-instrumented three year old dummy, in a child restraint, on the passenger's side rear seat

Side Impact

EEVC side impact test, on the driver's side of the car, using a TRL/Cellbond honeycomb barrier face (Figure 2)
One EUROSID dummy, at mid seating position, in the driver's seat
An un-instrumented three year old dummy, in a child restraint, on the passenger's side rear seat

Pedestrian Tests

Child and adult headform tests to the bonnet top head impact areas (Figure 3)
Upper legform tests to the bonnet leading edge
Legform tests to the bumper area

One car is used for the frontal impact and a second car is used for the pedestrian tests and subsequently the side impact test.

THE FIRST TEST GROUP

The first group tested consists of seven models of car in the super mini class. Economic constraints have prevented the testing of all the available models in the size category. The choice of cars to be tested was largely based on sales in the UK and throughout the rest of Europe. Usually, the most commonly sold variant was chosen and some attempt was made to standardise on options which might affect the cars' performance. All the cars were right hand drive, had two side doors, steel wheels and were

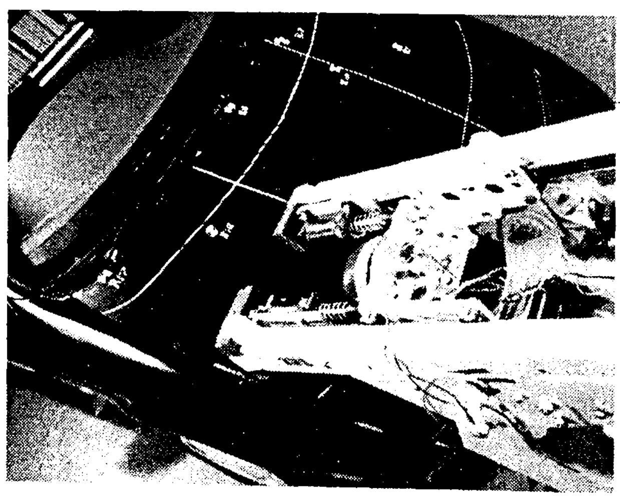
Figure 3. Pedestrian Headform Test

equipped with a driver's airbag. The car models tested were: Fiat Punto, Ford Fiesta, Nissan Micra, Renault Clio, Rover 100, Vauxhall Corsa and VW Polo.

INVOLVEMENT OF THE MANUFACTURERS

Some organisations invite the manufacturer's representatives to witness their tests, others conduct them in private. In this programme, manufacturers were invited to send two representatives to witness their tests. This proved useful, as the manufacturers' representatives were able to satisfy themselves about detailed aspects of the setup and, where necessary, update information supplied earlier.

Each manufacturer was asked to provide data they might have from similar tests. This was to help ensure that the UK-NCAP tests were representative of what could be expected of that car. Some manufacturers supplied such data, others agreed to share their data later. All agreed to compare what they could and advise us of any anomalies. To date, no manufacturer has advised us that our tests showed anything unexpected or that our data are very different from their own. In all cases, the manufacturers' representatives expressed their satisfaction with the test set up. When the programme is complete, each manufacturer will be given the opportunity to meet and discuss the results of the tests on their car. Any comparative data supplied by them, will be used solely to check on the validity of the UK-NCAP test. It will remain confidential to them and will not be used in the assessment.

At a later date, the manufacturers' representatives will be given the opportunity to view all the cars in the group. This should help them to see how their cars compare with those from other manufacturers.

ASSESSMENT

It is important that the parameters used for assessing the performance of the cars are scientifically based. In the frontal and side impact tests, data from the instrumented dummies will be used in the assessment and for frontal impact this will be supplemented by additional information. Intrusion data can help to show how well different sized occupants, in different seating positions, would be protected. Hazards for small occupants, seated near the facia and large occupants requiring more space can be identified. Such information can also help to compensate for inadequacies in the dummies' ability to assess all the injury risks. With all the cars being equipped with airbags, the dummy trajectories are important. They can help to show how well the seat belt restrains the occupant and how the occupant contacts the airbag.

For side impact, the assessment will be mainly based on information from the dummy. Research has shown that intrusion is a poor indicator of protection. Similarly, for the pedestrian tests, data from the bodyform impactors will form the basis of the assessment.

After the test, each car is carefully inspected and measured and the ease with which the doors can be opened and the dummy extracted is checked. Those parts of the interior which have been contacted by the dummy, or which could easily have been contacted, are examined to help understand why a particular dummy reading was obtained and to determine how sensitive that data might be to small variations in dummy positioning and impact configuration. In using dummy derived information, the limitations of the dummies, to reproduce human behaviour, will be taken into account. This will limit the extent to which such aspects as dummy trajectory can be used.

The test procedures were developed to give good repeatability. Statistically, it is very unlikely that manufacturing variations will combine together to make a particularly good or bad car, as far as all the assessment parameters are concerned. By basing the assessment on multiple parameters some of the problems caused by variations in build quality or test set up will be overcome. In making the assessment, care will be taken to ensure that different performance ratings represent real differences in injury risk.

The UK-NCAP tests are being carried out in groups, with each group being limited to a size category. This obviates the difficulty of comparing cars of widely different size. At present too little is known about how comparisons across size category can be made satisfactorily. This problem should be mainly confined to frontal impact, where mass and size can affect the outcome. The frontal test simulates a car hitting another car of similar mass. In accidents, large cars benefit from most frequently hitting smaller cars whilst small cars have the disadvantage of most frequently hitting cars larger than themselves. Size should have a much smaller effect on side impact or pedestrian impact performance.

PRESENTATION OF FINDINGS

For consumer information to be useful, it is necessary that the consumer can understand it and use it when choosing a car. The easiest format for the consumer is probably for the cars to be ranked in order or groups, with some associated indication of safety or injury risk. This can provide the consumer with a "best buy" option. Such an approach may be possible with a single test configuration but becomes more difficult when multiple configurations are considered. It is unlikely that the ranking orders for frontal, side and pedestrian impacts will be the same. An

overall ranking could be made, using some form of weighting. This might be based on the relative importance of the different accident types. However, the validity of such an approach might be difficult to establish. Even within test configurations, there are problems where comparisons have to be made between criteria which relate to threat to life with those which relate to disability.

The opposite extreme would be to detail all the test results with an indication of the levels normally considered acceptable. The consumer could then be left to make his own judgement, on the basis of what interested him most. Such an approach assumes a much greater expertise, on the part of the consumer, who might become confused by the information and ignore it.

There is no obvious best way of providing the information in an objective way that the consumer can understand. What is simple and understandable for some, will lack sufficient detail for others. A compromise might be to provide an overall ranking or grouping for each test configuration, with a breakdown for the major parameters or body regions, and to append the detailed data for those who want it.

FUTURE EXPANSION AND HARMONISATION

Various impact configurations and assessment methods are currently used in consumer tests. Although the need for manufacturers to meet a number of different requirements may aid safety, there is the potential for consumers to become confused and there may be unjustifiable costs to manufacturers. If cars start to be given conflicting ratings by different organisations, the overall credibility of consumer testing will be damaged and consumers will be confused. To obviate this, there is a pressing need to harmonise at least some elements of the test procedures and the assessment methods used. This will not be easy, each organisation can be expected to defend their own procedures. With increased harmonisation, results could be shared and manufacturers costs would be reduced by having fewer tests to carry out and a clearer goal to aim for.

The need for a new car assessment programme for Europe is gaining support. The cars sold in Europe should be amongst the safest available. The UK has chosen test procedures based on those developed by the EEVC because they are well founded. They could also be used to form the basis of a wider European programme. However, harmonisation within Europe alone is insufficient. Extending that harmonisation throughout the world should lead to car safety worldwide being raised to the same high standard. It might also help moves towards more globally harmonised legislation.

CONCLUSIONS

Following the lead of others, the UK is researching an NCAP procedure. There is good evidence that consumers want better safety information and that consumer testing leads to improved car safety. Europe is behind at present and it is important that cars sold in Europe are amongst the safest available. For the future, wider harmonisation has much to offer. It would allow data to be shared and reduce costs for manufacturers.

Experience with testing modern cars will also provide valuable experience, which can be used to help inform the reviews of the new European directives for frontal and side impact protection and support moves for a directive for pedestrian protection.

ACKNOWLEDGEMENTS

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CRASHWORTHINESS TESTING AND RATING FROM THE CONSUMER PERSPECTIVE, AND IN RELATION TO THE VISION OF ZERO DEATHS IN ROAD TRAFFIC

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ABSTRACT

The potential of increased occupant protection in cars is large with a possible reduction of deaths and disabilities of more than 50%. Increased protection is also a strategic area for the gradual implementation of the Swedish 0-goal, that is the goal of zero fatalities in the road transport system.

The possibilities to manage a further development of crashworthiness by simply a legislative process is limited, especially in Europe, and it can be estimated that the distance between the levels in vehicle regulations and best practice is 20 years. This is mainly because the technical development is driven by market forces, while the legislative process is not.

Such a process must be fed by adequate information about important differences between products, as well as possible solutions.

In this presentation, it is claimed that such information, partly derived from crash tests, must be dynamic in the sense that criterias and test methods must be changed gradually.

The Swedish approach to consumer information is presented, like Swedish NCAP, as well as the EURO-NCAP activities.

Background

The difference between individual car models in crash protection is large. From real life accidents it has been found, that the magnitude of these differences is in the region of 1:10 regarding life threatening and disabling injuries. These differences are partly attributable to weight of the vehicle, but for cars of the same weight, differences of up to 1:5 can be found. Among cars introduced in the 80-ties and the 90-ties, the safety level has improved, and especially for cars newly introduced, the risk of fatal and severe injuries has decreased dramatically, or in the order of 30%. The passive safety of cars is therefore one of the major instruments to eliminate health losses in road transport.

The reduction of injury risk in cars has been achieved by many factors that have encouraged technical development, but the main explanations are safety regulations and public demand for more crashworthy cars.

In order to strengthen the demand for safer cars, and to encourage the car industry to compete in the safety area, crashworthiness rating has been commonly used. There is a variety of methods and ways to use the results. In this paper the ideas behind rating and the methods used are described and discussed.

Passive safety and the vision about zero health losses in road traffic.

Recently, a new approach to traffic safety has been introduced in Sweden. In order to make it clear that road accident health losses are not acceptable, a vision about zero serious health losses has been formulated. In this vision, no possible accident is allowed to generate a higher accident severity than the biomechanical tolerance for a fatality or an impairment of the human. This approach has a major impact on the passive safety of vehicles. The increased passive safety of vehicles is a possibility for the industry to increase the attractiveness of the road transport system. If the car industry does not develop the safety of the vehicles, speed limits and other restricting measures will be sharpened. This is an overall market driven process, where there is a link between the passive safety of vehicles, and the way that they are used. The overall ability of the car industry to produce safer cars is directly linked to the future design of the road transport system and it will become clearer to the industry what is expected.

The role of crashworthiness rating

Crashworthiness rating is important from different aspects. Basically, it is worthwhile to encourage rating if:
- There is a distance between the level of safety stipulated in regulation and the current best practice, and there are important differences between different car models on the market.
- There is a possibility to develop the passive safety level beyond best practice.
- There is a need for detecting failures in the passive safety.

It is clear that all three aspects have been found realistic. There is, especially in Europe, a large distance between current safety regulations and the safety of vehicles sold today, but to a different degree for individual car models. There are also areas where technical solutions are possible, but have not yet been introduced.

Published failures has also been a major concern for the industry, where even major recall programs have been generated by findings in rating.

There are also other aspects on crashworthiness rating such as for whom, and for what purpose the rating is conducted.

Normally, crashworthiness rating is an instrument to help the consumer to choose a safer car. This is a way to encourage passive safety as an area for competition for the car industry, thus driving the process of increased safety further.

Rating the passive safety can also be an instrument from the society perspective, creating the best possible population of vehicles from the total safety point of view. This is quite different from the single consumer perspective, where the safety for the individual is focused, even if a possible collision partner can be at a higher risk. This problem arises when the consumer is guided towards heavier cars, that because of the mass relations in a two car collision, is favourised and the opponent is at higher risk. From the society perspective, it is, however, quite different, in that it is the sum of all injuries that should be minimized, and in a situation where i e economic incentives is to be used, the best possible situation might be slightly lighter cars for all, and not as many heavy cars as possible.

From a more general perspective, it should, however, be clear that the consumer rating is a strategic instrument for creating a process. While regulations are more and more complicated to enforce, as they are normally subject to a variety of aspects and are not enforced until a reasonable level of agreement has been reached, market forces will act much faster, and with only parts of the market and consumers demanding better protection. Treating the consumer rating as a complement to regulations, where regulations stipulate the minimum level of protection and rating as the tool for targeting the maximum level of protection, much attention should be paid to methods and ways to firmly direct the process.

One other question that must be dealt with is how tests and test results are performed and presented according to how sensitive and specific they are. Consumer testing is by definition for the benefit of the consumer. Of course tests and presentations should be as serious and clear as possible, but it is more unfair to have a situation where the "predicted" result is good, while the vehicle in fact was poor, than vice versa. To be "unfair" to the industry is to the consumer of low interest compared to be "unfair" to the consumer. Furthermore, reading instructions must be clear in the sense, that one negative outcome from a test is enough to guide the customer to choose a certain car, while a positive result is not a guarantee for a car performing well overall.

Different types of rating systems

Retrospective rating - Retrospective rating is based on accident statistics and can, if desired, be generalized to the whole accident population. This type of rating is sensitive to if the problem of exposure is solved in an adequate way. The fact that different cars are driven by different populations must be handled in a way that the safety of the car is measured, and not the users population. One method used is the paired comparison, where two car accidents are used.

The main drawback with the retrospective rating is the time lag between the introduction of a new car and accidents occurring to a sufficient number allowing statistically sound figures.

Predictive rating - Predictive rating is by definition not based on real life accidents. Crash tests are often said to be predictive rating, but is must be questioned if this is possible on the basis of one or few tests. The possibility to generalize single crash tests to the whole population is very small, unless the test results can be said to give the overall safety level of a vehicle.

There are however other methods that can be said to be predictive rating, One such method is technical inspections where different technical solutions are given weights that are supposed to be chosen in a way to give correct predictions in real life accidents.

Rating aiming at driving the process against safer cars - Crash tests are more adequate in this category, where the aim of the rating is to focus on a certain area to compare different car models in a certain aspect, such as frontal or side collisions. The test method is not necessarily a "representative" test (In fact, it is not possible to construct such a test), but instead a test that will focus on an area where cars are known to produce results that varies substantially, and is important for consumers. Therefore, such tests can direct towards special areas, such as luggage retention, CRS, rear seat occupants in mid rear etc, that is, areas that are important under special circumstances. Other such ratings can be lists of features.

Areas of development for consumer testing

The methods for driving the process further by testing and rating cars have mainly focused on frontal impacts to barriers. Some efforts has also been done in the area of lateral impacts. There are also some examples

of special areas, such as luggage retention. The variety of accident configurations and occupant populations asks for development of more and varied areas of rating. This becomes increasingly important as the consumers and the industry reacts on new safety aspects. If the consumer rating shall play an important role for really improving real life safety, reliable test methods must be prepared in order to have the possibility to meet new demands. One area of special interest is neck injuries in rear end impacts. Such injuries are often life lasting and therefore severe. The knowledge on injury criterias is limited, but it is well known that it is not the presence of a head restraint, or the height of it, that is important. New rating methods must be developed soon to help the consumer and to guide the industry in the right direction. Other areas are rear seat occupant protection, luggage retention, CRS, rollover protection, compatibility etc.

The "Swedish" approach

The "Swedish" approach to rating is that it is a meaningful and important tool to create a market for safer cars. The rating approach in Sweden is to publish both retrospective rating as well as predictive and crash tests. The method of "self-declaration" made by the industry will also be used, where the single car importer will be given the opportunity to declare if the car passes some well defined crash tests. Such a method is a cost/effective way of gaining information on a large number of cars.

The information to the consumers will be passed on by the media and by special reports made official. Other ways to implement rating results is to inform fleet buyers about the benefit of choosing safe cars. Customers of these cars, i e rental cars, will also be informed to choose safer cars. The possibility to integrate taxes on cars with safety will be further analyzed.

During 1996, a number of mid sized cars will be tested according to the forthcoming EUdirectives on crash protection in frontal and side impacts as well as pedestrian protection. The frontal tests will be performed in a higher velocity then the proposed directive (64 kmh instead of 56kmh) while the other tests will be driven according to the directives. The program is known under the name EURO-NCAP, where Sweden will take part.

Regarding the future, the intention will be to test cars according to the "0 goal", where it will be specified a number of situations where the car is supposed to meet the road furniture in a number of situations, and also other vehicles. In the "0-vision", a possible accident is not supposed to give a higher injury than the level of a serious health loss", means that if an accident can happen at a certain velocity and other circumstances, the crash protection must be designed in a way that a specified level of injury criterias is met. The target car can be defined, and the available cars on the market can be rated according to this target car. A Swedish NCAP might in the short run be a car to car impact where one car model collides with itself.

In the long run, the total ability of the car industry to market more crashworthy cars will be the limiting factor for the rest of the road transport system. If the industry fails in this part, the road user will have to take the burden for creating a road transport system with no serious health losses.

SUMMARY

The market process has been the key factor for the rapid improvement of the crash protection of cars during the 90-ties in Europe. Such a process is fed by adequate information about the performance of different products, and the possibility to improve the safety. During the 90-ties, the consumers have increasingly asked for better safety, giving incentives for a competition between car manufactures, that have in most areas been positive for the consumer. Such a process must continue as long as there are meaningful improvements to gain.

The idea about constructing an "overall" best test for predicting the passive safety of a car must be questioned in that it may hurt the general idea about rating.

The Swedish strategy is to give the consumer a number of possibilities to judge the car, but it is important to have an ongoing process in changing rating methods into areas where new challenges for the industry can be found. Otherwise, an objective to compare "over time" and have identical methods can be overrun by technical improvements and that new areas for protection are not covered. Very soon, methods for compatibility, neck injuries in rear end impacts, CRS, roll over etc must be found and used for rating and consumer information.

The idea about "zero-vision" must cover also the passive safety of cars, where "zero health loss cars" are defined and tested according to such a concept. In a sense, the "zero-vision" is also a market driven process, where it is up to the industry to increase the attractiveness of the road transport system by better protection and not let the road user take the whole responsibility to stay alive, by being more restricted by lower speeds limits etc.

REFERENCES

Krafft M, Kullgren A, Lie A, Nygren Å, Tingvall C. Car model safety rating based on real life accidents In: Pro ceedings of IRCOBI Conference 1991:25-40.

Gloyns PF, Rattenbury SJ, Kullgren A, Lie A, Tingvall C, Edwards J, Hill R. The correlation between the Consumers' Association rating system and the Folksam car safety ratings. In: Proceedings of IRCOBI Conference 1991: 49-60.

Kamren B, v Koch M, Kullgren A, Lie A, Nygren Å, Tingvall C. Advanced accident data collection - Description and potentials of a comprehensive data collection system. In Proc Experimental Safety Vehicles Paris 1991: Vol 1:41-45

v Koch M, Kullgren A, Lie A, Tingvall C. Car model safety rating - Further development using paired comparison method In Proc Experimental Safety Vehicles Paris 1991: Vol 1:78-83.

Kamren B, Kullgren A, Lie A, Sköld B-Å, Tingvall C. Side protection and child restraints - accident data and laboratory tests including new test methods. In Proc Experimental Safety Vehicles Paris 1991: Vol 1:341-345.

Hägg A, Kamren B, v Koch M, Kullgren A, Lie A, Malmstedt B, Nygren Å, Tingvall C. Car model safety rating 1991-92. Stockholm 1992 and Proc of Comparative Crash Tests within the EU 1993.
ETSC Consumer rating of passive safety of cars. Brussels 1996.

TEST AND RATING METHODS TO QUANTIFY THE PASSIVE SAFETY OF CARS

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ABSTRACT

In 1987 motoring clubs in Europe integrated crash testing in their consumer protection programme. Since that time more than 100 frontal, side, rear impact and rollover crash tests have been carried out. Alongside this work, the clubs have developed a rating system to evaluate the performance of passive safety based on crash test results and real life accident statistics.

In order to achieve the aim of obtaining the broadest possible range of information, the clubs' rating system is not restricted to dummy measurements, but also takes into account all parameters affecting passenger injuries related to the cars' assembly groups.

Further evaluation calls for the test results to be converted into assessment grades. This is done by using suitable rating scales, which are based, on the one hand, on state-of-the-art engineering and, on the other hand, on the generally recognised threshold values.

The rating system has been worked out predominantly for frontal and side impact and delivers both, total injury risks to the occupants and injury risks to body parts like head, neck, thorax, arms, abdomen, pelvis and legs.
The resulting information gives the consumer a reliable guide to the injury risks and the safety performance of each car's relevant components.

INTRODUCTION

With the view to get realistic evaluation on passive safety for consumer information one needs quantitative evidence on

injury risks for the occupants
occupant rescue
protection for the opponent vehicle occupants.

This information must at least cover the most frequent injury relevant situations of real life accidents. In order to gain such information from laboratory tests above all full size crash tests have to be carried out. The essential data to select the most suitable procedures can be generated by accident statistics. On the basis of this statistics four different types of collision can be distinguished:

1. Front impact	(49% ... 37 %)
2. Side impact	(43% ... 34 %)
3. Rollover	(6% ... 28%)
4. Rear impact	(2 % ... 1%)

The figures in parenthesis represent the frequency of casualties of the individual collision types expressed as percentages ([1] ... [2]). They give a first measure for the significance of these individual collision types with regard to total safety (the figure 28% for rollover includes 1/3 non belted occupants [2]). To get sufficient evidence it is necessary to decide for test procedures which cover as far as possible all collision types, or at least frontal and side impact collisions.

Crashtests generate a lot of individual data. For quantifying passive safety it is essential to use an appropriate rating system for condensing this data to a few figures, which can be easily understood by the consumer.

The most suitable test and rating procedures for producing consumer information on passive safety will be presented and described below.

TEST METHODS

Front Crash

As for all other collision types it is also not possible for front impact to cover the whole variety of real life accidents by a single laboratory crash. At least three test procedures seem to be of first rate importance:

1. The car to deformable barrier test with an offset, predominantly to gain information on vehicle structure performance and intrusion of vehicle parts, both for occupant and opponent vehicle occupant protection.

2. The car to rigid wall test with 100% overlap, predominantly to examine the restraint systems.

3. The car to pole test to simulate the most frequent single car accident.

In respect to the costs it will often be necessary to restrict the investigation to a single test per car model. In this case it is proposed to carry out the procedure car

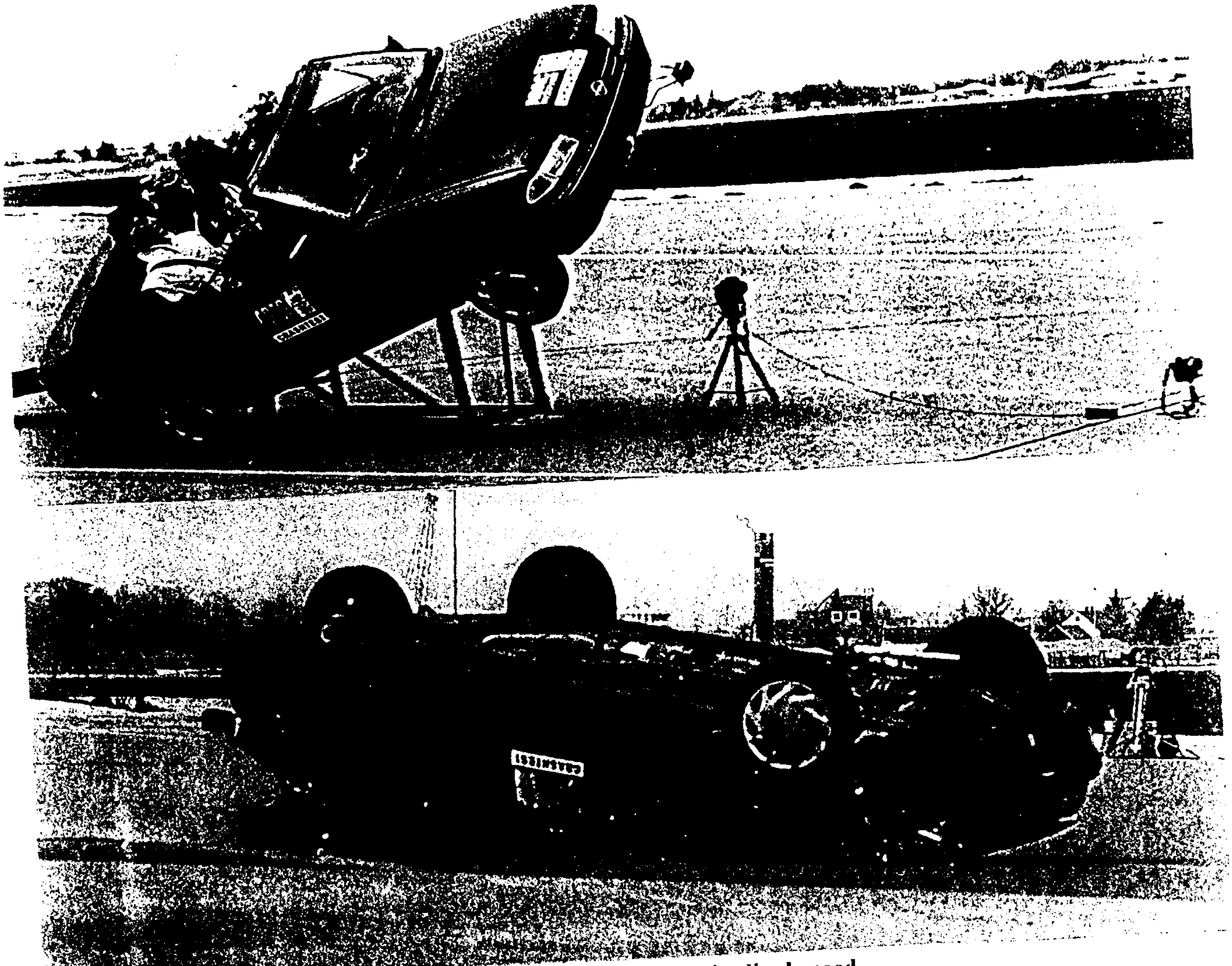

Figure 1. Rollover test should be carried out with 70 km/h longitudinal speed

to deformable barrier, since this test covers the largest part of the real life accident spectrum.

According to [3] the following test configuration seems the most appropriate:

* impact speed 60 km/h
* modified EEVC barriere (three stage honeycomb body)
* Hybrid III dummy, at least on driver and rear seat position
* luggage simulation with two 18 kg wooden cubes following DIN 75410 part 2

Side Impact

Here the following procedures are essential:

1. The 90° mobile barrier impact to the standing test vehicle as a simulation of a 90° car to car crash

2. An angled impact to the standing test vehicle simulating an intruding vehicle corner

3. The 90° pole impact to the standing test vehicle as a simulation of a single car accident

Again, if there is only the possibility to carry out a single test per car model . the 90° barrier test is proposed. According to [4] the procedure should follow EU standard with the features

* 50 km/h impact speed
* three stage honeycomb barriere with 3 mm precompression, characteristic after EU standard
* Eurosid dummy, at least driver and back seat passenger on impact side
* barrier ground clearance at least 300 mm

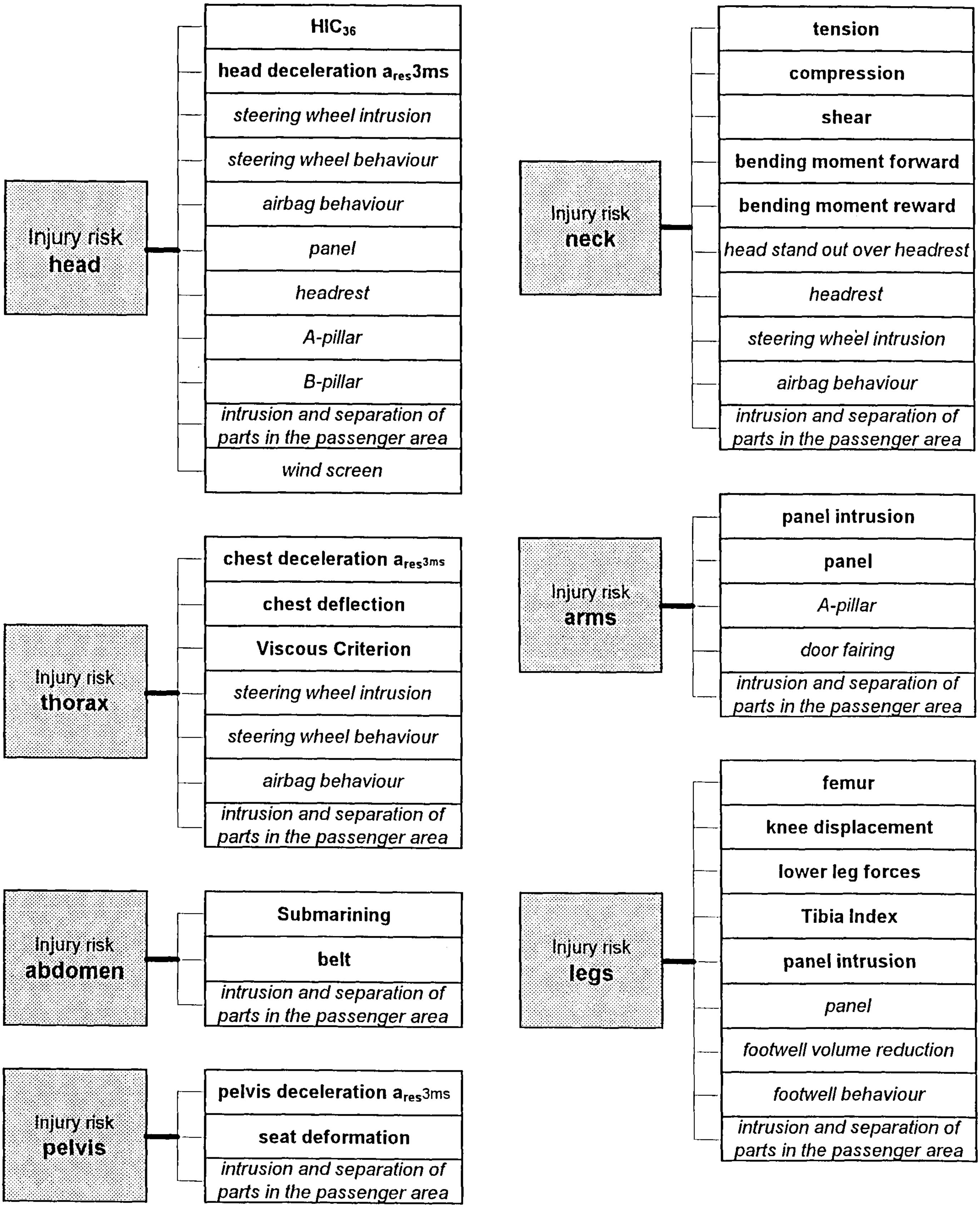

Figure 2. Criteria structure for frontal crash: injury risk for driver

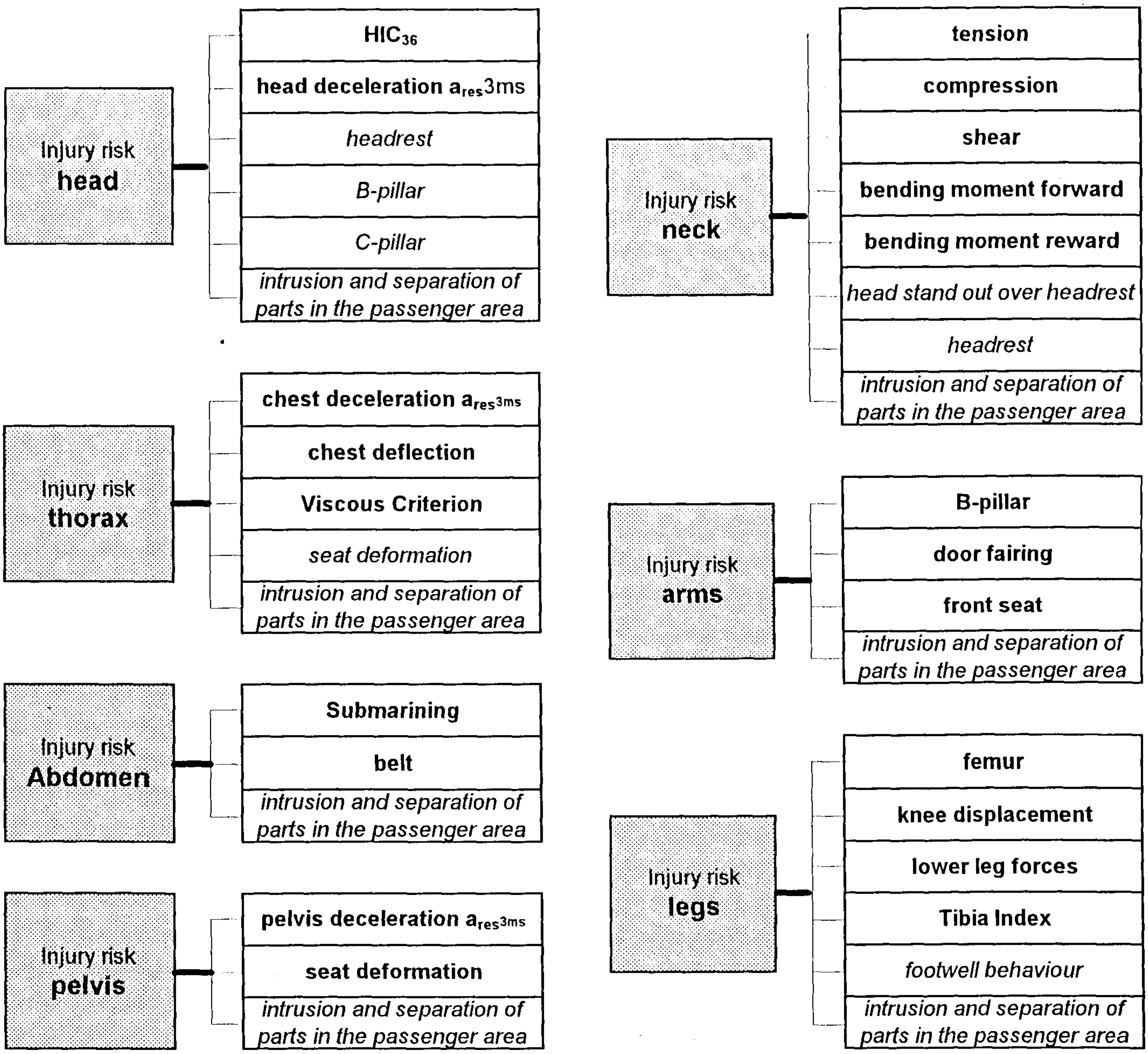

Figure 3. Criteria structure for frontal crash: injury risk for rear seat passenger

Rollover

The US standard FMVSS 208 requires a "pure" rollover without longitudinal speed. In general this test because of the missing longitudinal speed is not considered to be very realistic. Especially the load on the roof and pillars is very low and therefore rather unrealistic. Consequently on the basis of [1] and [5] the configuration with longitudinal speed is proposed, Fig 1:

* Longitudinal speed of the vehicle 70 km/h
* Dropping the vehicle from a trolley
* Simulated dropping height 2 m

Rear impact

Several methods are used for rear impact tests. In most cases a mobile rigid barrier is used as an impact obstacle. The weight of this barrier is between 1,000 and 1,800 kg, the overlap between 40 % and 100 %. Where only one test per vehicle model can be performed the following configuration is proposed:

* impact speed 50 km/h
* 1,800 kg mobile rigid barrier
* overlap 100 %
* Hybrid III Dummy, all seats occupied, at least one front and one rear dummy fully instrumented
* luggage simulation with two

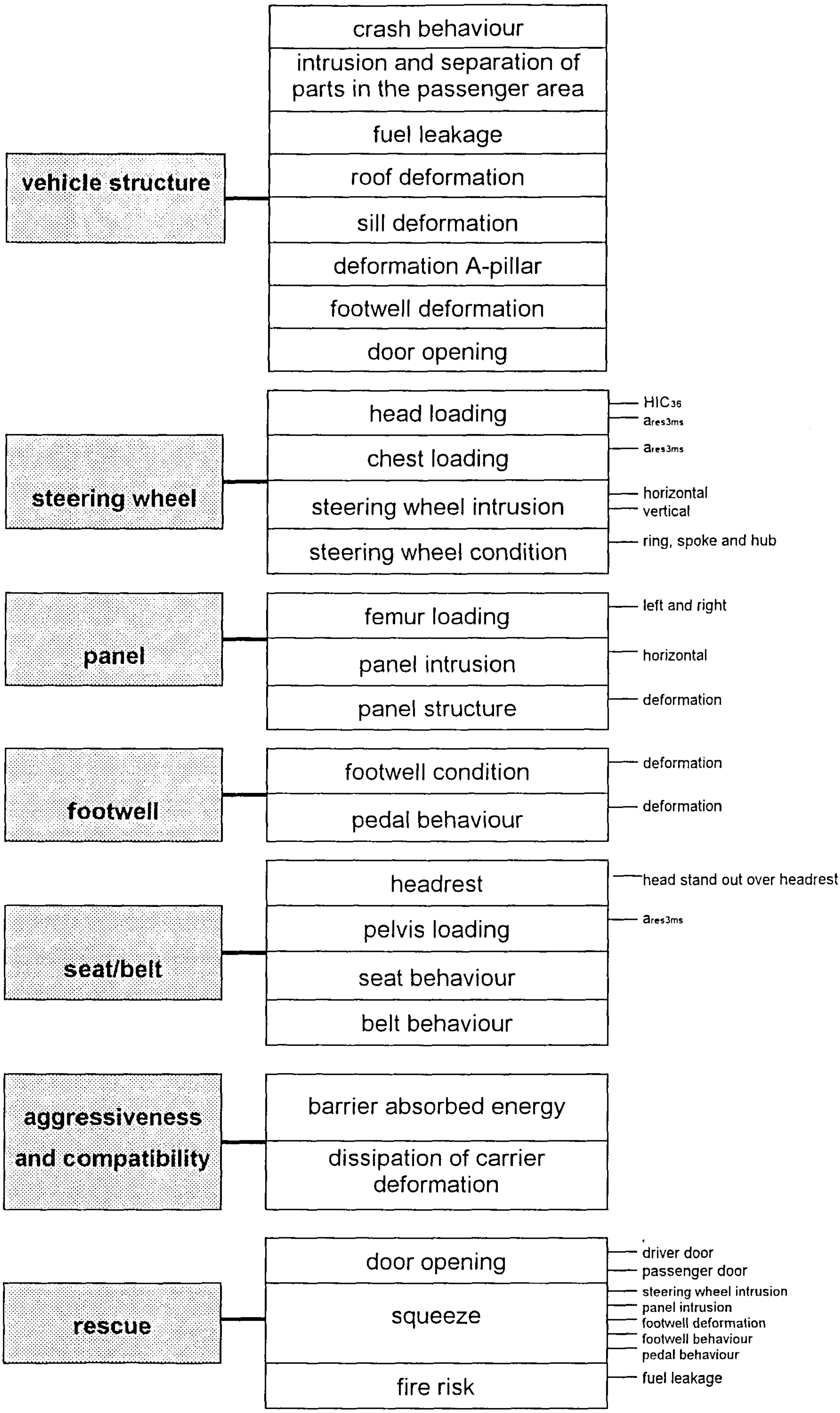

Figure 4. Criteria structure for frontal crash: crashworthiness of vehicle strutcure and vehicle parts, aggressiveness, compatibility and rescue

	DRIVER								PASSENGER							
	head	neck	thorax	ab-domen	pelvis	arm	leg	rescue	head	neck	thorax	ab-domen	pelvis	arm	leg	rescue
HIC 36	X								X							
ares3ms	X								X							
deflexion			X								X					
Viscous criterion			X								X					
loading force			X	X	X						X		X			
A-pillar intrusion/condition	X	X	X				X									
B-pillar intrusion/condition	X	X	X	X	X											
C-pillar intrusion/condition									X	X	X	X	X			
roof intrusion/condition	X															
door intrusion/condition			X	X	X	X	X				X	X	X	X	X	
seat deformation/condition				X	X		X					X	X		X	
headrest behaviour	X	X							X	X						
belt behaviour		X		X						X		X				
footwell reduction/behaviour							X								X	
side bag behaviour	X	X	X			X										
intrusion/separation of parts	X	X	X	X	X	X	X		X	X	X	X	X	X	X	
door opening								X								X
fuel leakage								X								X
buckle opening								X								X
squeezing								X								X

Figure 5. Criteria structure for side crash: injury risk an rescue risk for driver and passenger

18 kg wooden cubes following
DIN 75410 part 2

Test Criteria and Rating

The objective is to gain the most realistic and generally valid information on the basis of only a few tests. This means that there should in no case be a restriction to just a few dummy measures which may be required by the standards. It is essential to consider all injury-relevant factors. Again, accident statistics supply useful information [2, 6, 7] not only on the injuries of certain body parts of the vehicle occupants but also on the vehicle parts which have a potential to cause occupant injuries.

In Fig 2 to 5 all measuring and evaluation criteria for front and side crash safety required from a current point of view have been summarised. They have been taken from the relevant future EU standards and from the quoted accident research documents. Since the objective is to produce easily comprehensible information for the consumer as well as information on the safety performance of individual vehicle parts for the vehicle manufacturer result assessment is both passenger- and vehicle-specific. Fig 2 shows the criteria structure of the driver's injury risk and Fig 3 of the rear seat passenger. Fig 4 the criteria structure for the assessment of vehicle components as well as aggressiveness and compatibility. Because of the large number of data it would seem useful to input them into a data base and to automate evaluations through appropriate routines [8].

Evaluation scales for the conversion of individual crash results into rating marks form an essential part of a rating method. Fig 6 gives an example for such standards, i.e. the mark for the load on the neck depending on the time sequence of the neck traction force (two-dimensional scale).

The rating method step by step generates a condensation of individual results. In a first step injury risks for individual body parts are determined and the results are then combined to produce the overall injury risk separately for the driver and passengers. Currently there is still a conflict with regard to the objective. It is certainly true that the information is easier to understand for the consumer the more it is condensed, each condensation, however, will cause additional "inadequacies" of the information due to weightings which will always be prone to a certain arbitrariness. Current experience suggests that condensation should be restricted to the stage injury risk of the indivudual occupant depending on the respective crash configuration. Determination of an overall safety mark for the whole vehicle does not seem useful.

It is important to compare the results gained through test and rating methods with real life accident processes, at least for some vehicle models. An approach to achieve this is described in [3].

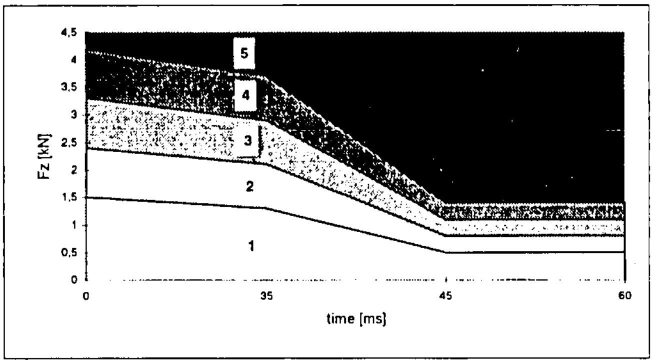

Figure 6. Evaluation scale for neck tension

CONCLUSION

Crash tests for gaining consumer information must normally be restricted to only a few tests per vehicle model. From the large number of known crash tests. also widely performed by the manufacturers during model development one test each for the collision types front. side. rollover and rear is proposed. The main features are: for front impact 60 km/h crash against a modified EEVC barrier. for side impact basically the future EU standard . for rollover 70 km/h longitudinal speed and for rear impact 50 km/h against the rigid barrier.

The test criteria should not be limited to the criteria defined in the standards. All criteria out of real life accident studies which are known to be relevant to occupant injury are indicated.

It is shown how individual criteria within the rating procedure have to be structured in order to gain information on the vehicle occupants' injury risk as well as on the safety performance of vehicle components. on aggressiveness and compatibility. Although a first validation of the described test and rating methods could be achieved there will be a need for further research.

REFERENCES

[1] F. Zeidler "Erfahrungen aus 25 Jahren Unfallforschung bei Mercedes Benz" Bag and Belt 1994. 3. Internationales Symposium für Fahrzeuginsassen-Rückhaltesysteme. Cologne April1994

[2] K. Langwieder. H. Bäumler "Priorities of Real Car Crashes and the Agreement of Real Accidents with Results from Crash Testing" 14th ESV Conference. Munich May 1994

[3] W. Klanner. K. Langwieder "The Correlation between Test and Real-Life Accidents for the Car--to-Car Frontal Crash" 15th ESV Conference, Melbourne 1996

[4] W. Klanner "Wie aussagefähig sind vergleichende Crashtests für das Schutzniveau im Realunfall" Comparative Crash Tests within the EC. TÜV Rheinland Verlag. Cologne 1993

[5] K. Brieter. B. Felsch "Cabrios so sicher wie Limousinen?" ADAC motorwelt. August 1994

[6] D. Otte " Änderungen von Verletzungsmustern durch moderne Sicherheitssysteme aus der Sicht der Unfallforschung" Medizinische Hochschule Hannover. 1994

[7] D. Otte " Spezielle Auswertung von Unfällen aus Erhebungen am Unfallort" Medizinische Hochschule Hannover. 1995

[8] W. Ablaßmeier "Körperteilbezogenes Crashtest--Rating" Diplomarbeit Fachhochschule München, ADAC

THE EUROPEAN SECONDARY SAFETY RATING SYSTEM FOR CARS

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ABSTRACT

This paper describes a unique, but very effective approach to the rating of cars for crash safety. The system introduced takes into account not only real accident data, but also the safety of all occupants, not just the average male driver. The output is a single safety figure for each model of car.

INTRODUCING THE CONSUMERS VIEW

There is no doubt that safety is high on the list for most people when they are looking for a new car. The equivalent to three Lockerbie jumbo jet disasters every week makes clear that there is a compelling need for comparative information on crash safety of cars for consumers. And car safety has become a political issue too in Europe, as is justified by the casualty toll.

In the view of European consumer organisations car buyers should be informed on the differences in secondary safety between cars on the market. Talking about secondary safety means, in this respect, the ability of the cars to minimise injury to its occupants in a crash. Importantly, this is a broader concept than simply defining the performance of a 50th percentile male dummy in a specific frontal crash at a certain speed. Any judgements must be made against the mix of accidents in the real world. We try to do that by means of the rating system which will be explained in this paper.

DIFFERENT SYSTEMS

Several methods of rating the crash performance of cars are currently in use in order to provide information which can guide car buyers. Broadly two categories of collecting information can be distinguished:

Retrospective Systems

Retrospective systems generate ratings on the basis of the actual performance of cars in real life accidents. The frequency and severity of injury to car occupants in individual models of cars are determined by examination of police accident statistics and / or insurance injury claim data. A disadvantage that cannot be ignored is that results are not available until a model has been on the road for several years. For less common car models it may even be impossible to get sufficient data. This makes such systems less suitable for new car buyers.

In detail one can see differences in the exact methodology of these systems, such as the types of accidents included, correction for seatbelt use and for the effects of driver behaviour and exposure. Many systems are based on driver casualties only. In practice it is very difficult to really eliminate these influences from accident outcome data and leave oneself with a convincing pure measure of secondary safety, the ability of the car to protect its occupants in a given range of accident conditions. Even if such analysis were possible, the explanations for the differences are not known, and thus the ability of such systems to encourage safe designs in new vehicles is limited.

Predictive Systems

Predictive systems can assess a car's safety performance before it is used on the road. Predictions are based on one, or a combination of the following approaches:

1.Controlled whole car crash test of individual models with rating based on recorded dummy values and the ability of the passenger compartment to maintain its integrity;

2.Tests on components of the car which have been proven to be important in accidents;

3.Visual inspections of the interior and bodyshell structure of the car, based on the knowledge of how different designs affect the risk of injury.

Also within these approaches there can be a large variation in the detailed specifications.

Both retrospective and predictive methods are applied all over the world to compare crash safety of cars. Apart from the variations mentioned above there are also huge differences in the way conclusions and recommendations are presented.

Single Test Systems

Looking at predictive systems we see that they are often based on crash tests. In some cases we see very general conclusions based on one single frontal crash test,

only using dummy readings. At best such an approach can only comment on the safety of one set of occupant contact points within the vehicle interior. There is a real need to assess to what extent the dummy readings can be generalised to give a view of the protection in a range of frontal impacts, and this important part of the process is often omitted.

There is a danger that a car in which the dummy 'happens' to hit the a soft part of the steering wheel rim, for example, will be declared good for protecting the head. Just how good the design really is in all frontal impacts depends in this instance on how typical the soft rim is of all foreseeable impact sites on the wheel. We have seen cars with aggressively stiff wheel hubs praised on the basis of the single dummy test in which the dummy just missed the large hazardous hub. Similar concerns also exist in assessment of knee impact areas, for example.

There also seems to be an increasing concern about the correct positioning of the dummy. When a dummy is 'out-of-position' this may influence the readings in the crash. This is not really a human-like approach and limits the value of the crash test results. Could you imagine a driver constantly being in exactly the right position? Concentration on a specific test configuration makes it possible to optimise a car to 50th percentile males in that configuration, ignoring the interests of other sized occupants. For example there are cars on sale in Europe cars that only provide side impact padding next to the mid position of the front seats! In order to do well in single crash test based publication manufacturers use the test procedure as their design aim. A more subtle way of dealing with this problem however is needed, for instance by using additional information from inspections, component tests and possibly several whole vehicle tests.

Publications

There are many differences in the way test results are presented. Often a scale from yes to no, plus to minus or red to green to indicate the safety of (a part of) the car and / or dummies in one crash situation is used. This leads to very detailed information and judgements on one specific situation. These judgements of different parts are not always combined into one, understandable final value. This leaves the problem of comparing results of different cars with the consumer, who has to decide whether his torso is more important than his legs, and whether frontal crashes are more important than side.

THE SECONDARY SAFETY RATING SYSTEM

In its approach the European Secondary Safety Rating System for Cars is different from most of the predictive systems as it is more global, taking into account as many real life accident situations as possible, rather than an in depth analysis of one crash. This is more satisfactory as it avoids sub-optimising to one single crash-test, as well as the possibility that a consumer, guided by results from frontal crashes, buys a car with insufficient side impact protection. The chances of being involved in such a crash cannot be ignored, as side impacts are the second most frequent type of crash.

It is an inspection based system, enhanced with data from component and full scale crash tests. The system allows combination of these inputs in a way based firmly on accident research findings. It aims to make the informed judgement of experienced accident investigation specialists as accessible as possible to the interested consumer. The inspections are carried out by experienced accident investigators using their expertise and knowledge of how people are injured in real world accidents. The system is operated by the independent consumer organisations in Europe, under the umbrella of International Testing Ltd (IT), who publish the results in their magazines, such as Which? in the UK, Consumentengids in Holland, Der Test in Germany, Que Choisir in France and Test Achats / Test Aankoop in Belgium.

The system is described in two manuals. The handbook for the system allows the interested engineer to interpret the judgements and ratings given to the various areas of the cars within the system without getting too deeply involved in the technical background.

In addition a technical manual has been produced to outline the structure and thinking behind the system for those wishing to examine it in more detail than the handbook allows. This manual attempts to describe as fully as possible the data used and steps taken in the construction of a systematic evaluation procedure for the secondary safety of cars. Both are available from the IT London office (Ref. 1 and 2).

How the System works

The rating system combines the results from inspections of more than fifty safety critical areas of car design in a systematic way. These areas, such as the steering system, bodyshell construction, seats and head restraints, belt systems, and fuel lines, are known to play a role in different accident situations. Each area is described in one or more variables that has an allocated weight that reflects the relative contribution to the total occupant injury as observed in real life accidents in European countries. Table 1 shows one of the underlying tables, other data used are the more detailed distributions of serious and fatal casualties, and their relative importance. Moreover assumptions are made with respect to seat belt wearing rates for different seating positions in the car.

Table 1.
Casualties in Cars by seating Position (%)

	Driver	Front Passenger	Rear Passenger	Total
Fatal	0.086	0.030	0.017	0.133
Serious	0.521	0.219	0.127	0.867
Total	0.607	0.249	0.144	1.000

The system aims to predict the performance of the vehicle in all types of accidents. Design characteristics which are important in accident types that are more common receive a higher weighting (e.g. head on collisions vs roll-over accidents). The weighting gives proportionately greater importance to the prevention of fatal as opposed to serious injuries. Therefore good design in an area which plays a big potential role in injury causation and risk of death scores highly and good design in an area of less importance adds little to the final outcome. Other influencing factors include assumptions about seat belt wearing and the seat occupancy rates. A major advantage of the system is that it is sensitive to injury of occupants in all different seating positions.

Some examples of variables (out of the list of 57) and their weights are shown in table 2.

Table 2.
Examples of Variables and their Weights

	Variable	Variable Weight
6	Fuel tank	0.61
12	Body shell resistance to intrusion in a frontal impact	29.71
14	Occupant protection in side impact	28.23
23	Steering wheel, head and face protection	89.93
37	Front seat belts, geometry	23.65
49	Rear seat belts, geometry	3.17

Each variable is assessed against a fixed set of criteria which range from the best possible example of good design in that area, through to an example where little attempt has been made to protect the car occupants. The basic philosophy behind the rating system is that the variable weights reflect the maximum contribution of a given area to the overall safety performance of a vehicle. So in general, a category weight of 1 will indicate the best practically achievable design within the limits of current knowledge. For designs which fall short of the "state-of-the-art" ideal, a fractional score between 0.1 and 0.9 is used to indicate the degree to which the design falls short of the ideal. Recent and future technical developments may merit a weight above 1.

Where possible, accident data has been used to provide a background against which the judgements of category weights can be made. An example of the category weighting for variable 23 is shown in table 3. For each area inspected, the variable weight is multiplied by the category weight to give the contribution to the final score.

Table 3.
Example of categories within variable 23:
Steering system, head and face protection - Weight 89.93

No.	Weight	Description.
1	1.0	Steering wheel equipped with air bag.
2	0.8	Steering wheel hub and spokes covered with deep energy absorbing material, free from hard spots.
3	0.5	Column end moderately well recessed, but little energy absorbing covering to wheel frame.
4	0.2	Column end and wheel hub substructure close to surface of wheel, poor protection of wheel frame.
5	0.1	As above, with sharp metallic wheel frame edges exposed.
6	1.4	As category 1 but with pretensioner
7	1.2	As category 2 but with pretensioner
8	0.9	As category 3 but with pretensioner
9	0.6	As category 4 but with pretensioner
10	0.5	As category 5 but with pretensioner

Note: An objective test is routinely used to verify the categorisation of this area. Steering systems that comply with the TRL faceform test criteria would normally be placed in category 2 or 7.

Calculating the Final Rating

The weighted total for all the areas examined is summed to give the "raw score" for the car. The raw score is a indication of how well the car has been designed in terms of secondary safety, but it is independent of the weight of the vehicle. The raw score can, therefore be used to directly compare the secondary safety design of cars irrespective of their size and weight. (See table 4)

All other things being equal a heavier car will protect the occupants better in an accident. So the raw score is "corrected" to take account of the vehicle weight giving final numerical value for the secondary safety of the car. This means that big cars can achieve higher total scores than small cars. Each final score is translated into a single rating and then published.

Table 4.
Example of Some of the 57 Contributions to the Raw Score of a Hypothetical Make and Model

	Variable	Category	Cat. Weight	Score	Difference
6	Fuel tank	1	1	0.61	0.00
12	Body shell resistance to intrusion in a frontal impact	3	0.5	14.85	-14.85
13	Front doors, side impact strength	5	0.4	2.43	-3.64
23	Steering, head and face protection	4	0.2	17.99	-71.95
37	Front seat belts, geometry	4	0.8	18.92	-4.73
49	Rear seat belts, geometry	1	1	3.17	0.00

The scores can be compared both within and across various weight classes and give an indication of the overall safety of a car against the mix of accidents: the higher the score the better.

At the moment ratings are available for nearly all models on the market in the (super)mini class, as well in the (small) family class. Only in the executive cars class the coverage of the market could be improved. Table 5 shows results in the small family cars class.

Working on a European Basis

The system initially was developed for the Consumers' Association in the UK. Later it was modified for use in the Netherlands and France, taking into account local accident figures and assumptions. As the system appeared to remain stable, it has been shown that it is not critically influenced by small changes in individual assumptions. Although there were differences in the basic assumptions between the original systems developed for the UK, Dutch and French consumer groups prior to the advent of the European system, the final results were broadly similar. Since cars are generally manufactured and distributed on a European wide basis, it seemed appropriate to develop a single European system that could be used by a number of consumer groups.

For the European version, data from several European countries has been combined to provide "average" European assumptions. There is no such thing as a "typical" European accident however, and as such the European system will not truly represent every aspect of the situation in any one country. However, it is hoped that it will provide a balanced European assessment that will provide useful guidance to the "European" consumer.

Table 5.
Some Final Ratings of Small Family Cars

Make and Model of Car	Driver Airbag	Date	Rating
Ford Escort *(Feb 95 on)*	✓	may-96	8,5
VW Golf	✓	may-96	8,0
Fiat Brava	✓	may-96	8,0
Alfa 146	✓	may-96	8,0
Nissan Almera	✓	may-96	8,0
Opel Astra	✓	may-96	7,5
Seat Cordoba	✓	may-96	7,5
Rover 400	✓	may-96	7,0
Daewoo Nexia	✓	jan-96	7,0
Peugeot 306	✓	may-96	7,0
Citroen ZX	✓	may-96	6,5
Honda Civic	✓	may-96	6,5
Toyota Corolla	✓	may-96	6,5
Hyundai Accent	✓	jan-96	6,0
Rover 200 *(oct 89 on)*		jan-93	6,0
Subaru Imprezza		jun-94	5,5
Suzuki Baleno	✓	jan-96	5,5
Renault 19		oct-92	5,0
Honda Concerto		oct-92	5,0
Honda Civic *(old)*		oct-92	5,0
Proton Persona		apr-95	5,0
Mitsubishi Colt *(old shape)*		jun-93	5,0
Nissan Sunny *(Mar 91 on)*		jan-93	5,0
Ford Escort/Orion *(old shape)*		jan-92	5,0
Fiat Tipo		jan-92	5,0
Alfa Romeo 33		jun-91	5,0
Hyundai Lantra		oct-92	4,5
Daihatsu Applause		jun-91	4,5
Skoda Felicia		jan-96	4,0

Reviewing the System

The system is under constant review. One of the many strengths of the system is that it can be readily adapted for different accident data or new designs. When new information or data about a relevant aspect of safety design is published it is used to adjust the weight of a variable or categories within a specific area.

Needless to say there is nothing absolute or fixed about this rating system and some of the field evidence that ideally would be needed to refine areas is simply not available. In most cases it would, in principle, be possible to extract useful data from existing databanks if access could be arranged. It is hoped that an open discussion of the assumptions underlying

the rating system will stimulate the release of data that can be used to refine various areas.

The current system, then must be considered to be simply based on the best evidence that we have been able to trace at present. It is hoped that the assumptions will be further refined in the light of new accident evidence, as and when it becomes available. Those holding suitable data banks may wish to examine the detailed assumptions on the basis of their own information.

Component Testing and Whole Vehicle Crash Tests

Clearly the system is fundamentally based on the judgements of the accident specialists who inspect the cars. Any one of the component assessments could be replaced by suitable test procedures, and indeed such a trend may well be desirable in the future, at least for the more important components. At the moment possibilities for including more tests results are under consideration.

One component test has already been adopted for the most important area in the system. The steering wheels are routinely tested according to the UK Transport Research Laboratory's faceform method for their ability to protect the driver's face and head in an accident.

The results of whole vehicle frontal and side impacts have also been successfully integrated into the system on a number of occasions. The combination of results from individual crash tests and the rating system gives a systematic method for providing an overall rating for the safety of the vehicle.

However, the cost of operating the system increases very rapidly once destructive testing is included. If further testing is envisaged at a later stage, the basic rating system framework will still enable the test based observations to make an appropriate sized contribution to the overall secondary safety rating of the vehicle.

Pedestrian Safety

At this stage, the rating system is concerned only with the car occupants and does not consider how the design of the exterior of the car may affect pedestrians and other unprotected road users. Because a large proportion of unprotected road users are injured by striking the outside of cars, this area of design is in practice very important and should not be ignored.

In our view, this is an area which should be explored in the near future perhaps with the intention of developing a separate "pedestrian" safety rating. It will almost certainly be better to keep this distinct from the "occupant" safety rating system described in this paper.

Manufacturers Comments

After each assessment, and before publication, the manufacturer is presented with the results, including a table which details the scores in each area and includes a list of the salient good and bad features. This gives the opportunity for a technical dialogue with the manufacturer about the points featured and the process of assessing secondary safety in general. At this stage additional test information that the manufacturer chooses to present is evaluated and if appropriate the rating is adjusted in the light of this input. By looking at the scores in each area and comparing them against the ideal score the manufacturer is encouraged to concentrate on areas where improvements will make the largest difference to accident outcome.

The Link With Real World Accidents

Research has been undertaken to establish whether the predictive results from the original system, operated by the Consumers' Association (CA) in the UK, reflect accident experience in practice. In a paper given at the annual meeting of the International Research Council on the Biokinetics of Impacts (IRCOBI) in 1991 the correlation between retrospective crash data collected by the Swedish insurance company, Folksam and the predictive UK version of the Secondary Safety Rating System was examined. The Folksam system uses a complex analysis to rank cars utilising information from insurance claims and post-crash vehicle inspections. It found that in a subset of 22 cars which were common to both systems the correlation between the predicted performance and the accident outcome was high (ref. 3).

We would welcome further research to examine the ratings produced by this system in terms of subsequent accident performance of the vehicles concerned. There are, however, major difficulties in isolating secondary safety design factors from all the other influences within accident data. Nevertheless we hope that others with suitable data will consider such correlations.

Relation with legislation

Over 350 cars have been inspected over the last 13 years, many models more than once. This allows us to spot trends over the years (cars generally have become safer over the years) and follow specific models over the years. It is also possible to use this knowledge to influence legislation. There is a big discrepancy between the state of the art on one hand and the level of legislation (though improving) on the other. Cars on the market are floating somewhere in between with the point of gravity still too near the lower end.

Detailed inspections of most of the models of the actual car fleet generates a lot of detailed information that can be used in relation with legislative work. The data with respect to the position of the seat belt anchorage points in cars on the market were helpful when modifying those of the test-sled for child restraints (ECE R44.03), as did the obvious finding that cars tend to be equipped with inertia reel belts instead of static ones as in R44.02. We also hope that our data on head restraints will lead to improved legislation, as we found in our inspections very poor designs that cannot be banned under current legislation. Another inspection item is the construction of the backrest of the rear seats. The judgement that many of them cannot keep luggage in its compartment in a frontal crash is confirmed by crash tests and, sadly enough, by some reported accidents. Hopefully legislation will correct this shortcoming in the near future.

We encourage manufacturers to design beyond current legislation. Therefore some specifications of advanced test methods are mentioned in our manual. For example credit is given for steering wheels that meet the TRL steering wheel tests, or cars that meet the side impact tests at 350mm barrier height, including all dummy criteria. As early as in 1992 we performed our first deformable barrier test which was so convincing that we supported the principle since then in the rating system.

Car Manufacturers

There is a growing interest on behalf of manufacturers in dealing with the system. Our findings are communicated before publication to them as a standard procedure. Over the last years manufacturers have changed their attitude to the system. More and more we see that this results in thorough technical dialogues on a strictly confidential basis. These discussions may even result in a modified final rating, for instance when a manufacturer can prove that their car fulfils one of the advanced standards mentioned above. Some manufacturers have adopted its philosophy, and even use it when developing new cars.

CONCLUSIONS

The European Secondary Safety Rating System offers a simple and reliable tool for the average consumer to take safety into account so that he can make an informed choice when buying a car. The advice is based on a broad view of the car's safety rather than focusing on the results of one test.

It's main strength is this global approach that does not encourage optimisation to one specific scenario. There is no other program of this size in the world.

References

1. Technical Background to the European Secondary Safety Rating System for Cars, International Consumer Research and Testing Ltd, London 1996.

2. The European Secondary Safety Rating System for Cars, International Consumer Research and Testing Ltd, London 1994.

3. Gloyns P F, Rattenbury S J, Kullgren A, Lie A, Tingvall C, et al. "The Correlation between the Consumers' Association Secondary Safety Rating System and the Folksam Car Ratings." 1991 IRCOBI Conference, Potsdam. IRCOBI Bron, France, 1991.

4. Consumer Information on the Crash Performance of Cars: The Role of the EU, European Transport Safety Council, Brussels, 1995.

CRASH PERFORMANCE RATING SYSTEMS AND CO-OPERATIVE ACTIVITY IN EUROPE

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ABSTRACT

This paper summarises the findings of a review conducted in 1995 by the European Transport Safety Council on Consumer Information on the Crash Performance of Cars. Secondly, it reports on co-operation by those involved in consumer information activity in Europe through a forum providing loose co-ordination, the European Crash Safety Evaluation Consortium.

The need for objective information

There are 500 car user deaths weekly in European Union countries. Car crash protection measures have enormous potential to reduce injury in the event of a crash (1). However, there is a large difference in the level of crash protection which is offered by various car makes and models even when they are in the same class. Research in Sweden and Finland indicates that if all cars were designed to be equal to the best current car in each class, 50 per cent of all fatal and disabling injuries and 27 per cent of all injuries in urban car-to-car crashes could be avoided (2,3).

While car design is also influenced by legislation and product liability, it is widely acknowledged that market forces continue to play a major role in shaping car design. Safety is an increasingly important aspect in buying decisions. According to a UK survey among British car drivers, safety features are now the second most important aspect that they would like to see improved in their next car, closely following security features (4). At the same time, manufacturers highlight increasingly car safety characteristics in their marketing (5). In order that car buyers may judge the safety claims being made by manufacturer, then they need relevant and impartial information and in a form that is easily digestible.

A variety of crash safety rating systems are used internationally to inform consumers of the relative performance of different car models in certain test conditions and in accidents. Such ratings seek to provide information about the crash performance of a car in the event of an impact rather than about the risk of an accident occurring in the first place. Monitoring has shown that consumers find this information useful and that it contributes to increased awareness of the importance of car crash safety features, not only amongst consumers, but also amongst car manufacturers (7).

Crash performance ratings

The ETSC review categorised crash performance rating systems into predictive and retrospective systems (6).

Predictive systems

These systems predict a car's crash performance before it is used on the road and are based on one or a combination of the following approaches:

-controlled whole car crash tests of individual models with ratings based on recorded dummy values and the ability of the passenger compartment to maintain integrity eg. New Car Assessment Programmes (NCAP);

-tests of components of the car which have been proven to be important in accidents and/or visual inspections of the interior of cars with a rating based on knowledge of how different safety devices and materials affect the risk of injury (eg; secondary safety ratings). These systems are particularly useful for new car buyers.

Retrospective systems

These are based on the actual performance of cars in real accidents where the frequency and severity of injury to car occupants in different car models are determined by examination of police accident statistics and/or insurance injury claim data. These systems are particularly useful for second hand car buyers.

Experience to date shows that both approaches have an important role, albeit different, to play in providing consumers with information when purchasing a car. In ETSC's view, ratings are most useful when the crash tests used are realistic; when they take account of possible confounding factors which might bias the results and where the rating publication explains clearly what the particular

safety rating means. While various crash test-based, inspection-based and retrospective systems have evolved largely independently, the co-ordination of approaches could enhance the quality and usefulness of the information further. Standardised crash test data could improve the accuracy of the inspection-based systems as could the subsequent feedback from retrospective methods. Similarly, a co-ordinated method of expressing the results to the consumer could improve public understanding of the results. The Swedish Roads Administration, for example, will shortly draw together in one publication the results of different types of safety ratings.

Rating the crash performance of new cars

Predictive ratings have the greatest potential for influencing people's decisions when buying a new car, since these will be available as soon as a new car model is launched. Ratings are based on *expected* performance in real life crashes as deduced from whole vehicle crash tests, component testing or visual inspection. They have the advantage that factors other than design which may affect injury severity, are controlled. To date, available data show that there is good similarity between predicted and actual crash performance in real accidents, but this needs continuous monitoring (8,9).

There is an important difference between legislative crash tests and crash tests for consumer information. Whole car legislative crash tests represent a minimum level of crash performance with many cars already in production exceeding these tests and manufacturers readily pointing to features which are additional to the legislative requirement. Crash test performance rating for consumer information gives comparative information about the availability of good protection. There is no pass/fail criterion as in legislative tests. Tests selected for consumer information purposes may be necessarily different, therefore, from legislative tests.

New Car Assessment Programme (NCAP)

Whole vehicle crash tests generally take place in the framework of the New Car Assessment Programme (NCAP). An NCAP has run in the USA since 1978 using a full frontal rigid barrier test, and in Australia since 1992 using an offset deformable barrier frontal test and a full frontal rigid barrier test. The UK has just started a feasibility study for a 'state of the art' NCAP with EEVC-based procedures for an offset deformable barrier frontal impact test, full-scale side impact test and pedestrian protection tests. In addition to NCAP, motoring organisations and journals, and insurance institutes also carry out and publish whole vehicle crash tests.

Types of whole vehicle tests (frontal impact, side impact, pedestrian friendliness) and test procedures (e.g. velocity, ground clearance height, percentage overlap) vary across the various programmes, and inhibit the comparison of crash test based systems. The methods of presenting results to consumers also vary.

Secondary safety rating systems

Secondary safety rating systems rely on a combination of visual inspection and component testing of a number of areas of car design taking into account the current state of knowledge about injury causation. With the support of the European Commission a European secondary rating system has been developed and is being used by consumer groups throughout the European Union (10). The European system is based on the UK Consumers Association secondary safety system which was first introduced in 1983. Inspection-based techniques are relatively cheap and, when fed with data from crash tests and in-depth accident data, predict safety performance in many different accident circumstances and for different seating positions.

Predictive methods have both advantages and limitations. Predictive methods have the greatest potential for influencing people's decisions when buying a new car, since ratings will be available as soon as a new car model is launched. Of the predictive systems, NCAP tests provide the most objective assessment of vehicle crash protection, but only for the conditions tested. The laboratory approach also requires that reference is paid to real world accident data to ensure the test's validity. Inspection-based techniques are cheaper. If fed with data from crash tests and in-depth accident data, they can predict safety performance in many different accident circumstances and for different seating positions.

Communicating safety information to consumers

Given the variety of crash performance rating systems which exist, both predictive and retrospective, it is important that each publication explains clearly what that particular safety rating means.. It should always be emphasised that such ratings measure crash performance in the event of

an accident rather than affect in any way the chance of an accident occurring in the first place.

When relevant data have been collected, there is a generally a large amount of information on each car model. This information is very technical and needs careful interpretation. It is clear that in this raw form, data cannot be presented to the general public. Currently, the ways of presenting the results vary considerably across the various systems and programmes. Some have a very high degree of simplification, other try to communicate much more detail.

No studies have been traced which have systematically investigated the effectiveness of different ways of communicating results to consumers. In general, it can be said that the simpler the message, the more subjective weighting of results has taken place, and vice versa.

The need for an EU crash testing programme

Currently, there is no EU-wide NCAP programme, although two Member States are looking into such a course of action at national level. As indicated previously, a European Secondary Safety Rating System has been developed and commands wide respect, but does not yet maximise its potential in taking whole vehicle crash test performance and component testing fully into account.

The ETSC review concluded that a co-ordinated programme of crash testing work in EU countries with harmonised realistic test procedures should be established.. With support from the EU as well as from individual Member States, consumer and motoring organisations, this could allow the setting up of an EU NCAP as well as the further development of the European Secondary Safety Rating System. Such a programme would have the following advantages in:

- furthering EU Treaty objectives to promote road safety;
- recognising the role of market forces in improving car safety design;
- allowing more models to be tested than could be done by any one Member State;
- avoiding unnecessary duplication and cost;
- providing a framework for sharing of results amongst different crash testers;
- ensuring that the results of crash tests, which are quite expensive are utilised most effectively, feeding through into secondary safety rating systems as well as new car assessment programmes.

<u>Realistic test procedures</u>

The most relevant safety information from new car assessment programmes will undoubtedly come from those using test procedures which are most representative of real accident scenarios producing serious injury (MAIS 3 or above). For European cars, ETSC believes that the current test procedures from frontal impact, side impact and pedestrian protection developed by the European Experimental Vehicles Committee form the ideal basis for testing for consumer information.

<u>Test speeds</u>

Results from accident studies indicate that the speed which will probably be adopted in the new European frontal impact legislative proposal (56 km/h) will address only about a half of severely injured casualties (MAIS 3 or above) and a smaller proportion of fatal casualties. Most severely injured casualties wearing seat belts have DeltaVs of at least 60 km/h as do the majority of the fatal casualties (11). Taking into account further technical considerations associated with CRASH3, the commonly used computer program which estimates DeltaV, and the dynamics of the offset deformable barrier, then ETSC considers a speed of 64 km/h is considered to be the appropriate speed to represent real world severe injury producing accidents..

European Crash Safety Evaluation Consortium

In anticipation of an EU-supported programme (a decision on funding is expected shortly on proposals from motoring and consumer organisations) and in recognition of the benefits of co-operation amongst crash testers for consumer information, the European Crash Safety Evaluation Consortium (ECSEC) came together last year. This comprises international motoring and consumer organisations and governmental organisations who are either studying or embarking on new car assessment programmes.

The aims of ECSEC are to provide a forum for the loose co-ordination of crash testing evaluation work for consumer information, to ensure that crash test results are utilised most effectively and are presented as objectively as possible.

To date, agreement has been reached in three key areas. Firstly: the need to harmonise test protocols for consumer testing using the EEVC

frontal offset deformable barrier test and the EEVC full scale side impact tests, which are considered to be the most representative of European car accident conditions; secondly to co-ordinate selection of test models to avoid duplication and finally partners have agreed to share test results.

References

(1) EUROPEAN TRANSPORT SAFETY COUNCIL *Reducing traffic injuries through vehicle safety improvements - the role of car design,* Brussels, 1993.

(2) HÄG A., KAMRÉN B., v. KOCH M., LIE A., MALMSTEDT C, NYGREN Ä, TINGVALL C. Folksam Car Model Safety Rating 1991-92, Folksam Research, Stockholm, 1992.

(3) TAPIO, J., PIRTALA, P. and ERNVALL, T. *The accident involvement and injury risk rates of car models.* University of Oulu, Road and Transport Laboratory, Oulu,1995.

(4) LEX SERVICE PLC, LEX Report on motoring *The consumer view.* London, 1994.

(5) BELL, P., FRAPE, G., BEMBO, P. *Assessment of safety features in vehicle advertising.* Report CR 3/94. Roads and Traffic Authority of New South Wales, 1994.

(6) AUSTRALIAN AUTOMOBILE ASSOCIATION, Crash test program for car safety. *Motoring Directions, Vol. 1 (2),* 13-16, 1995.

(7) EUROPEAN TRANSPORT SAFETY COUNCIL *Consumer information on the crash performance of cars,* Brussels, 1995.

(8) GLOYNS, P.F., RATTENBURY, S..J., KULLGREN, A., LIE, A., TINGVALL, C., EDWARDS, J. and HILL, R. *The correlation between the consumers' association secondary safety rating system and the FOLKSAM car safety ratings.* In: Proceedings of the 1991 International IRCOBI Conference on the Biomechanics of Impacts, p. 49-60, 1991

(9) KAHANE, C.J. *Correlation of NCAP performance with fatality risk in actual head-on collisions.* Washington: National Highway Traffic Safety Administration (NHTSA), 1994.

(10) IT,*The European Secondary Safety Rating System for Cars.* London: International Testing, 1994.

(11) RATTENBURY, S.J. and GLOYNS, P.F *Frontal impact accident study - a review of relevant technical literature.* Annex 1 to "Impact Test Procedure for a better protection of car passengers in a frontal collision". Brussels: Commission of the European Communities, DG VII, 1993.

Section 6
International Harmonized Research Agenda Report

Results of the Meeting on Sunday, May 12, 1996
By the ESV Government Focal Points

U.S. Department of Transportation
National Highway Traffic Safety Administration

REPORT ON

INTERNATIONAL HARMONIZED RESEARCH AGENDA

June 1996

NHTSA
People Saving People
On the Road for a Healthier Future

Introduction

This report was prepared by the United States, National Highway Traffic Safety Administration, Research and Development, on behalf of the 1996 International Harmonized Research Agenda Committee* (IHRA). Committee members are:

Australia	**Mr. Peter Makeham** Federal Office of Road Safety
Canada	**Mr. Harvey Layden** Transport Canada
European Commission	**Mr. Richard Wright and Mr. Herbert Henssler** Directorate - General III
European Experimental Vehicle Committee (EEVC)	**Prof. Dr. B. Friedel** Chairman, EEVC
France	**Mr. J. P. Medevielle** INRETS
Germany	**Prof Dr. Ing. K-H. Lenz** BASt
Hungary	**Mr. Sandor Szabó** AUTÓKUT
Italy	**Dr. Claudio Lomonaco** Department of Transport
Japan	**Mr. Masakazu Kume** Ministry of Transport
Netherlands	**Mr. Gerard J.M. Meekel, M.Sc.** Department of Road Transport
Poland	**Mr. Wojciech Przybylski, M.Sc.** Motor Transport Institute
Sweden	**Dr. Kåre Rumar** Swedish National Road Administration
United Kingdom	**Mr. Keith Rodgers** Department of Transport **Mr. Richard Lowne** Transport Research Laboratory
United States	**Mr. William A. Boehly** National Highway Traffic Safety Administration

*See Appendix D for a complete listing with addresses and telephone numbers

International Harmonized Research Agenda

Why an International Harmonized Research Agenda?

-- Injuries are universal in nature
-- Globalization of an industry that is affected by motor vehicle regulations
-- Provides the foundation for a harmonized regulatory program

-- Privatization of R&D Facilities
-- Shrinking research dollars and fewer experts in the field
-- Emerging Nations seeking to establish a regulatory system
-- Injuries are a leading drain on the economics of emerging nations Nation's economy (World Bank Report)
-- Opportunity for harmonized motor vehicle regulations
-- Improved safety benefits worldwide

Actions Taken During the Time Period September 1994 - April 1996

The National Highway Traffic Safety Administration (NHTSA) established a team, in September 1994, to develop a paper describing opportunities for increased involvement of international government regulatory agencies in motor vehicle safety research. The paper, outlined the challenges and barriers, and proposed the most viable option, using the U.S. Department of Transportation's International Technical Conference on the Enhanced Safety of Vehicles (ESV) Government Focal Points (GFP) as the forum to establish a steering committee for harmonized research. (Appendix A)

In January 1995, NHTSA sent letters to each of the ESV Government Focal Points detailing its concept of an International Harmonized Research Agenda (IHRA), proposed the ESV Focal Points as the primary contact, and solicited their views and recommendations.

During the time period of February thru September 1995, NHTSA held discussions with domestic and foreign automobile manufacturers soliciting views on what such a program should include and the forum for developing an IHRA. Positive feedback and strong desire to move forward at a rapid pace was received in response to the NHTSA proposal. During this same time period, feedback was received from the ESV GFP's. Consensus was reached that the ESV Forum should be used, and the United States should take a leadership role in developing a proposal for agreement among our international partners.

NHTSA Administrator, Ricardo Martinez, M.D., met with the ESV GFP's on November 5, 1995, at a meeting held in conjunction with the 107th Session of WP29 being held in Geneva. During this meeting, Dr. Martinez requested that each representative forward to the United

States their respective country's research priorities and the objective for each items submitted. He also presented the following proposal:

- Use ESV as a forum for developing an IHRA,
- March 1996 -- GFP's provide U.S. with a list of potential research topics and the objectives of each,
- April 1996 -- U.S. disseminates responses to participants,
- May 1996 -- ESV GFP Meeting
  - -- reach consensus in the selection of research topics
  - -- identify leadership
  - -- establish milestones
  - -- form working groups
- May 1996 -- ESV Plenary Executive Session -- present actions taken and status on an IHRA.

In April 1996, the U.S. sent to each of the Government Focal Points for their review, comment, and approval an aggregated list of four priority research agenda items and a proposed process/next steps. This list represented the proposals received to date from each country and provided the foundation for the meeting to be held in Melbourne, Australia on May 12, 1996. (Appendix B)

May 12, 1996 Meeting

A meeting was held with the ESV GFP's prior to the opening of the 15th International Technical Conference on the Enhanced Safety of Vehicles (ESV) for the purpose of:

- obtaining approval of proposed research priorities,
- identifying lead countries and their responsibilities,
- identifying the role of industry,
- agreeing upon process and next steps.

Nine countries, the EC, and the EEVC were represented at the meeting. (Appendix C) Dr. Martinez, gave the opening remarks, and Mr. Michael Brownlee, Associate Administrator, Safety Assurance, NHTSA, Chaired the meeting on behalf of Mr. William A Boehly, Associate Administrator for Research and Development, NHTSA. The representatives reached consensus on an International Harmonized Research Agenda consisting of the elements listed below.

Research Priorities and Lead Countries:

Based upon original input received from the participating countries, prior to the May 12 meeting, the first four research topics represented the views to date. After further discussion and input two items were added. All items were approved.

Biomechanics --United States

Develop advanced injury criteria and test surrogates for the head, neck, face, thorax, and lower limbs and develop test procedures for all crash modes.

Advanced Offset Frontal Crash Protection -- the EC/EEVC

Develop harmonized test procedures based on real world crashes to assess safety performance and compatibility for offset frontal crashes.

Pedestrian Safety -- Japan

Develop harmonized test procedures based on real world crashes to assess safety performance of passenger vehicles in their interaction with pedestrians.

Intelligent Transportation Systems (ITS) -- Canada

Develop test procedures to assess driver/vehicle interaction and safety potential of ITS crash avoidance and driving enhancement for in-vehicle systems.

Vehicle Compatibility -- EC/EEVC

Develop a harmonized method for assessing compatibility between cars (1st stage) and cars and trucks (2nd stage)

Functional Equivalency -- United States in cooperation with Australia

Develop an acceptable scientific and technical model for determining functional equivalency of existing regulatory requirements.

Process/Lead Country Responsibilities

Process

- All participating ESV countries/organizations will participate in conducting research on the research priorities.

- A permanent technical working group will meet every six months to coordinate and follow the IHRA activities. The ESV Government Focal Points will form the core for this working group. (Appendix D)

- As a cost saving measure and to utilize as many resources as possible, existing international meetings, i.e. SAE International, WP 29, ISO, etc. will be used to hold subsequent meetings for the IHRA.

- A time frame of 5 years was established for the research agenda. Some priorities, like functional equivalency will be on a much faster schedule. It was further agreed that an IHRA session(s) would be added to the ESV Conference to provide for the reporting of the research.

  2 years -- progress of research to date -- 1998 ESV Conference in Canada
  5 years -- final report -- 2001 ESV Conference -- Location to be determined

Lead Country Responsibilities

- Summary of current knowledge report
- Develop a plan which includes research objectives and end product
  - -- Identify tasks involved
    - Identify which countries will perform which tasks
  - -- Identify data collection needs
- Identify resources needed
- Establish milestones
- Establish review procedures
- Assumes responsibility for administrative process
  - -- gathering of information
  - -- writing/dissemination of report to all parties involved
  - -- planning meetings, making appropriate notification, disseminating minutes

Role of Industry and other Interested Partners

It is a given that a harmonized research agenda cannot take place without the involvement of the automotive industry, consumer groups and other interested parties. The representatives agreed that industry should be included in the research. Several points were agreed upon:

-- At the SAE meeting to be held in Detroit, February 1997, a separate meeting is to be arranged between the IHRA Committee and Automotive Industry Representatives and other interested parties.

-- The role of the automotive industry varies from country to country, therefore, each country would work with its industry between now and the February meeting.

-- That existing organizations, i.e. ISO, WP 29, EEVC Working Groups, SAE, would be used as resources to the extent possible.

-- The United States, would hold a public meeting during the Summer of 1996 to invite all interested parties, i.e. consumer groups, insurance companies, special interest groups, etc. to provide their comments and recommendations.

Next Steps

- The U.S. will prepare a written report summarizing the results of actions taken to date. After approval by the ESV GFPs this report will be presented to the WP 29 committee in June 1996.

- The first IHRA Committee meeting will be held in Geneva, November 1996, in conjunction with the regularly scheduled WP 29 meeting, but not as a part of the WP29 Session. During this separate meeting, the lead countries will provide an updated status report, and discuss any outstanding issues.

- In conjunction with the February 1997, SAE meeting a separate meeting will be held for the 2nd IHRA Committee meeting. Automotive industry representatives and other interested parties will be invited to attend the IHRA Committee meeting. During the SAE meeting lead countries will present their plans relating to the responsibilities described above.

Summary

It is important to clarify the priority research agenda item on functional equivalency. It is agreed by all parties, that this is being undertaken as a "short term" research function to develop a scientific technical model. It does not mean, nor should it be construed by any individual or organization to mean, that the participating countries have agreed to a moratorium on regulations. The objectives of the undertakings in this agenda are research, not regulatory.

As agreed by the representatives in attendance during the May 12, 1996, meeting, the results of the actions taken and agreements reached on the IHRA were presented during the Plenary Session on Opportunities for Worldwide Harmonized Regulations of the 15th ESV Conference by NHTSA Administrator, Ricardo Martinez, M.D. The conference was held in Melbourne, Australia, May 13-16, 1996.

APPENDIX A

INTERNATIONAL HARMONIZATION THROUGH COORDINATED RESEARCH

(Draft, 10/3/94)

ABSTRACT

The purpose of this paper is to suggest how to increase the involvement of international government regulatory agencies in common research areas as a means to help resolve incompatible regulations. The paper discusses the organizations currently involved in international harmonization of regulations, the challenges of harmonization and research cooperation, and several options for increasing NHTSA involvement in international research.

PROBLEM/BACKGROUND

Increasing the worldwide compatibility of vehicle safety regulations can help facilitate international trade and improve motor vehicle safety. NHTSA currently works with several organizations focusing on international harmonization. The primary forum for harmonization is the Working Party on the Construction of Vehicles (WP29) of the UN/ECE (United Nations Economic Commission for Europe). WP29 receives recommendations for regulations through working groups composed of government and industry technical representatives, including participation by the U.S. and Japan. The AAMA (American Automobile Manufacturers Association) participates in the working groups and informs NHTSA about their international harmonization activities. NHTSA Rulemaking representatives attend the government committees supporting the WP29.

NHTSA is also the primary supporter of the Enhanced Safety Vehicle Conference (ESV) which is a forum for information on worldwide research activities. A spinoff of ESV is the European Experimental Vehicles Committee (EEVC), which is composed of representatives of European government research facilities. Its purpose is to help exchange technical information between governments and ensure that they collaborate on motor vehicle research. It also acts as a technical advisor to the European Economic Community (EEC). Non-European countries can be observers in the various EEVC working groups, e.g., NHTSA representatives in Working Group 12 on the Improved Frontal Impact Dummy.

In the area of research, NHTSA has directly sponsored or coordinated work at international research organizations that may develop a basis for regulatory action. Examples of such efforts, e.g. initiating human factors research at the TNO research institute in The Netherlands to study driver response to headlight glare, coordinating basic biomechanics research at the University of Heidelberg, and coordinating vehicle to vehicle side impact testing with Transport Canada.

Although these avenues can be effective, more concerted action at the research level is needed

to provide a common basis for possible worldwide actions to harmonize vehicle components/performance, measurement procedures, definitions of regulatory terms, and specific performance values or component designs. Without strong research that is accepted worldwide, developing compatible regulations through national and regional regulatory/advisory bodies such as WP29, ISO, and the EEC may have a limited chance of success. When a government is considering a new safety regulation, the main supporting research is usually complete and the associated test devices, injury criteria, etc. are typically developed, making it too late for achieving effective compatibility of requirements.

CHALLENGES OF INTERNATIONAL RESEARCH COOPERATION TO SUPPORT VEHICLE SAFETY REGULATIONS

There are several challenges associated with international cooperative research and the development of compatible safety regulations. Many of these challenges relate to the differences in the safety environment and approaches to regulation between countries. These differences include:

The motoring environments are different in different countries. For example, the U.S. has more air bag equipped vehicles, more large cars, and different road characteristics. Also, and most important, the accident pictures are different. European and Asian countries have a larger proportion of crashes involving pedestrians, bicyclists, and motorcyclists. Also, fatalities are a larger proportion of the total harm caused by motor vehicle crashes.

The regulatory process is not the same in the different countries. The U.S does not have type approval of vehicles as Europe does. This means that in Europe, Governments are involved in the safety certification of motor vehicles and equipment. In the U.S. we have self certification in which manufacturers certify that their vehicles meet regulations.

Another challenge is the difference in the relationship between the governments and auto industry which leads to a different political environment for safety regulation. In Europe, the relationship is less adversarial than here.

Different countries have different priorities relative to their auto industry. Fuel economy and vehicle cost may supersede auto safety as areas of higher priorities. Therefore, some governments provide commensurate funding levels for automotive safety research.

In some countries, e.g., some of the European community, the regulatory organizations do not control or directly support the research organizations. Thus, there is no guarantee that the governments will be committed to turning research results into rulemaking. On the other hand, research is part of the regulatory structure in the United States.

The above factors can result in differences in research priorities and the capabilities to support certain types of research. These factors also lead to the resolution of harmonization issues that rely more on the basis of political arguments than on research findings.

An administrative issue restricting NHTSA participation in international research is that both travel funds and support staff have been consistently too limited to allow technical representatives to participate fully in overseas meetings and to sponsor meetings and coordinated research efforts.

PROPOSED APPROACH TO INTERNATIONAL HARMONIZATION-RELATED RESEARCH

To enhance the success of international research cooperation and to cultivate an environment supportive of harmonization, the international partnering should be initiated at the research and working level. It should focus on areas of commonality and comparable needs. It should aim for common test devices, common test procedures and common data exchange formats. The research should also focus on issues that are more susceptible to resolution by research support than by political factors. For example, research could be coordinated in the following areas: the response of the human body to crash forces, dummy design, the deformation of vehicle materials, the performance capabilities of drivers, advanced analytical and structural modeling tools, etc. These areas have universal research interest and the same test devices and criteria can be developed. This approach would hopefully enhance worldwide vehicle safety and may distribute the development costs even if the application of the results and the corresponding regulation are not exactly the same in different countries.

PROPOSED FRAMEWORK FOR INTERNATIONAL RESEARCH COOPERATION

The proposed framework for international research cooperation could be structured as follows:

A. Utilize the ESV forum to set up a steering committee for International Research Cooperation and Harmonization. This committee would be composed of the heads of Research and Development (R&D) of any country who wishes to participate. Logistically, this steering committee can be an ESV working committee. The basic functions of this committee are to:

   1. Identify the general topics/areas for cooperative research:

      a. Identify common existing and planned vehicle safety research areas worldwide
      b. Identify common planned regulations worldwide
      c. Identify new areas for research at international level based on a. and b. above and data needs

2. Identify research priorities under categories of:

   a. Basic research
   b. Common test procedures and formats for data exchange
   c. Development of research tools

3. Determine how to implement research:

   a. Where should research be performed?
   b. Where will funding be obtained?
   c. How will research be coordinated among interested parties?

B. For each area, set up intergovernmental research teams whose members are designated by the steering committee. Upon government discretion, consultants can be designated as team members for certain program areas. Each team will have a team leader. The position of team leader will rotate on a yearly basis from one country to another.

The team members would be represented in associated ISO, SAE, EEVC working groups/committees, etc.

They communicate through the Internet, i.e., via electronic mail as a group forum (group mailing list) with quarterly updates on progress including testing and new activities. The team leader is responsible to provide a quarterly update (via the Internet if applicable) to the steering committee. The quarterly report should provide feedback to the steering committee relating to part A. above and progress in the different research conducted.

Other than primarily sharing ideas and findings, the teams are charged with the following goals if applicable:

1. Establish/develop joint testing and evaluation programs for new procedures, instrumentation and dummy.

2. Exchange analytical models (e.g., finite element models of vehicles, dummies, and humans) advanced tools, and test data.

3. Establish harmonized formats for data interchange, and structural models of occupants and vehicles.

C. As part of the ESV International Congress that takes place every two years, set up a session on "International Research Cooperation and Harmonization" with a panel discussion by the steering committee. This session will be chaired by a steering committee member on a rotation basis from each country represented. The functions in

part A. above will be revisited at this session.

D. In each participating government, as part of the R&D office, bring in new (or currently designated) staff (one or two people) dedicated to support International Research Cooperation and Harmonization. Also, designate a new budget item to support the international cooperation effort and provide travel funds for the research team members. The support functions of the new staff include:

1. Set up and maintain the Internet group mailing list and insure communication among the research teams and with the steering committee members.

2. Coordinate and setup the ESV session

3. Coordinate with and support other agency staff that are represented in the various international bodies (in our case the Director of International Harmonization and several staff members from Rulemaking and Plans and Policy)

4. Set up meetings as needed for the different research teams and the steering committee.

ALTERNATIVE PROPOSED FRAMEWORKS

1. NHTSA could solicit topics for international research cooperation with a Federal Register Notice and dissemination of the notice overseas to various international organizations and government regulatory agencies. NHTSA could then identify the high priority research issues related to a critical harmonization problem. NHTSA could solicit international partners to plan, fund, and conduct the research based on the research priority, feasibility, and availability of funding.

2. NHTSA could request the EEVC set up working groups to formulate specific research statements of work, identify experts to participate, fund the research, monitor the progress, and report the results to the ESV conference. The EEVC could arrange for the working group leaders to set up e-mail communications via INTERNET with all parties interested in the research topic. Although, EEVC is primarily a European organization, it has been opening its deliberations to other countries and thus may be a good forum for international research cooperation.

APPENDIX B

April 8, 1996

Dear:

Over the past several months, in response to the International Harmonized Research Agenda (IHRA) meeting held on November 9, 1995, in Geneva, many of you have sent us your country's research priorities. During this meeting, it was also agreed to hold a subsequent meeting at the 15th ESV Conference in Melbourne, to:

- arrive at an agreed upon set of priorities.
- identify a lead country for each priority,
- agree upon a process,
- agree upon the next steps,
- make an announcement on actions taken to date.

Before I get to the proposals and our next steps, I want to share with you a couple of related items.

1. Meeting Date. Based on the responses received, from you the Government Focal Points, it is a pleasure for me to extend to you an invitation to attend the Harmonized Research Agenda meeting with Dr. Martinez, SUNDAY, MAY 12, 1996, 2:30 p.m. - 4:30 p.m.. The meeting location is the Howqua Room, World Congress Centre, Melbourne, Australia.

2. EEVC Participation. While examining the enclosed materials, you will notice there is no formal response from the Chairperson of the EEVC. I am, however, pleased to inform you that we held an informal telephone conversation with the EEVC Chairperson, and shared with him the responses received. While he could not give a commitment for the EEVC to take a leadership role, or become an active participant without first consulting with the participating countries, he has indicated an interest for the EEVC to become an active participant in this effort.

In an effort to help facilitate the process of identifying international research priorities, we have received proposal from many countries (these are enclosed as Attachment A). To move to the next step of developing the research priorities that all could agree upon, the United States synthesized the proposals in order to develop the research priorities. These research priorities

reflect what the majority of countries felt should be undertaken. The proposed list is enclosed as Attachment B. As the next step, prior to the meeting in Melbourne, we would ask that you

- provide us with your approval and/or comments on the recommended priorities,
- make a recommendation or assume a leadership role for each priority,
- provide comments on the proposed process/next step.

Recognizing that the Conference is four weeks away, and to allow for enough time for the U.S. to provide you with additional feedback, please provide your response by April 20th. The enclosed form has been developed in an effort to expedite this request.

Also enclosed you will find information regarding:

Suggested Process/Next Step (Attachment C),
Proposed Agenda for May 12 meeting (Attachment D), and
Response Form (Attachment E).

In closing, it is with deepest regrets that I must tell you that I cannot attend the 15th ESV Conference due to unforeseen personal matters. My colleague, Mr. Michael Brownlee, Associate Administrator for Safety Assurance will be representing me during the Conference, and will serve as Conference Chair along with Mr. Peter Makeham. I wish you a most successful conference. I am confident that Mr. Brownlee will demonstrate the leadership role deserving of this vital event, as well as address any issues or concerns that may arise during the conference, the Government Focal Point luncheon and the Harmonized Research Agenda meeting. As always, Linda and I stand ready to be of any assistance or answer any questions you may have.

Sincerely,

William A. Boehly
Associate Administrator for
Research and Development

Enclosures

Telephone: 202-366-5929
Telefax: 202-366-5930

INSTITUT NATIONAL DE RECHERCHE
SUR LES TRANSPORTS ET LEUR SÉCURITÉ

L'Ingénieur en Chef des Ponts et Chaussées
Directeur délégué du Centre de Lyon-Bron
Le Directeur Général Adjoint

BRON, le 20 Février 1996

FAX TO M. BOEHLY
ASSOCIATE ADMINISTRATOR FOR R. and D.
NATIONAL HIGHWAY TRAFFIC AND SAFETY ADMINISTRATION
U.S. DOT

....

SUBJECT : global research and development program for safety vehicle standardization.

I apologize not to answer quicker to your proposal about the setting up of a global research and development program for safety vehicle standardization.

Firstly France thinks that on behalf of European Union Treaties it is impossible to answer directly to your question at a level that is not a European one.

Secondly for this purpose, France supports the idea that the good body should be E.E.C.V. where the State members DOTs of E.U. are members as public research institutes involved in safety standardization research programs.

Thirdly, the needs for research program for preparing standardization are discussed and presented to share funding between E.U. and State members.

Fourthly for France, the only acceptable international forum for the harmonization is the WP 29 of UNO EEC in Geneva.

Fifthly, it should be - within the budget reducing context - the one possibility for European State members to take case of this problem.

With my best regards

Jean-Pierre MÉDEVIELLE
Deputy General Director of INRETS
ESV French Governmental Focus Point

c.c.: M. FRIEDEL Chairman of EECV
A.BODON Directeur de la Sécurité et de la Circulation Routières

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Mr William A Boehly
Associate Administrator, R&D
NHTSA
400 Seventh Street. S.W.
Washington
D.C. 20590

Date: 24 January 1996

Dear Mr Boehly

International Harmonisation of Research.

Thank you for your letter of 26 December 1995, enclosing the presentation made by Dr Martinez in Geneva. This was very helpful since, regrettably, I was unable to attend the meeting in Geneva.

I shall be please to participate in the proposed meeting in Melbourne. I can attend at any of the times suggested, but my preferences (in order) would be Sunday 2 - 5:30 and Friday 9:30-12:30.

I have discussed the list of research topics that might be suitable for a harmonised approach with my colleagues in the UK DoT and you will receive a consensus response on that from Malcolm Fendick.

I am very enthusiastic about a cooperative approach to researching the problems of vehicle safety and, indeed, made that point strongly in my paper to the 1991 SAE Govt/Industry meeting in the session on the biomechanics research needs for the 1990s. I also try to ensure as wide an input as possible to the EEVC Working Groups that I chair. Apart from the obvious optimisation of resources, it should form a good basis for a degree of harmonisation of test procedures, if not complete regulations, At least the legislative procedures would be based on the same common knowledge base.

Yours sincerely

Richard Lowne

THE DEPARTMENT
OF TRANSPORT

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Mr William A Boehly
Associate Administrator for
Research and Development
US Department of Transportation
National Highways Traffic Safety
Administration
400 Seventh Street S.W.
Washington, D.C. 20590

25 January 1996

Dear Mr Boehly

Thank you very much for your letter of 26 December to Malcolm Fendick on the harmonisation of research. I have been asked to reply as I will be representing Mr Fendick at the ESV Conference in Melbourne.

We have discussed with TRL the areas of research which we both feel will be suitable for international harmonisation. These topics are:-

Priority	Title/Description
1	Biomechanics and (Frontal) dummy development
2	Development of a new generation of side impact dummies
3	Brake compatibility of vehicle combinations
4	Antilock brakes, their influence on accidents
5	Crashworthiness compatibility of cars
6	Impact testing for motorcycles
7	Development of a range of new child dummies

With regard to the discussions to be held at the 15th ESV in Melbourne I would suggest meeting earlier In the week rather than at the end and therefore the two periods which I favour would be:

2:00pm - 5:30pm - Sunday May 12

5:30pm - 8:30pm - Thursday May 16

Hopefully this will allow our return flights to be booked on Friday May 17.

I look forward to meeting you at the Conference.

Yours sincerely

KEITH RODGERS
Vehicle Standards & Engineering Division

TELEFAX TELEFAX TELEFAX TELEFAX TELEFAX

Date: March 10, 1996 Pages: 1 + 3

To: Mr William A. Boehly, Ass. Administrator for Research & Development, NHTSA, Washington DC, USA

Fax: 0091 - 202 366 5930

From: Kåre Rumar, SNRA, S-781 87 Borlänge, Sweden
Fax office: + 46 243 75 773

Re. Harmonized vehicle research within ESV

Dear Mr Boehly,

Attached you will find my comments and answer to the US initiative and suggestions. Initially I have tried to structure my comments and after that I am presenting my suggestions for a prioritized list of research topics. These topics are split into two parts -- active and passive -- which I consider to be almost incomparable.

A. Comments

1: Do we need a better coordination of vehicle safety research with the purpose of reaching worldwide harmonized vehicle regulations in the area of road safety?

- Yes!

2: Is ESV the right forum for such a worldwide coordination?

- Yes and no! EEVC is presently doing a very good job, of course in Europe and especially within some prioritized areas. That work should not be disturbed but coordinated with corresponding actvities in other regions. ESV has the advantage of working world wide and having a natural forum for presentation and discussion of the research -- the conference. One important aspect is that vehicle safety research should be more open. That speaks for ESV. There are various ways to solve this potential conflict. Such a solution should also involve UN ECE WP 29 and its working groups because it is there that most of problems appear and where most of the decisions are made.

B. Prioritized research topics

See attached list!

Yours sincerely

Kåre Rumar
Professor

K. Rumar, Sweden March 8, 1996

Prioritized research topics

These proposals are split into two parts - active safety and passive safety. During the last decades we have no doubt been more successful in the area of passive safety to a large extent due to initiatives coming from ESV. Personally I think the concept of risk compensation has been misused in the meaning that it has been argued that improvement of active safety is impossible due to risk compensation. As I see it that is the wrong conclusion. More knowledge of the risk compensation mechanism should be used to come up with proposals of how to prevent risk compensation (e.g. by speed limiters).

A. Research proposals to improve active vehicle safety

1. Task: Study the interaction between driver behaviour and vehicle characteristics concerning active safety (risk compensation)
Objective: Develope harmonized methods and techniques that make it possible to tailor vehicle characterstics to driver characteristics, to prevent risk compensation reactions and to predict the safety potential of various active safety systems (brakes, steering, stability, visibility, conspiquity, speed limiters, belt usage control, black boxes etc)

2. Task: Analyze the safety effects of various proposed in-car-ITT systems (navigation, ICC, collision avoidance, driver monitoring etc)
Objective: Establish harmonized requirements on in-car ITT systems -- especially long time effects, effects of function integration (adding of several functions) and effects of system malfunctioning. The purpose is both to avoid increasing risks and to to Increase safety

3. Task: Study stability, steerability and braking performance of vehicles especially in curve driving and avoidance maneouvres -- both heavy vehicles and vehicle combinations and passenger cars
Objective: Harmonize test methods and based on those methods establish harmonized stability, steerability and braking performance requirements that will increase safety especially of heavy vehicles and vehicle combinations. This includes IT-functions that improve vehicle handling characteristics.

4. Task: Study vehicle headlight performance especially the low beam function
Objective: Establish harmonized headlight requirements that will increase driver visibility conditions and thereby safety in night traffic

5. Task: Study methods for accident-in-depth investigations
Objective: Establish improved and internationally agreed methods to study accidents by means of accident-in-depth methods

B. Research proposals to improve vehicle passive safety

1. Task: Study the chock mechanisms, the tolerances and the injury criterias of the neck in car crashes
   Objective: Establish harmonized test methods and criterias to be used in crash tests and in simulations

2. Task: Study various ways to design intelligent protection systems
   Objective: Establish needs and methods to trigger and control the characteristics of the protection systems based on individual parameters and position, on the crash condition and seriousness. Establish harmonized requirements on intelligent protection systems

3. Task: Study the construction variables that decide the crash performance of cars in real crashes.
   Objective: Establish an international rating system that makes it possible to predict already in the construction phase the crash performance of the car in real crashes

4. Task: Study vehicle compatibility in various collision types, especially between heavy vehicles and passenger cars (NB this is a project where EEVC (WG 15) is active and proceeding)
   Objective: Establish harmonized compatibility requirements on various types of vehicles to reduce injury patterns (NB this compatibility task should also include two-wheelers)

5. Task: Study the collision characteristics in various collisions between car and road side furniture (poles, trees etc)
   Objective: Establish harmonized car and road furniture design that Interact to minimize the violence on the human body in car collisions

6. Task: Study crash characteristics In higher speeds (more than 70 kmh)
   Objective: Establish harmonized vehicle requirements that reduce the violence against the human body at car collisions in higher speeds

7. Task: Study the relation between seat performance and injury patterns in various car collisions - especially rear end collisions (NB this project is related to and partly an alternative to project 1 above)
   Objective: Establish harmonized seat requirements that reduce human injury,severity and frequency in car collisions - especially rear end collisions

8. Task: Study the crash biomechanics, the tolerances and the injury mechanisms of the brain in car crashes
   Objective: Establish harmonized injury criterias to be used in crash tests, in simulations

9. <u>Task</u>: Develope an improved frontal collision dummy which better corresponds to the performance of the human body (NB this is a project where EEVC is active)
<u>Objective</u>: Use that harmonized and more valid collision dummy in national and international testing of vehicle performance in collisions

10. <u>Task</u>: Develope an improved side collision dummy (global SID) which better corresponds to the performance of the human body
<u>Objective</u>: Use that harmonized and more valid side collision dummy in national and international testing of vehicle performance in collisions

11. <u>Task</u>: Study the the violence and injury patterns caused by vehicles on pedestrians in collisions (NB this is a project where EEVC already has a proposal)
<u>Objective</u>: Specify harmonized functional requirements on vehicle fronts in order to reduce pedestrian injuries in collisions with cars

12. <u>Task</u>: Develope methods that make it possible to predict from vehicle and vehicle component design and protection system the violence on the human body in car collisions
<u>Objective</u>: Agree on harmonized prediction methods to estimate the violence against the human body in car collisions

K. Rumar
Sweden

Nov 6, 1995

Preliminary proposals within an internationally coordinated research aiming at improved and harmonized vehicle safety standards.

A: Passive safety

- The shock biomechanics, tolerances and injury mechanisms of the brain
- The shock biomechanics, tolerances and injury mechanisms of the neck
- Side collison dummy (global SID)
- Vehicle compatibility in various collision types
- Vehicle seat performance to protect from rear collision injuries
- Protection against lower limb injuries in frontal collisions
- An improved frontal collision dummy corresponding better to the performance of the human body
- Vehicle protection performance at very high speeds (more than 70 kmph)
- Reduced violence levels from heavy vehicles in collisions
- Reduced violence levels from automobiles in collisions with pedestrians
- Interaction between road furniture and vehicle characteristics in collisions
- Shutterless, scratch resistant and energy absorbing vehicle windows
- A general description of present knowledge concerning human biomechanical limitations
- Development of methods to predict the effect on collision safety of various vehicle designs, protection systems and other factors
- Intelligent protection systems
-

B. Active safety

- Development of methods to predict the safety potential of various active safety systems (e.g. braking, steering, stability, visibility, conspicuity etc)
- Safety potentials of various proposed IT-functions (e.g. navigation, ICC, collision avoidance, driver monitoring, etc)
- Improved braking performance especially of heavy vehicles and vehicle combinations
- Harmonized and improved vehicle headlight performance (especially low beam)

Transport Canada / Transports Canada

Surface / Surface

344 Slater Street
Ottawa, Ontario
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December 15, 1995 ASF 1206-2

Mr. William A. Boehly
Associate Administrator for
Research and Development
National Highway Traffic Safety Association
Department of Transportation
400 Seventh Street, S.W.
Washington, D.C., 20590
U.S.A.

Dear Mr. Boehly:

In response to the meeting held in Geneva with Dr. Martinez, I have attached two lists of activities we suggest for consideration as international cooperative research: one deals with biomechanical tolerance data and injury criteria, and the other deals with human factors related research.

In addition, we reviewed and fully support the list of detailed items provided by Mr. K. Rumar of Sweden that was handed out at the meeting in Geneva (copy attached).

As I stated at the meeting, we welcome and look forward participating in this endeavour.

Yours truly

Harvey J. Layden
Director
Motor Vehicle Standards & Research

Attachments

BIOMECHANICAL TOLERANCE DATA AND INJURY CRITERIA

BACKGROUND

The performance of vehicles in protecting their occupants is commonly evaluated by measuring specific responses of anthropomorphic dummies in simulated collisions. Those responses are then (usually) manipulated in some way, so that the results may be compared with the values of various injury criteria. The values of the criteria are intended to represent the levels of specific types of mechanical insult that are toelrable by defined subsets of the population of vehicle occupants.

The criteria and the associated performance levels are, however, often set by reference to data obtained twenty or more years ago, under poorly defined and controlled experimental conditions and using primitive data acquisition systems. The validity of the resulting criteria and associated tolerance levels may further be called in question by fundamental errors of experimental design and analysis. Basic errors embodied in the formulation of injury criteria that are widely accepted to-day include:

(1) assuming that the occurrence of human injury under a range of different *dynamic* conditions may be predicted from a rigid-body *kinetic* response of a dummy;

(2) assuming the existence of a statistical association between a dependent (response) variable and an independent (input) variable when all accepted statistical methods show inputs and responses to be uncorrelated;

(3) defining an injury criterion exclusively on the basis of statistical association, in the absence of any basis in mechanics for the relevant injury mechanism.

PROPOSAL

A two-stage approach is suggested. In the first stage, the theoretical and experimental bases of the principal existing injury criteria would be subjected to an impartial and objective review, concentrating on such fundamental questions as the validity of experimental designs, the control of experimental conditions and measurements and the statistical analysis and interpretation of results. (In this context, impartiality implies that authors of the original work leading to a particular criterion not be parties to the review.)

Having conducted the review of existing injury criteria and associated levels, an international co-operative research plan might then be proposed to remedy deficiencies in the formulation of specific criteria or in the empirical basis of existing criteria and tolerance levels.

Selected[1] Human Factors Research Needs in Traffic Safety: Opportunities for Collaboration

1. Intelligent Transport Systems

Basic research issues
- safety evaluation test protocol development
- workload measurement and regulation
- ITS and behavioural adaptation

Applications
- collision warning systems: human factors considerations
- driver impairment detection and intervention
- cellular telephone use: impact on safety
- human factors performance standards for navigation systems
- HUD performance criteria
- legibility criteria for visual and auditory in-vehicle displays

2. Vision and Lighting
- issues related to driving with enhanced vision systems (IR, laser radar) under visually degraded conditions due to driving at night, in fog, rain, snow, etc: e.g., effects of display location, field of view, and transfer of visual orientation.
- indirect vision enhancement (proximity sensors)
- definition of requisite visibility areas for window size and location, mirrors, obstruction due to headrests and other vehicle structures
- effects of vehicle styling: e.g., window rake angle, etc.
- night driving performance
- window tinting

3. Fatigue
- role of sleep-deprivation, task monotony and stress on the nature and extent of fatigue
- fatigue interventions (trucks, private motor cars)
- role of habituation in accident causation (resulting from radical change in road and/or vehicle environment)

4. Restraint Usability
- child restraint system usability
- usability criteria for lap and shoulder belts
- human modeling - anthropometric criteria

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[1] Pertaining to ASF mandate. There are numerous other Human Factors issues pertaining to older drivers, driver training and licensing, etc.

PROPOSED INTERNATIONAL R & D PROJECTS
(In order of priority for Canada)

1. OCCUPANT RESTRAINT SYSTEMS

Seat Belts:
- ◇ Belt Deployment Test Device (BTD)
- ◇ Reduction of Abdominal Injuries

Supplemental Restraints (Air Bags):
- ◇ Deployment thresholds, e.g. seat belts worn or not, seat occupied or not
- ◇ Aggressivity

Child Restraints:
- ◇ Incompatibility of CRS and seat belts
- ◇ ISOFix, CANFix, and other potential attachment mechanisms as alternatives (GM Clinic)
- ◇ Tether anchorages

Other Technology:
- ◇ Load Limiter
- ◇ Pretensioner
- ◇ Air Bags Sensors

Restraint Usability:
A major problem with existing occupant restraints is poor usability (ease of correct use) and/or fit. In the case of children, available evidence suggests that approximately one third of child passengers in automobiles are not properly restrained in infant or child restraint systems (CRS) and, consequently, are exposed to increased risk of injury in the event of collision. A significant part of the problem is incorrect installation of the CRS in the vehicle. There is a need to improve the compatibility of CRS and vehicles. There is also a need to develop a standardized usability test procedures for measuring the ease with which a CRS can be correctly installed. A recent Transport Canada study employed a usability protocol to identify specific design problems with CRS's and provide valuable information on user behaviour. Further development of the protocol is required before usability testing can become required practice within the restraint system industry. Similarly, there is a need to develop usability critera for all classes of occupant restraints. Relevant issues include:
- ◇ child restraint system usability - development of test protocol
- ◇ development of usability criteria for lap and shoulder belts;
- ◇ human modeling - antropometric criteria

.../2

2. HUMAN IMPACT TOLERANCE DATA AND INJURY CRITERIA

BACKGROUND

The performance of vehicles in protecting their occupants is commonly evaluated by measuring specific responses of anthropomorphic dummies in simulated collisions. Those responses are then (usually) manipulated in some way, so that the results may be compared with the values of various injury criteria. The values of the criteria are intended to represent the levels of specific types of mechanical insult that are tolerable by defined subsets of the population of vehicle occupants.

The criteria and the associated performance levels are, however, often set by reference to data obtained twenty or more years ago, under poorly defined and controlled experimental conditions and using primitive data acquisition systems. The validity of the resulting criteria and associated tolerance levels may further be called in question by fundamental errors of experimental design and analysis. Basic errors embodied in the formulation of injury criteria that are widely accepted today include:
(1) assuming that the occurrence of human injury under a range of different *dynamic* conditions may be predicted from a rigid-body *kinetic* response of a dummy;
(2) assuming the existence of a statistical association between a dependent (response) variable and an independent (input) variable when all accepted statistical methods show inputs and responses to be uncorrelated;
(3) defining an injury criterion exclusively on the basis of statistical association, in the absence of any basis in mechanics for the relevant injury mechanism.

PROPOSAL

A two-stage approach is suggested. In the first stage, the theoretical and experimental bases of the principal existing injury criteria would be subjected to an impartial and objective review, concentrating on such fundamental questions as the validity of experimental designs, the control of experimental conditions and measurements and the statistical analysis and interpretation of results. (In this context, impartiality implies that authors of the original work leading to a particular criterion not be parties to the review.)

Having conducted the review of existing injury criteria and associated levels, an international co-operative research plan might then be proposed to remedy deficiencies in the formulation of specific criteria or in the empirical basis of existing criteria and tolerance levels.

.../3

3. COLLISION AVOIDANCE

Intelligent Transport Systems
Advanced in-vehicle transport information and control systems introduce auxiliary tasks that require some degree of interaction with the driver. To minimize the risk of driver distraction, confusion or overload it is important for designers and regulators to understand the performance tradeoffs of alternative driver interface designs. Previous Transport Canada studies have attempted to determine the potential of auxiliary tasks to interfere with driving and to develop specialized techniques for evaluating the ergonomics and safety of such systems. Current research is aimed at further developing experimental paradigms for safety evaluation and applying these to address specific issues such as the relative safety of visual and auditory auxiliary displays. Related research issues which would benefit from international collaboration include:

- ◇ safety evaluation test protocol development
- ◇ workload measurement and regulation
- ◇ ITS and behavioural adaptation

Human Factors - Vision and Lighting:
There are a multitude of vision and fighting research issues, some of which are fundamental in nature but remain unresolved and others which arise from advances in automotive technologies. There is a need to consolidate the data that do exist and to embark on new research to advance our knowledge in the area. The topics listed below illustrate the breadth of this area.

- ◇ issues related to driving with enhanced vision systems (IR, laser radar) under visually degraded conditions due to driving at night, in fog, rain, snow, etc. e.g. effects of display location, field of view, and transfer of visual orientation
- ◇ indirect vision enhancement (proximity sensors)
- ◇ definition of requisite visibility areas for window size and location, mirrors, obstructions due to headrests and other vehicle structures
- ◇ effects of vehicle styling, e.g. window rake angle, etc.
- ◇ night driving performance
- ◇ window tinting

Data Recorders
There is a widely held opinion that crash avoidance would be advanced if more information were available about vehicle and driver parameters in the moments leading to a crash. Technology is available to capture and record certain data in a vehicle "black box" for use by researchers and traffic authorities. The development and widespread implementation of this kind of initiative has not received serious attention to date largely because it is likely to have low public acceptance.

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There are certain classes of vehicles and groups of drivers, however, for which such devices could be targeted. A collaborative research project aimed at exploring the feasibility of the concept and developing a standard data recorders may have an important influence on future crash avoidance directions. In particular there is a need to identify the critical variables that could be recorded, assess their value in terms of their contribution to a more complete understanding of the causes and precursors of the crash, and specify technical requirements for the data (e.g., resolution, sampling frequency, recording duration, etc.).

4. REAR IMPACT PROTECTION

Rear Restraints/Seat Back Strength:

◇ Identification of updated Counter-measures
◇ Validation of Counter-measures

5. SIMULATED TESTING/MODELING

This project is aimed at exploring the possible use (and limitations) of computer modeling not only for design work, but also for testing, certification and compliance verification. Proper seat belt fit is one application currently being studied by Transport Canada.

Federal Office of Road Safety

Office of the Director
Peter Makeham

Our Ref: K95/830

Mr. William A. Boehly
Associate Administrator for Research and Development
National Highway Traffic Safety Administration
Department of Transportation
400 Seventh Street SW
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USA

Dear Mr Boehly

Thank you for your letter of 26 December 1995 regarding the discussions during the meeting on the international harmonisation of research in Geneva last December.

As I articulated in Geneva, Australia supports broader international cooperation at the research stage to develop globally harmonised vehicle safety standards. In order of priority, Australia sees the following research topics as worthy of our resources into the next century:

- Offset frontal crash standard to address lower extremity injuries
- "Smart" airbag systems
- Harmonised side impact standard
- Pedestrian Safety
- Vehicle Compatibility
- Intelligent Transport Systems

The attached paper expands on these topics and provides the objectives of each project.

I also think we need to give attention to the process side of the issue - how do we go about harnessing the collective expertise to produce harmonised requirements? While history is not encouraging, I think we need to take advantage of what I see as an opportunity to set effective processes in place. The EEVC work on offset frontal crash protection might offer a useful model.

I agree with your proposal to have a meeting with the ESV focal points on these issues in Melbourne. My preferences for a meeting time would be (in order of preference) Sundav May 12, Thursdav May 16 or Friday May 17 but I would, of course, be please to fit in with any consensus decision. An issue to be taken into account is that by Thursday, delegates will have been there for four days' and there is a likelihood of "conference fatigue". On this basis, Sunday might be a better choice if this is possible.

Thank you for inviting me to comment on these issues. I believe that the initiative is worthwhile and you have our support.

Yours sincerely

Peter M. Makeham
19 January 1996

PRIORITY RESEARCH TOPICS
(Submitted by the Australian Federal Office of Road Safety)

INTRODUCTION

Vehicle safetv research relies on crash statistics to tell us what the problem areas are. Accident statistics tell us that frontal and side impact crashes cause the majority of road trauma each year. In addition, pedestrians account for nearly 20% of fatalities annually.

We generally have good information on fatalities. What the statistics don't tell us very well is a detailed breakdown of what injuries to focus on and the how they are caused. There are many injuries which result in lifelong debilitation which translates to enormous social cost.

We believe that there is a need to give more attention towards injury reduction. While many of the countermeasures will reduce both deaths and injuries, there may be areas of investigation which have the potential to reduce injuries per se; eg mitigation of leg injuries by better design.

The globalisation of the vehicle industry and the various economic forums involving countries in different continents are providing impetus to the development of globally harmonised standards.

Australia believes that the **BIG** problems are the same - frontal and side impacts, and pedestrian safety. The smaller problem areas are those unique to particular countries.

1 AN OFFSET FRONTAL CRASH STANDARD TO ADDRESS LOWER EXTREMITY INJURIES

Objective

Mitigate debilitating lower extremity injuries in offset frontal crashes

Discussion

The National Injury Surveillance Unit's report "Road Injury in Australia 1991" shows that patients with lower extremity injuries are hospitalised longer than any other type of injury, including head injuries. You don't die from leg injuries but the debilitation is lifelong.

Australia has been participating in the work of the European Experimental Vehicle Committee to develop a globally harmonised offset frontal crash test procedure.

Recent developments in Europe is expected to see the adoption of the EEVC work as an EEC directive early next year for implementation around 1999. It is expected that a complementary ECE Regulation be finalised and adopted very shortly.

FORS has commissioned a project to examine the likely benefits of introducing an offset frontal crash Protection ADR in addition to the full frontal rigid barrier standard (ADR 69/00).

This draft ADR on offset frontal crash protection based on the work coordinated internationally by the EEVC will be released for public comment in early 1996 and will include a draft Regulatory Impact Statement. This ADR will focus on reduction of intrusion based injuries particularly lower extremities.

2 "SMART" AIRBAG SYSTEMS

Objective

Maximise the protection offered by airbag systems

Discussion

We already have an Australian Design Rule (ADR 69/00) in place for full frontal, high deceleration crashes based on injury criteria which will see most cars fitted with at least driver's side airbags. ADR 69/00 is essentially US FMVSS 208 except the test is only performed with the dummies restrained.

Coupled with our high seat belt wearing rate, this should see a significant reduction in fatalities and serious injuries.

However, there is scope for manufacturers to develop "smart" airbag systems which can detect whether there is an occupant in the passenger seat as well as the mass, and seating position of the occupant to enable the best firing algorithm to be used to maximise the protection provided by the airbag system.

This issue is particularly relevant in the US where the requirement is to protect both the unrestrained and the restrained occupant. This has led to injuries from aggressive airbag systems.

It is important that these issues are taken forward at an international level so that any standards flowing from this work are harmonised.

3 HARMONISED SIDE IMPACT STANDARD

Objective

Harmonised dynamic side impact standard to maximise protection in a side impact crash.

Discussion

There are two dynamic side impact regulations - US FMVSS 214 and ECE Regulation 95. While the intent of the two regulations are similar, the actual test procedures and injury criteria are quite different. Although some work was done initially to arrive at a harmonised standard, there is currently no activity in this area.

Vehicle manufacturers are forced to make minor design changes to the same model to make it comply with the two standards. With the global nature of the car industry it seems to make economic sense to have to design each model to one harmonised dynamic side impact regulation.

4 PEDESTRIAN SAFETY

Objective

Reduce pedestrian road trauma.

Discussion

In Australia, pedestrians account for nearly 20% of fatalities annually. These are generally children and the aged. Similar figures are seen in other developed countries while some emerging countries are much higher.

Currently there are no requirements to measure the "pedestrian-friendliness" of a passenger car's front structure. There is a draft EEC directive as a result of work done by the EEVC but this has not been finalised into a regulation. There is an ISO working group developing a test procedure for vehicle front structures.

FORS has commissioned a literature review of recent research into the issue of pedestrian friendly vehicle front structures. This is the first part of a process of developing requirements aimed at producing pedestrian friendly vehicle front structures.

5 VEHICLE COMPATIBILITY

Objective

Ensure that passenger vehicles of disparate size provide equal levels of occupant protection.

Discussion

With all the recent and upcoming changes to vehicle structures and restraint systems aimed at improving occupant protection in frontal and side impacts, the issue of vehicle compatibility will become increasing important.

The fleet consists of vehicles of differing configurations, masses and sizes. Our job would be much easier if everyone drove around in identical vehicles. Unfortunately, this is not the case and the inescapable laws of physics mean that when a large heavy vehicle collides with a smaller, lighter one, the former will be the winner.

How do we provide occupants of small light vehicles the same level of protection in crashes with disparate vehicles?

This question of vehicle compatibility will occupy the efforts of road safety researchers for many years to come. Crash energy management is a closely related issue and is an important area that needs to examined when looking at the small percentage of crashes at high speeds.

6 INTELLIGENT TRANSPORT SYSTEMS

Objective

Ensure compatible systems are developed for crash avoidance technology.

Discussion

In recent years, there has been much work on developing intelligent vehicle systems for satellite navigation, vehicle tracking, crash avoidance and other means to improve vehicle safety in adverse traffic and weather conditions.

While there are groups overseeing the compatibility issues overall, it would probably be useful to have a vehicle systems focus on this work.

MINISTRY OF TRANSPORT

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April 11, 1996

Mr. William A. Boehly
Associate Administrator for
Research and Development
National Highway
Traffic Safety
Administration

Dear Mr. Boehly,

I have received your facsimile dated on 26th December from Mr. Watanabe for MITI.
But, we, Ministry of Transport, has been the Japanese Focal Point concerning the project of harmonization of research. So, please providing to me the information concerning this project.
I am enclosing a list of prior potential research topics and objectives of our country. we apologize for the delay in your receiving these document.
I hope you will find this information helpful. And I inform you that Mr. Shimodaira, Director of Engineering Planning Division, Ministry of Transport, will attend the next meeting in Melbourne.
And, Mr. Shimodaira's available data for meeting is following,

5:30 p.m. - 8:30 p.m. - -Thursday, May 16

sincerely

Masakazu Kume
Dircetor
Office of International Affairs
Engineering Planning Division
Engineering and Safety Department
Road Transport Bureau
Ministry of Transport

Japanese list of Prior Potential Research Topics and Objectives

The order in this list is not related to our priority.
The item with "O" are most prior research topics and objectives in our country.

O1. *Further international harmonization of light distribution characteristics of headlumps* (starting FY1997, term 4years)
[Abstract of research]
Concerning the tight distribution characteristics of headlumps, the proposal of international harmonized regulation for four common points has been prepared. But, in order to harmonize the regulation completely, we will study to harmonize the regulation about other point and criteria.

O2. *International harmonization of geometric visibility requirements for the installation of lighting and light-signalling devices*
(starting FY2000, term undecided)
[Abstract of research]
The proposal of international harmonized regulation for installation of lighting and light signalling devices has been prepared, but the geometric visibility requirements will be studied in ECE/WP29/GRE. We will study to harmonize the regulation about these requirements based on scientific ground.

3. *Electromagnetic Consistent Character(EMC) of electric devices of motor vehicles*
(starting FY1996, term 3years)
[Abstract of research]
The tendency of adopting the electric devices on motor vehicles is encouraged in the future. In EU, these requirement have been studying to standardize, And thereafter, In ECE/WP29/GRE, these requirement will be discussed Considering these tendencies, we study to get the basic data in order to establish our regulation.

4. *Injure and Shock Tolerance in the each parts of human body*
(starting FY1992, term 5 ~ 10years)
[Abstract of research]
In order to get the basic data to establish our future regulation, we study to make clear the relationship between intensity(tolerance) or possible moving range of the each parts of human body and injury, analyze the injury mechanism in the each parts of human body in the traffic accidents.

5. *Dummy characteristics*
(starting FY1996, term 3years)
[Abstract of research]
In order to contribute to making world common dummy, we will study the characteristics of future dummy developed in foreign countries.

6. *Future frontal collision test*
(starting FY1996, term 3years)
[Abstract of research]
We will study the test by offset deformable barrier, studying as frontal collision of next stage, and we will collect the basic data to decide the future frontal collision test.

7. *Lateral collision test*
(priority D, starting FY1995, term 5 ~ 10years)
[Abstract of research]
In order to get the basic data to making international harmonized regulations of lateral collision test, superior to existed test in the points of reproducebility and repeatability.

8. *Pedestrian Protection*
(starting FY1992, term 5 ~ 10years)
[Abstract of research]
In order to get the basic data to study the improved measures, standards or regulations to decrease the damage of pedestrians, we study the data of pedestrian accidents.

9. *Protection of the passenger of trucks and buses*
(starting FY1996 term 5years)
[Abstract of research]
We will study to get the basic data for improvements of vehicle structure for protection of the passenger of trucks and buses, thinking it problem socially recently.

10. *ITS*
(starting FY1996, term 5 ~ 10years)
[Abstract of research]
We will study the measures of structures and devices of motor vehicle in the ITS technologies.

11. *The measures for Traffic Safety*
(starting FY1996, term 5 ~ 10years)
[Abstract of research]
After we will research for the traffic situation, the realities of traffic accident in our country and other countries, we will collect the basic data in order to establish or revise our safety regulations in future.

APPENDIX C

International Harmonized Research Agenda Meeting
Sunday, May 12, 1996
Attendees

Attendee	Country/Organization
Mr. Peter Makeham and Mr. Dennis McLennan	Australia
Mr. Harvey Layden Mr. Dainius Dalmotas	Canada
Mr. Herbert Henssler	EC
Dr. Prof Bernd Friedel	Federal Republic of Germany and the EEVC
Mr. Jean-Pierre Medevielle	France
Mr. Takashi Shimodaira and Mr. Naoki Esumi, Mr. Yoshiyuki Mizuno	Japan
Mr. W. Przybylski	Poland
Mr. Kare Rumar	Sweden
Mr. Keith Rodgers and Mr. Richard Lowne	United Kingdom
Mr. Michael Brownlee and Mr. Frank Turpin, Ms. Linda O'Connor	United States
Dr. Ricardo Martinez Opening Remarks	United States

APPENDIX D

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