REAL WORLD OLDER OCCUPANT CRASH DATA AND SENSITIVITY OF THOR-NT AND WORLDSID DUMMY THORACES

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ABSTRACT

Thoracic injury to elderly occupants in motor vehicle crashes is a serious concern. If these injuries to elderly occupants are to be reduced, several things need to be considered: 1) How is crash severity (Delta V) related to serious thoracic injury of older occupants? 2) Are crash test dummies sensitive enough for use in estimating thoracic injury risk to older occupants? and 3) What are the injury measurements in advanced dummies related to injury risk for older occupants?

Analysis of National Automotive Sampling System Crashworthiness Data System (NASS CDS) cases was performed to study the relative risk of serious thoracic injury among younger and older males and females, examine the distribution of Delta V (velocity change) for older occupants with serious thoracic injury, and identify Delta V's with the largest percentage of older occupant serious thoracic injury cases in frontal and side impacts. Cases of occupants in motor vehicle crashes were drawn from NASS CDS for vehicle model years 1997-2008 for side impacts (all seat positions) and for vehicle model years 1994-2008 for frontal impacts (front seat only). Age groups utilized for data analysis included 20-39 and 65+ for side impacts and 20-39 and 60+ for frontal impacts.

To evaluate sensitivity of current midsize male crash test dummies, certification-type pendulum impacts to the thorax of the Thor-NT and the WorldSID dummies were conducted at impact velocities between 1.0 and 6.5 m/s.

Age-adjusted injury risk curves for the WorldSID midsize male were generated based on data by Petitjean et al. (2009). Injury risk curves for the Thor-NT dummy are not yet available.

Results of the current study show that occupant gender has a negligible effect on injury vulnerability in side impacts, whereas in frontal impacts, gender appears to play a more important role than age. In recent model year vehicles, the distribution of Delta V for older occupants with serious thoracic injury was approximately 10 km/h lower than that for seriously injured younger occupants in side impacts, but they were similar among seriously injured older and younger occupants in frontal impacts. The rate of older female injury was 6.5 times higher than that for younger females in frontal impacts, warranting further research. In real-world side impacts, 70% of older occupants with serious thoracic injuries were in crashes with a Delta V of 26 +/- 10 km/h in the current data set. In real-world frontal impacts, 42% of older occupants with serious thoracic injuries were in crashes with a Delta V of 29 +/- 10 km/h in the current data set. The WorldSID and Thor-NT dummies demonstrate excellent sensitivity and could potentially be used for evaluating injury risk for elderly occupants in lower severity impact tests. Injury risk curves for the WorldSID dummy have been generated for 65 year old mid-sized male occupants, from which a risk level can be established for use in evaluating injury risk to older occupants in side impact.

INTRODUCTION

Thoracic injury to elderly occupants in motor vehicle crashes is a serious concern. Although older occupants travel fewer miles, are involved in fewer crashes (Cerelli, 1998), and are more likely to be belted than younger occupants (Kent et al., 2005; NHTSA, 2009), the relative rate of serious injury and/or fatality is higher for older occupants than younger occupants (Kent et al., 2005; Evans, 2001; Zhou et al., 1996, Welsh, et al., 2006). Kent et al. (2005) also found that of the injuries sustained by drivers in fatal frontal impacts, the majority of injuries were to the chest for older drivers and to the head for younger drivers. Similarly, Morris et al. (2003) found that the chest was more frequently seriously injured in frontal crashes than the head for older occupants. In addition, Augenstein et al. (2005) found that the chest is the most frequently injured body region for older occupants in frontal and near-side crashes. If these serious thoracic injuries to elderly occupants are to be mitigated, several things need to be considered before developing a crash test for older occupants. First, how is crash severity (Delta V) related to serious thoracic injury of older occupants? Second, are crash test dummies appropriately sensitive to be used for estimating thoracic injury risk to older occupants? And third, are there injury risk curves available for estimating thoracic injury risk of older occupants based on crash test dummy deflections?

METHODS

Real World Older Occupant Crash Data

To identify the relative risk of serious thoracic injury among younger and older males and females and to examine the range of velocity change (Delta V) for seriously injured older occupants, real-world crash data was analyzed. A dataset from the National Automotive Sampling System Crashworthiness Data System (NASS CDS) was selected utilizing the following search criteria:

- NASS CDS crash years 1993-2008
- Front and side crashes
- Model years 1994-2008 for frontal crashes; 1997-2008 for side crashes
- Age groups: Frontal crashes – “younger” = 20-39 years old and “older” = 60+ years old; side crashes – “younger” = 20-39 and “older” = 65+
- Front seat occupants only for frontal crashes
- All seat positions included for side impact crashes (near and far side included)
- Primary event rollovers were excluded by rejecting any crash where the primary damage (variable TDD1) was overturn damage.
- No ejections
- Occupants with number of injuries coded as injured with severity unknown (INJNO=97) were excluded.
- For analyses using Delta V, cases with unknown Delta V were excluded.
- For analyses using occupant gender, cases with unknown gender were excluded.

Frontal impacts were those with direction of force (DOF1) from 11 o’clock to 1 o’clock, as well as those at 10 or 2 o’clock only if the general area of damage (variable GAD) was to the front of the vehicle. Side impacts were defined as all other cases with direction of force from 2 to 4 o’clock and 8 to 10 o’clock. The model years and age groups selected for frontal and side impacts were chosen based on an analysis of the rates of serious thoracic injury. Serious thoracic injury cases were identified by AIS (Abbreviated Injury Scale) codes in NASS CDS, which were based on the Association for the Advancement of Automotive Medicine’s AIS-90 from 1993 to 1999, and on AIS-90/98 Update from 2000 to 2008. Serious injuries are those with AIS score of 3 to 6. Analysis was performed with SAS statistical software, Version 9.2 (SAS Institute Inc, Cary, NC). Standard errors were calculated for the rate estimates using SAS’s survey analysis procedures to account for the variance in the weighting of CDS cases and reflected the estimated error that occurs as a result of using probability sampled case data.

The following data analyses were performed on the weighted data from the selected datasets for front and side impacts:

- Rate of serious thoracic injury cases were estimated by age group and gender.
- The cumulative distribution of Delta V among all serious thoracic injury cases was estimated by age group and by gender.

In addition, in order to illustrate the frequency of crashes in the Delta V ranges where injuries are occurring most frequently, the cumulative Delta V distribution of all front and side crashes, whether injury occurred or not, was estimated by age group for NASS CDS crash years 2006-2008, without regard to vehicle model year. All other inclusion criteria were the same as that used for serious injury cases described previously. Crash years 2006-2008 were used in order to obtain more recent crash exposure data.

Sensitivity of Thor-NT and WorldSID Dummy Thoraces

In order to determine whether the Thor-NT and WorldSID dummy thoraces were sensitive, the dummies were each subjected to certification-type pendulum impacts at various energy levels. The WorldSID was tested without the arm and the Thor-NT was tested in the upper thorax region. Both dummies were tested using a 23.4 kg mass pendulum with 152.4 mm diameter face. Before sensitivity tests began, each dummy was subjected to its thorax certification test to establish acceptable performance. Each of these certification tests was conducted at the prescribed velocity range of 4.2-4.4 m/s. Once dummy performance was deemed acceptable per the certification responses, the dummies were tested at velocities above and below that of the certification test, ranging from approximately 1 to 6 m/s. The tests followed the procedures prescribed in each dummy's certification manual (GESAC, 2005; ISO, 2009), with the exception of the impact velocity.

Transducer data from the dummy tests were recorded according to the digital data sampling requirements of SAE J211-1 (SAE, 2003). Following acquisition, all transducer data were processed in software as follows:

- WorldSID IR-Tracc displacements – filtered at CFC 600
- Pendulum force, Thor-NT upper thorax left and right crux displacements, WorldSID spine lateral accelerations – filtered at CFC 180
- Thor-NT left and right crux displacements were processed using THORTEST software (GESAC, 2010) and averaged together to obtain total chest deflection, per the Thor Certification Manual (GESAC, 2005).

Injury Risk Curves

In order to determine how injury measurements in advanced dummies are related to injury risk for older occupants, age-adjusted injury risk curves for the appropriate dummy needed to be generated. Petitjean et al. (2009) presented thoracic injury risk curves (and the data used to generate them) scaled to a 45 year old for the WorldSID midsize male side impact dummy. As part of that analysis, a relationship among post mortem human subject (PMHS) injury, WorldSID thorax deflection and PMHS age was established and the linear regression coefficients were reported (Equation 1, Petitjean et al., 2009).

$$AIS_x = a*WSD_x + b*Age_x + c \qquad (1).$$

where AIS_x = the injury severity for PMHS subject x
Age_x = the age of PMHS subject x
WSD_x = scaled WorldSID deflection corresponding to PMHS subject x
a = 0.066, b = 0.044, c = -4.077.

In the current study the relationship and coefficients established by Petitjean et al. in Equation 1 were used to generate age-adjusted WorldSID deflections for a given level of risk for a 20 year old, a 65 year old and a 75 year old. For example, for two PMHS having the same injury severity (AIS), where one is 65 years old (left side of Equation 2) and the other is X years old (right side of Equation 2), then:

$$a*WSD_{65} + b*65 + c = a*WSD_x + b*X + c \qquad (2).$$
$$WSD_{65} = WSD_x + (b/a)*(X-65)$$
$$WSD_{65} = WSD_x + (0.044/0.066)*(X-65)$$

The age-adjusted scaled WorldSID deflection data for a 20-, 65- and 75-year old, paired with the corresponding PMHS injuries, were used in performing survival analysis with Weibull distribution to generate injury risk curves for the three ages. The age adjustment was performed prior to the survival analysis, rather than as a variable in a multivariate survival analysis, in order to follow the same method as in Petitjean et al. Appendix A shows the data utilized from Petitjean et al., the age-adjusted scaled WorldSID deflections, and the resulting scale and intercept values from the survival analysis which were used to generate the risk curves.

Injury risk curves for the Thor-NT dummy thorax response do not exist at the current time.

RESULTS

Real World Elderly Crash Data

Tables 1and 2 show the number of raw and weighted serious thorax injury cases for side and front impacts, respectively, utilized from NASS CDS. In addition, for the analyses that used Delta V, the percentage of cases with known Delta V is indicated in Tables 1 and 2.

<u>**Rate of Serious Thoracic Injury**</u> Figure 1 shows the rate of serious thoracic injury for younger and older females and males in front and side crashes, where the rate of injury is the number of occupants with at least one serious thoracic injury in a given age/gender/crash mode bin divided by the number of occupants in the bin.

Table 1.
Number of raw and weighted occupants with at least one serious thorax injury (AIS 3+) for selected side crashes by age group and gender

Impact Mode	Side					
Age Group	Younger (20-39)			Older (65+)		
Gender	M	F	B	M	F	B
n (Raw)	142	109	251	65	67	132
n (Weighted) 1000's	8.7	5.5	14.2	4.9	4.3	9.2
% of (Weighted) Occupants in Crashes with Known Delta V	73	82	77	94	89	92

M = male; F = female; B = male & female

Table 2.
Number of raw and weighted occupants with at least one serious thorax injury (AIS 3+) for selected frontal crashes by age group and gender

Impact Mode	Front					
Age Group	Younger (20-39)			Older (60+)		
Gender	M	F	B	M	F	B
n (Raw)	377	220	597	180	194	374
n (Weighted) 1000's	21.7	11.7	33.4	12.0	16.8	28.8
% of (Weighted) Occupants in Crashes with Known Delta V	55	62	58	54	67	62

M = male; F = female; B = male & female

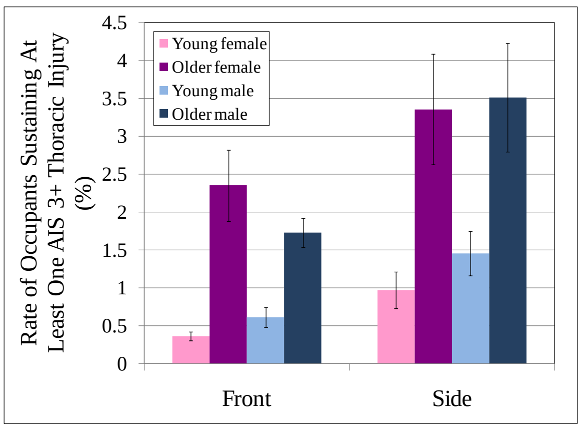

Figure 1. Rate of serious thorax injury for younger and older females and males in front and side impacts (with standard error).

The following observations can be made from Figure 1.

- The injury rate for side impact is higher than that for frontal impact for each occupant age/gender group.
- The injury rates for older occupants are significantly higher than those for younger occupants in both side and front impacts, regardless of occupant gender.
- In side impacts the injury rates for older men and women are approximately the same.
- The injury rate of older women is 6.5 times that of younger women in frontal impacts, whereas the older-to-younger ratios for all other occupant groups are in the vicinity of three (Table 3).

Table 3.
Relative injury rate between older and younger occupants

Relative injury rate = older rate/younger rate		
	Front	Side
Female	6.5	3.5
Male	2.8	2.4

Occupant Age, Delta V and Serious Thoracic Injury Figure 2 shows the cumulative distribution of Delta V in serious thorax injury cases for younger (red line) and older (blue line) occupants in side impacts (all seat positions). Fifty percent of older occupants with serious thoracic injury were in crashes with Delta V of 25 km/h or below. Fifty percent of younger occupants with serious thoracic injury were in crashes with Delta V of 35 km/h or below. The 25th and 75th percentile Delta V's for seriously injured older occupants were approximately 10 km/h lower than those of seriously injured younger occupants. The Delta V range for the lowest 25% of seriously injured older occupants was between 10-17 km/h, compared to 16-29 km/h for seriously injured younger occupants.

Figure 3 shows the cumulative distribution of Delta V in serious thorax injury cases for younger (red line) and older (blue line) occupants in the front seat only in frontal impacts. The median Delta V for older occupants with serious thorax injury in frontal impacts is 38 km/h, compared to 41 km/h for younger occupants with serious thorax injury. The 25th and 75th percentile Delta V's for seriously injured older occupants were approximately 2-4 km/h lower than those for seriously injured younger occupants.

Occupant Age and Gender, Delta V, and Serious Thoracic Injury Figure 4 shows the cumulative distribution of Delta V in serious thorax injury cases for younger and older males and females in side impacts (all seat positions). The median Delta V's for seriously injured younger and older males (dashed lines) are 36 and 24 km/h, respectively, compared to 34 and 25 km/h for seriously injured younger and older females (solid lines), respectively. The median Delta V's for male and female occupants (per age group) are not very different from the median Delta V's for younger and older from Figure 2. The same general trend from Figure 2 is evident among seriously injured older and younger males and females in side impact: the Delta V's for older males and females with serious thoracic injury are approximately 10 km/h lower than those for younger males and females with serious thoracic injury.

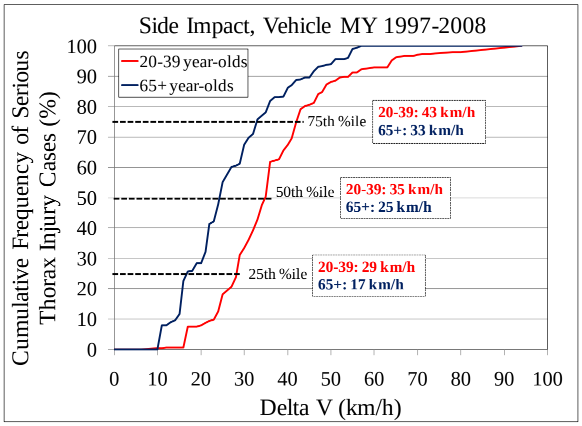

Figure 2. Cumulative Delta-V distributions for younger and older occupants with serious thoracic injuries in real world side impacts in vehicles with model years 1997-2008.

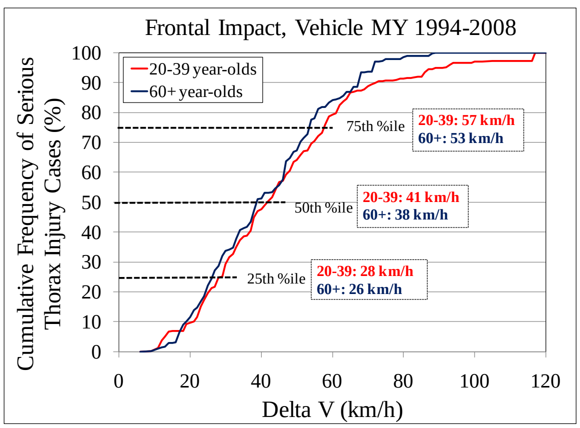

Figure 3. Cumulative Delta-V distributions for younger and older front seat occupants with serious thoracic injuries in real world frontal impacts of vehicles with model years 1994-2008.

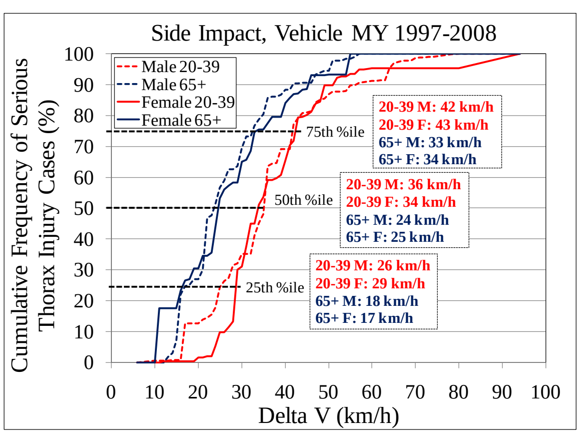

Figure 4. Cumulative Delta-V distributions for younger and older males and females with serious thoracic injury in real world side impacts in vehicles with model years 1997-2008.

Figure 5 shows the cumulative distribution of Delta V in serious thorax injury cases for younger and older males and females in the front seat in frontal impacts. Among seriously injured younger occupants (red curves) in frontal impacts, the median Delta V is 44 km/h for men and 37 km/h for women. The 25th and 75th percentile Delta V's for younger female occupants with serious thorax injury were approximately 9-13 km/h lower than those of younger male occupants with serious thorax injury.

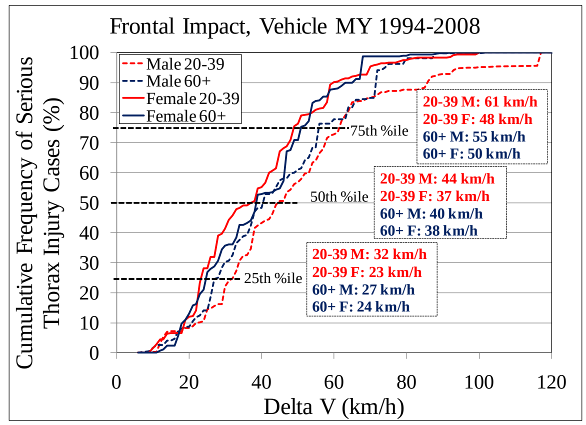

Figure 5. Cumulative Delta-V distributions for younger and older males and females with serious thoracic injury in real world frontal impacts in the front seat of vehicles with model years 1994-2008.

Among seriously injured older occupants (Figure 5, blue curves) in the front seat in frontal impacts, the median Delta V is 40 km/h for men and 38 km/h for women. The 25th and 75th percentile Delta V's for older female occupants with serious thorax injury were approximately 3-5 km/h lower than those of older male occupants with serious thorax injury.

Among seriously injured females, (Figure 5, solid curves) in frontal impacts, the median Delta V is 37 km/h for younger females and 38 km/h for older females. The 25th and 75th percentile Delta V's were approximately the same for seriously injured younger and older females.

Among seriously injured males, (Figure 5, dashed curves) in frontal impacts, the median Delta V is 44 km/h for younger males and 40 km/h for older males. The 25th and 75th percentile Delta V's were approximately 5 km/h higher for seriously injured younger males compared to seriously injured older males.

Sensitivity of Thor-NT and WorldSID Dummy Thoraces

Tables 4 and 5 show peak responses for the measurements obtained during thorax pendulum tests with the WorldSID and Thor-NT, respectively. Table 4 shows that, for a range of impact velocities between 0.99 and 5.98 m/s, the WorldSID maximum rib deflections ranged from 4.1 to 58.8 mm, the maximum spine accelerations ranged from 2.7 to 24.2 g, and the maximum pendulum force ranged from 851 to 4663 N. Table 5 shows that, for a range of impact velocities between 1.30 and 6.59 m/s, the Thor-NT maximum upper thorax deflections ranged from 14.7 to 69.8 mm and the pendulum force at maximum deflection ranged from 718 to 5326 N.

Figure 6 shows peak force vs. impact velocity responses with 2^{nd} order polynomial curves fit to each dummy's data. Figure 7 shows peak deflection vs. impact velocity responses with linear curves fit to each WorldSID rib deflection and to the Thor-NT average crux x deflection. Figure 8 shows peak spine lateral acceleration responses at T4 and T12 for the WorldSID with linear curves fit to the data.

Injury Risk Curves

The resulting equations from the survival analysis using age-adjusted WorldSID deflections and PMHS injuries are shown in Appendix A. Figure 9 shows risk curves for AIS 3+ thoracic injury for a 20 year old, a 45 year old, a 65 year old and a 75 year old mid-size male, as a function of maximum WorldSID thorax or abdomen rib deflections in side impacts. The injury risk curves show, for example, that a WorldSID impact that produces 50 mm maximum deflection predicts a 29% risk of injury for a mid-size 45 year-old male and an 89% risk of injury for a mid-size 75 year-old male. A 50% risk of AIS 3+ thorax injury is associated with the following thoracic deflections measured by the WorldSID 50^{th} percentile midsize male side impact dummy:

- 74 mm for a 20 year old,
- 57 mm for a 45 year old,
- 44 mm for a 65 year old,
- 37 mm for a 75 year old.

Table 4.
WorldSID Thorax Sensitivity Test Results

	Velocity (m/s)	Upper Rib Deflection (mm)	Middle Rib Deflection (mm)	Lower Rib Deflection (mm)	T12 Y Acceleration (g)	T4 Y Acceleration (g)	Max Pendulum Force (N)
	Filters	CFC 600	CFC 600	CFC 600	CFC 180	CFC 180	CFC 180
Specs	4.2-4.4	33-43	35-43	32-40	14-22	14-20	3200-3800
Data	4.31	33	**37**	33	15	14	3764
	4.31	33	**38**	34	14	14	3769
	0.99	4.1	6.2	**6.3**	2.7	2.8	851
	1.50	8.1	**10.7**	10.1	4.0	4.7	1335
	1.51	8.1	10.0	**10.2**	4.5	4.8	1363
	1.97	12.6	**15.4**	14.5	5.9	6.5	1771
	2.50	14.8	**18.8**	17.8	8.3	8.6	2367
	2.50	15.3	**19.6**	18.1	7.5	8.4	2348
	2.99	21.2	**24.9**	22.7	9.5	9.9	2721
	3.00	17.5	**21.8**	21.5	12.0	10.0	2895
	3.61	26.8	**31.0**	29.4	11.2	11.5	3228
	3.81	29.1	**32.7**	30.9	12.4	12.5	3391
	3.99	31.4	**35.3**	33.1	13.0	12.6	3520
	4.70	37.9	**41.0**	36	15.4	15.6	3997
	5.18	43.4	**46.0**	40.6	18.8	18.5	4264
	5.64	52.1	**53.1**	46.5	20.3	19.8	4465
	5.98	55.2	**58.8**	52.1	24.2	21.3	4663
Min	0.99	4.1	6.2	6.3	2.7	2.8	851
Max	5.98	55.2	58.8	52.1	24.2	21.3	4663

Bold text indicates maximum rib deflection
Shaded rows indicate certification specs and data.

Table 5.
Thor-NT Thorax Sensitivity Test Results

	Velocity (m/s)	Max. Avg. Upper Thorax X Deflection (mm)	Force at Maximum Average Deflection (N)
Specs	4.2-4.4	49.0 – 59.0	2450 - 2950
Data	4.4	49.1	2765
	1.30	14.7	718
	1.82	20.5	1032
	1.95	21.9	1060
	2.27	25.1	1207
	2.50	28.1	1366
	2.85	32.7	1500
	3.32	37.8	1884
	3.81	42.0	2211
	4.13	46.7	2579
	5.00	54.7	3397
	5.49	58.8	3875
	5.92	62.6	4440
	6.59	69.8	5326
Min	1.3	14.7	718
Max	6.59	69.8	5326

Shaded rows indicate certification specs and data

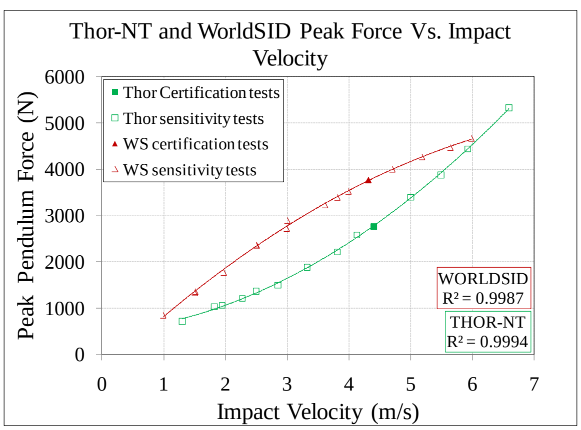

Figure 6. Peak pendulum force vs. impact velocity for Thor-NT and WorldSID thorax certification and sensitivity tests.

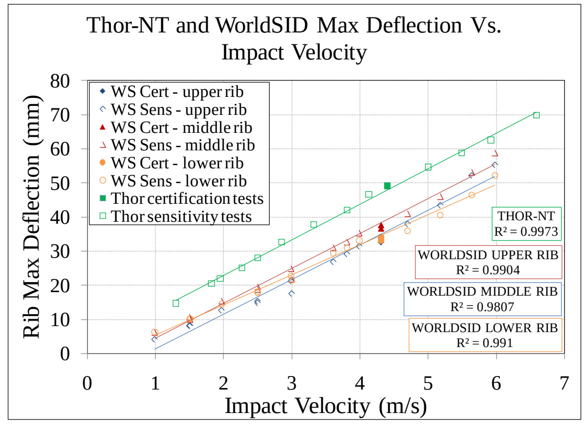

Figure 7. Peak thorax deflections vs. impact velocity for Thor-NT and WorldSID thorax certification and sensitivity tests.

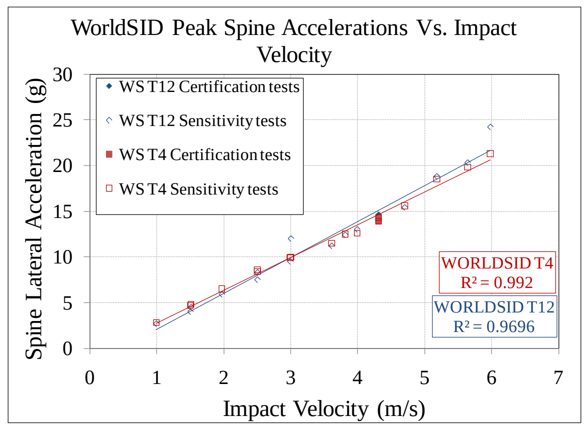

Figure 8. Peak spine lateral accelerations vs. impact velocity for WorldSID thorax certification and sensitivity tests.

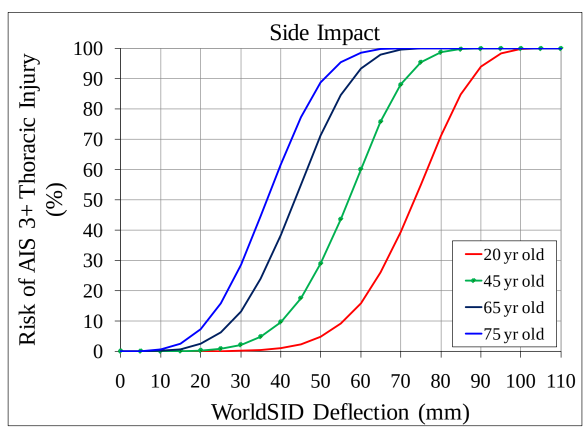

Figure 9. Risk of AIS 3+ thoracic injury for various ages of mid-sized male occupants as a function of maximum thorax or abdomen WorldSID deflection in side impact.

DISCUSSION

Real World Elderly Crash Data

Analysis of NASS CDS cases was performed to study the relative risk of serious thoracic injury among younger and older males and females, examine the Delta V for seriously injured older occupants and identify Delta V's with the largest percentage of older occupant serious thoracic injury cases in frontal and side impacts.

Rate of Serious Thoracic Injury The relatively increased injury rates for older occupants in the current study underscore the reported lower injury tolerance of older occupants relative to that of younger occupants (Evans, 2001; Zhou et al., 1996). In addition, the increased rates of serious thoracic injury in side impacts relative to front impacts in the current study supports that side impacts present a higher thorax injury risk for all age groups (NHTSA, 2009) However, in frontal impacts, the current study results showing that the rate of serious thoracic injury to older female occupants is 6.5 times greater than that to younger female occupants (Figure 1) is unexpected.

Accuracy of Delta V Funk et al. (2008) evaluated the magnitude of error in NASS-reported Delta V data. Delta V data for individual NASS cases were corrected for bias error, and distributions of Delta V data were corrected for scatter error. To illustrate the magnitude of the total error, Funk et al. calculated injury risk curves for frontal crashes as a function of age, gender, and belt use using the raw and corrected NASS Delta V data. The effect of the bias error and the effect of the scatter error in the NASS Delta V data counteracted each other. In spite of the considerable errors in the Delta V estimates in NASS, Funk et al. found that the risk curves calculated using uncorrected NASS data were generally accurate at low Delta Vs and somewhat conservative at higher Delta Vs. Therefore the Delta V distributions shown in the current study were analyzed without correction.

Effect of Vehicle Model Year On Serious Thoracic Injury In Frontal Crashes In frontal impact there is only a small difference in the distribution of Delta V's for older and younger seriously injured front seat occupants (Figure 3). In contrast, Kent et al. (2005) showed that for NASS CDS years 1992-2002 the distribution of Delta V for fatally injured older drivers (65+ years old) was in the range of 10 km/h lower than that of fatally injured younger (16-33 years old) drivers in frontal crashes; however, early model vehicle years were not excluded. As a result, the Kent dataset is expected to describe a much earlier vehicle fleet than the current study which included only vehicle model years 1994 and newer (Figure 3). To illustrate the effect of limiting the current study to recent model year vehicles, Figure 10 shows the cumulative distribution of Delta V for older and younger occupants with serious thoracic injury in frontal impact in vehicles with model year between1994-2008 (same as in Figure 3) and with model year previous to 1994.

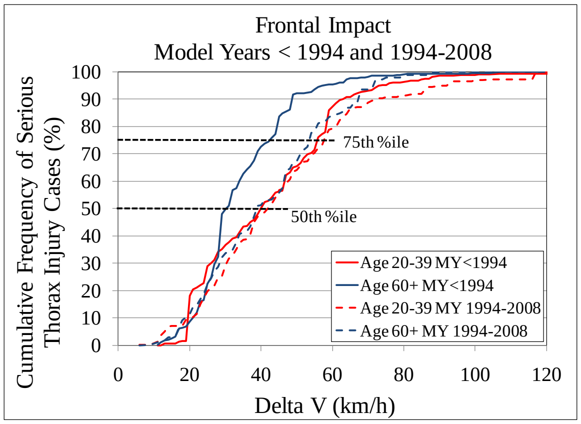

Figure 10. Cumulative Delta-V distributions for younger and older front seat occupants with serious thoracic injury in real world frontal impacts in vehicles with model years previous to 1994 and model years 1994-2008.

If model years prior to 1994 (solid lines, Figure 10) are compared to model years 1994-2008 (dashed lines, Figure 10) for front seat occupants in frontal crashes, a change is observed. For frontal crashes in older vehicles with Delta V > 29 km/h, a similar finding to that of Kent is illustrated in that the median Delta V for seriously injured older occupant crashes is approximately 10 km/h lower than that for younger occupants (Table 6). For the dataset that includes only vehicles from 1994 and more recent, it appears that this disparity between the Delta V's for younger and older seriously injured occupant crashes is greatly reduced. In addition, the median Delta V for serious thoracic injury crashes in frontal impacts is higher in the more recent model year vehicles than in the older model year vehicles (Table 6), especially for older occupants. This contrast suggests that vehicle design has had an effect on the frontal crash Delta V for occupants with serious thoracic injuries, in particular for those aged 60+.

The advent of frontal air bags and/or force-limiting belts may be partially responsible for the reduction in lower-speed injuries to the elderly in frontal crashes

(Morris et al., 2003). Due to the effect of more recent vehicle model year on older occupant serious thoracic injuries, further examination of the current frontal impact data set may include limiting the vehicle model years to even more recent, such as 2000+.

Table 6.
Delta V of 50th and 75th Percentiles of Cumulative Distribution of Front Seat Serious Thoracic Injury Cases in Frontal Crashes for Model Years 94-08 and Prior to 94

		Delta V (km/h)			
Percentile		50th		75th	
Model Years		94-08	<94	94-08	<94
Age Group	60+	38	30	53	42
	20-39	41	39	57	55

Occupant Age and Gender, Delta V, and Serious Thoracic Injury When considering occupant gender in side impacts, the distributions of Delta V for older men and women with serious thoracic injuries are approximately the same; the same is true among younger men and women (Figure 4), indicating a negligible effect of occupant gender on an occupant's vulnerability to injury in side impacts. However, the distributions of Delta V for side impact serious thoracic injury cases are lower for older males and females vs. younger males and females. These results may be indicative of the relative vulnerability of older occupants compared to younger occupants in side impacts.

In frontal impacts the effect of occupant gender appears to be more important than occupant age regarding the relative vulnerability of occupants (Figure 5). Among seriously injured female occupants in frontal impacts, the distributions of Delta V are approximately the same for younger and older ages. Among seriously injured male occupants, the distribution of Delta V for the older age group is slightly lower than that for the younger age group. The distribution of Delta V for seriously injured men is slightly higher than that for seriously injured women. These results may suggest that women are more vulnerable than men in frontal crashes, or perhaps the results may reflect the effect of occupant mass or occupant position/height relative to intruding structures. Additionally, restraint system components, such as force-limiting belts, may be tuned better to protect a larger occupant. These details concerning occupant size or mass, occupant position, contact surface and belt type/use deserve further examination, especially with regard to the elevated rate of serious thoracic injury to older females in frontal impacts as well as the lower Delta V distribution for crashes with seriously injured younger and older women.

Range of Delta V's For Older Occupants With Serious Thoracic Injury The Delta V for the largest percentage of older occupants with serious thoracic injury was identified for front and for side impacts. A tolerance of +/- 10 km/h was utilized for selecting the range of Delta V that had the largest percentage of serious injury cases. In side impacts, because there is no significant difference in the Delta V distribution for seriously injured older male and female occupants, Delta V data for seriously injured older occupants in side impacts were not separated by occupant gender. In frontal impacts, because the difference was small between seriously injured older male and female occupants, Delta V data for seriously injured older occupants in frontal impacts were not separated by occupant gender.
Figure 11 shows the cumulative frequency distributions of Delta V for all younger and older occupants who were in NASS CDS side crashes between 2006 and 2008, whether injury occurred or not ("exposed", dashed lines). Figure 11 also shows cumulative Delta V distributions for seriously injured thorax cases for vehicle model years 1997-2008 ("injured", solid lines, same as in Figure 2) by age in side impacts. The shaded region in Figure 11 highlights the range of Delta V for older occupants in which the largest percentage of serious injury cases occurred in side impact.

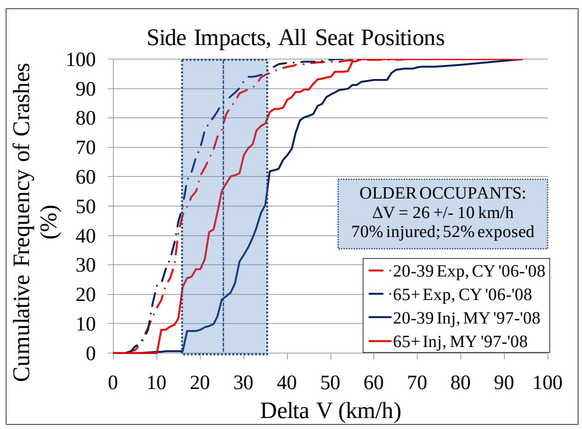

Figure 11. Cumulative distribution of Delta V for crashes with exposed (NASS CDS crash years 2006-2008) and seriously injured (NASS CDS model years 1997-2008) younger and older occupants in any seat position in side impact, shown with shaded area indicating the range of Delta V for which the largest percentage of older occupants with serious thoracic injury cases occurs.

Table 7 shows, for side and frontal impact, the range of Delta V with the largest percentage of older occupant serious thoracic injury cases, the percentage of older occupants seriously injured in that Delta V range and the percentage of older crash occupants exposed in that Delta V range.

Table 7.
Delta V +/- 10 km/h with Largest Percentage of Older Occupant Serious Thoracic Injury Cases in Side and Frontal Impact Crashes, Showing Percent Injured and Exposed in Given Delta V Range

OLDER OCCUPANTS	Side Impact	Frontal Impact
ΔV Range (km/h)	26 +/- 10	29 +/- 10
% Injured	70	42
% Exposed	52	31

In side crashes, 70% of older occupants with serious thoracic injury were in crashes with a Delta V of 26 +/- 10 km/h, which accounts for 52% of weighted NASS CDS older occupant side impact exposures (Figure 11, Table 7).

Figure 12 shows the cumulative frequency distribution of Delta V for all younger and older occupants who were in the front seat of NASS CDS frontal crashes between 2006-2008, whether injury occurred or not ("exposed", dashed lines). Figure 12 also shows cumulative Delta V distributions for seriously injured thorax cases for vehicle model years 1994-2008 ("injured", solid lines, same as in Figure 3) by age in frontal impacts (front seat only). The shaded region in Figure 12 highlights the range of Delta V in which the largest percentage of older occupant serious injury cases occurred in frontal impact.

In frontal crashes, 42% of seriously injured older occupants were in crashes with a Delta V of 29 +/- 10 km/h, which accounts for approximately 31% of weighted NASS CDS older occupant frontal impact exposures (Figure 12, Table 7).

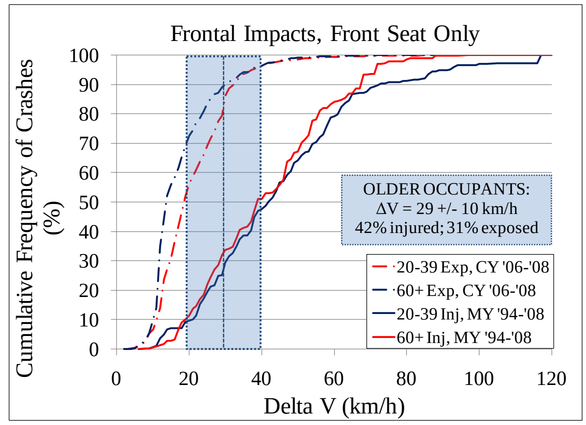

Figure 12. Cumulative distribution of Delta V for crashes with exposed (NASS CDS crash years 2006-2008) and seriously injured (NASS CDS model years 1994-2008) younger and older occupants in the front seat in frontal impact, shown with shaded area indicating the range of Delta V for which the largest percentage of older occupant serious thoracic injury cases occurs.

<u>**Summary**</u> The analysis of older occupant serious thoracic injury case data in NASS CDS showed the following observations:

- In both frontal and side impacts older occupants were more likely to sustain serious thoracic injuries vs. younger adults.
- Similar to younger occupants, older occupants were more likely to sustain serious thoracic injuries in side impacts vs. frontal impacts.
- The rate of older female injury was 6.5 times higher than that for younger females in frontal impacts, warranting further research.
- Occupant gender has a negligible effect on injury vulnerability in side impacts.
- In recent model year vehicles, the distributions of Delta V for older males and females with serious thoracic injury were approximately 10 km/h lower than those for seriously injured younger males and females in side impacts.
- In recent model year vehicles, Delta V's for seriously injured older occupants were similar to those of seriously injured younger occupants in frontal impacts. This finding is different from that of Kent (2005) who analyzed a dataset with older model year vehicles, indicating that model year plays a role in crash injury outcomes.
- In recent model year vehicles, the median Delta V for serious thoracic injury cases in

frontal impacts is higher than in older model year vehicles, especially for older occupants.

- In frontal impacts, the effect of occupant gender appears to be more important than occupant age regarding the relative vulnerability of occupants.
- In frontal impacts, Delta V's for females with serious thoracic injury were lower than those for seriously injured men.

Some of the most important observations from this NASS CDS study include:

1. Occupant size, seating position, contact surface and belt type deserve further examination, especially with regard to the elevated rate of serious thoracic injury to older females in frontal impacts as well as the lower Delta V for crashes with seriously injured younger and older women compared to seriously injured younger and older men.
2. In real-world side impacts, 70% of older occupants with serious thoracic injuries were in crashes with a Delta V of 26 +/- 10 km/h in the current data set.
3. In real-world frontal impacts, 42% of older occupants with serious thoracic injuries were in crashes with a Delta V of 29+/- 10 km/h in the current data set.

NASS CDS Search Inclusion Criteria Considerations In addition to limiting vehicle model year to 2000+ as previously mentioned, future NASS CDS data analysis may consider the effects of driver vs. front seat passenger and unbelted vs. belted vs. belted w/airbag deployment, as well as looking at occupant mass and height rather than gender for frontal impacts. Also, the effect of near side vs. far side seating position in side impacts could be investigated in order to gain further insight on crash and occupant characteristics that are associated with older occupant serious thoracic injury.

Sensitivity of Thor-NT and WorldSID Dummy Thoraces

In order to assess occupant injury risk in crash tests, the crash test dummy that predicts the injury level needs to be sensitive and biofidelic at the intended test severity level. If a low severity test were considered, the potential crash test dummies to be used need to be evaluated for sensitivity and biofidelity at this low severity level. There is a need for establishing human response in low severity impacts, especially among older occupants who sustain injury at a lower threshold, so that biofidelity of the crash test dummies can be evaluated. The Thor-NT dummy exhibited thoracic deformation and kinematic responses similar to those observed in PMHS, with the exception of higher lap belt loads and pelvis accelerations, in 29 km/h Delta V sled tests (Forman et al., 2006). The WorldSID dummy achieved an overall biofidelity score of 8.0, indicating excellent biofidelity based on the ISO biofidelity ranking scheme, for tests outlined in ISO 9790 (ISO, 2009; ISO 1999).

The Thor-NT and WorldSID dummies demonstrate excellent sensitivity for the range of velocities experienced in the pendulum test condition. Since the dummies show linear relationships between deflection and impact velocity, these dummies could potentially be used for evaluating injury risk for older occupants. From the range of sensitivity tests performed the maximum WorldSID rib deflections of 4 and 59 mm are equivalent to 0% and 92% risk of AIS 3+ thoracic injury for a 65 year old midsized male, according to Figure 9, indicating that the dummy is sensitive enough to measure injury risk over a wide range of impact severities. Although risk curves have not been developed for the Thor-NT dummy to determine the corresponding range of risk levels, the wide range of deflection produced in sensitivity tests on the Thor-NT suggests that it also shows promise to predict risk over a wide range of impact severities.

Injury Risk Curves

For the WorldSID dummy, a 50% risk of AIS 3+ thoracic injury for a 65 year old occupant would be equivalent to 44 mm, 13 mm less than the current value for a 45 year old. However, in order to determine what level of risk would be appropriate for use in a crash test evaluation, it may be useful to examine the real-world rate of injury at the crash test speed. If IARV's in lower speed tests are set at less than 50%, the corresponding deflection limits could be determined from the risk-deflection relationship presented in this paper.

CONCLUSIONS

In real-world side impacts, 70% of older occupants with serious thoracic injuries were in crashes with a Delta V of 26 +/- 10 km/h in the current data set. In real-world frontal impacts, 42% of older occupants with serious thoracic injuries were in crashes with a Delta V of 29+/- 10 km/h in the current data set. The WorldSID and Thor-NT dummies demonstrate excellent sensitivity and could potentially be used for evaluating injury risk for elderly occupants. Injury risk curves for the WorldSID dummy have been generated for 65 year old mid-sized male occupants, from which an IARV can be established for use in evaluating injury risk to older occupants in side impact. Injury risk curves for the Thor-NT dummy are not yet available.

Additional research is warranted to determine why older females have such an increased rate of serious thoracic injury as well as a lower Delta V distribution compared to seriously injured men in frontal crashes. Variables that may be important in this effort include occupant mass and height, seating position, contact surface and belt use.

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APPENDIX A

(Petitjean et al, 2009)					Current Study		
Thorax test number	PMHS AIS (AIS_x)	PMHS Age (Years) (Age_x)	WorldSID scaled deflection (mm) (WSD_x)	WorldSID scaled deflection corrected to age 45 (mm)	WorldSID scaled deflection corrected to age 65 (mm)	WorldSID scaled deflection corrected to age 75 (mm)	WorldSID scaled deflection corrected to age 20 (mm)
76T062	3	69	41.7	57.6	44.3	37.7	74.2
76T065	0	63	37.8	49.7	36.4	29.8	66.3
77T071	0	60	35.5	45.5	32.2	25.6	62.1
77T074	2	60	39.2	49.1	35.9	29.2	65.7
0503LTH25R01	0	79	28.6	51.1	37.9	31.2	67.7
0504LTH25L01	0	80	26.6	49.8	36.6	29.9	66.4
0507LTH25R01	0	53	28.7	34.0	20.8	14.1	50.6
0602LTH25R01	0	79	26.7	49.2	36.0	29.3	65.8
SC101	3	73	60.1	78.6	65.4	58.7	95.2
SC102	0	27	60.3	48.4	35.1	28.5	65.0
SC120	0	67	59.0	73.6	60.4	53.7	90.2
SC121	3	86	56.1	83.3	70.0	63.4	99.9
SC124	0	45	62.3	62.3	49.1	42.4	78.9
SC135	3	56	63.4	70.7	57.5	50.8	87.3
SC137	3	73	66.3	84.8	71.6	64.9	101.4
SAC102	3	51	69.0	73.0	59.8	53.1	89.6
SIC-07	4	66	59.7	73.6	60.3	53.7	90.2
SIC-05	4	67	63.7	78.3	65.0	58.4	94.8
SC125	3	68	68.1	83.3	70.1	63.4	99.9
SC129	3	51	65.4	69.4	56.1	49.5	86.0
SC144	3	76	55.5	76.0	62.8	56.1	92.6
SC139	3	56	58.4	65.7	52.4	45.8	82.2
SC110	3	78	52.4	74.3	61.1	54.4	90.9
SC111	4	84	48.8	74.6	61.4	54.7	91.2
SC115	3	72	43.3	61.2	47.9	41.3	77.8
SC136	3	54	45.1	51.1	37.9	31.2	67.7
SC138	3	58	47.8	56.4	43.1	36.5	73.0
SC119	3	75	32.3	52.2	38.9	32.3	68.8
SC107	3	50	64.6	67.9	54.7	48.0	84.5
SC133	4	73	71.3	89.9	76.6	70.0	106.5
SC116	3	67	65.0	79.6	66.4	59.7	96.2
SC134	3	58	68.3	76.9	63.6	57.0	93.5
94LSI32P03= OSU323	3	59	72.3	81.6	68.3	61.7	98.1
94LSI32P04= OSU321	3	75	66.6	86.5	73.2	66.6	103.0
95LSI32P06= OSU320	5	82	71.6	96.1	82.9	76.2	112.7
LSI32P12=OSU581	3	80	71.6	94.8	81.6	74.9	111.4
LSI32P14	3	79	71.6	94.1	80.8	74.2	110.7
LSI32P15	4	68	76.1	91.3	78.0	71.4	107.9
LSI32P16	5	77	73.7	94.9	81.7	75.1	111.5

(Petitjean et al, 2009) Linear Regression Coefficients		
c(intercept)	b(Age)	a(WSD)
-4.077	0.044	0.066

After performing survival analysis with Weibull distribution on age-adjusted scaled WorldSID deflection data and PMHS AIS, the following results were obtained:

	Age 65	Age 75	Age 20
Scale =	0.235	0.273	0.146
Intercept =	3.86	3.7	4.35

$AIS_x = a*WSD_x + b*Age_x + c$

For a given risk level:

$a*WSD_{65} + b*65 + c = a*WSD_x + b*X + c$

RISK OF INJURY = 1-EXP(-EXP(1/SCALE*LN(DEFLECTION VALUE)+(INTERCEPT/SCALE*-1)+(0/SCALE*-1)))