ASSESSING INJURY RISK OF CAR OCCUPANTS ON REARWARD FACING SEATS IN A FULL FRONTAL IMPACT – SLED TESTS IN A GENERIC TEST ENVIRONMENT

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ABSTRACT

With the introduction of fully-automated vehicles, new seating configurations of the passenger compartment has been proposed. Rearward facing front seats are considered to provide so-called living room seating. At least as long as conventional and fully-automated vehicles share the same roads in mixed traffic, crashes may occur. Occupant protection on a rearward facing seat must therefore be on the same level as on a forward facing seat to comply with legal requirements. In order to assess dummy response on a rearward facing seat in a 56 km/h full frontal impact, sled tests were performed, analysed, and discussed.

A total of 23 sled tests in three series with a Hybrid III 50th percentile adult male dummy were performed to simulate a vehicle frontal impact against a rigid barrier at impact speeds up to 56 km/h. In the first test series, a serial vehicle seat was used, but it showed already considerable deformation at an impact speed of 40 km/h. Therefore, a generic concept seat was developed. In the second test series, the concept seat was tested and tuned to enable it to perform tests at the target impact speed of 56 km/h. In the third series, tests to investigate repeatability were performed. Dummy loadings at 56 km/h were compared with reference values from legislation and literature. Focus was set on thorax and lumbar spine loadings.

For a qualified interpretation of dummy loadings and the performance of the restraint system, the crash was divided into three phases: (1) impact phase until the maximum dummy rearward displacement, (2) dummy rebound before interaction with the seat belt, and (3) dummy in rebound and interaction with the seat belt. The impact phase (1) is characterized by the highest 3 ms chest acceleration, close to 60 g in 56 km/h tests. Notably, this was the loading closest to the injury assessment reference value (IARV). The lumbar spine was mainly loaded in compression with forces rising up to 5.8 kN. Chest deflection of about 8 mm was caused by inertia of the dummy rib cage. The rebound phase before interaction (2) did not show any substantial dummy loading. The rebound interaction phase (3) was influenced by the seat belt system, chest deflection ranged from 5 mm in the test with lap belts to 19 mm in the test with two crossed shoulder belts (crisscross belt). The viscous criterion was below 0.1 m/s in all tests. Overall, the tests showed good repeatability and the ability of the generic concept seat to control dummy kinematics.

A limitation of our study is, that only full frontal loading directions were studied, dummy kinematics of oblique impact direction, simulating e.g. ±30° impacts to the barrier, were not included. The head rest was not in focus of our investigation and the head was fixed to the head rest without any gap in between.

INTRODUCTION

The development of automated driving systems of SAE levels 4 and 5 [1] allows for new seating options in automobiles. Swivel front seats are desirable to provide so-called living room seating [2]. With this, the front row passengers would sit on a rearward facing seat. At least as long as conventional and fully-automated vehicles share the same roads, crashes may occur. Occupant protection on a rearward facing seat must therefore be at least on the same level as on a forward facing seat.

Although few car models are equipped with rearward facing seats, e.g. Volkswagen Caravelle, Mercedes Viano, or several models of ambulance cars and motorhomes, almost no accident analysis focusing on adult car occupants on rearward facing seats is published. An analysis of the German In-Depth Accident Study (GIDAS) identified only five cases with rearward facing adult occupants in ECE M1 vehicles. Only one occupant on a rearward facing seat was injured (MAIS 2), but in all collisions the speed change Δv of the impacted vehicle was below 25 km/h [3].

Sled testing in this occupant loading direction is mainly to determine neck injury risk in low speed rear impacts. Further, some studies were performed to determine injury risk in so-called high speed rear impacts with a Δv of up to 40 km/h [4, 5]. Pulses for these studies are to represent loadings in a car to car rear impact and are much softer than pulses in a frontal car to car or car to barrier collision at the same Δv.

Recently simulations with the human FE model THUMS on rearward facing seats in full frontal impact conditions were performed. Kitagawa et al. [6] described occupant kinematics on rearward facing and conventional seats, Xin Jin at al. [7] compared injury risk in different loading directions and concluded that the rearward facing seating position has the lowest injury risk.

The scope of our work was to study occupant loading on rearward facing seats in sled tests. For this, we established a generic test environment. The initial requirements were as follows:

1. The test setup should be sufficiently stable to withstand a stiff crash pulse taken from a small vehicle in a full frontal crash according to FMVSS 208 [8] at 56 km/h.
2. The rearward displacement of the back rest during crash should be adjustable and limited to about 200 mm rearward displacement in order to avoid possible occupant head contact to the windscreen.
3. The environment should be simple in order to build up and validate a finite element model for further investigations.

The dummy used for the investigation was a Hybrid III 50th percentile adult male. For the rearward loading direction of this dummy, injury reference assessment values (IARV) only exist for low speed rear impact. These are however to protect from AIS 1 injuries and are thus not applicable for high speed impacts we are looking at. In a first assumption, we applied IARV for the frontal impact of this dummy. It must be pointed out, that this can only be a first approach as the dummy was not validated for this loading direction. In the first step, we were concentrating on injury assessment of chest and lumbar spine as loading to these body parts mainly dependent on the back rest performance. Head and neck loadings are mainly dependent on the head rest and should be investigated in a next step. As a guideline, IARV given in European or US legislation were taken into account first, the respective lower value was taken as our reference for this paper. For the chest the 3 ms chest acceleration clip of 60 g was taken from FMVSS 208 [8], for chest deflection and the viscous criterion the values were taken from ECE-R 137 (42 mm and 1 m/s) [9]. No reference values in automotive regulations exist for the lumbar spine forces. For helicopter emergency landing the European Aviation Safety Agency (EASA) specifies a limit in compression of 6674 N [10]. An internal specification of General Motors (GM) [11] specifies 12.2 kN in tension and 6.4 kN in compression. The compression value is well comparable to the EASA requirement and was used together with the value for tension as reference in this paper.

To have control of all loadings to the dummy we also used IARV for other body parts. A list of all used IARV and its source can be found in the Appendix.

METHOD

All the tests were performed on a deceleration sled using either a hydraulic brake or a bending bar brake to generate the crash pulse. The seat was mounted to the sled and a Hybrid III 50th percentile male dummy placed on it.

In the first tests series, a serial production seat was used. The dummy was seated according to the definition in [12]. The speed was increased until a Δv of 40 km/h was reached. Already at Δv of 40 km/h a considerable deformation of the seat back occurred and it was decided to design and build a generic seat which could withstand a Δv of at least 60 km/h which compares to a barrier impact speed of 56 km/h.

Figure 1 shows the generic concept seat that was designed and built. It consists of a stiff seat pan which has a steel frame with a surface of acrylic glass and a back rest which has a frame of standard aluminium profiles. This was chosen in order to easily replace in case of damage in crash. The seat back frame has a polycarbonate shell surface to support the back of the dummy. All the surfaces which are in contact with the dummy have a padding of at least one layer of comfort foam. In the second test series, which was the first one with the generic seat, a standard head rest supported by an aluminium frame at its back was used. This design showed not to be very reliable and in the third test series a stiff steel frame head rest was implemented. It has a wooden plate towards the dummy’s head and three layers of comfort foam. The dummy head is taped to the head rest to avoid a gap between both. The back rest is fixed to the sled ground plate by ball bearings at both sides. The torso angle of the dummy is set to 25°. A controlled rearward displacement of the back rest during crash is provided by each two layers of seat belt webbing of 12% elongation at 10 kN and of a length of 1200 mm on both sides of the back rest. The other side of the webbing is fixed to a steel frame mounted to the sled. At the upper cross member of the back rest, seat belt systems can be mounted at each side.

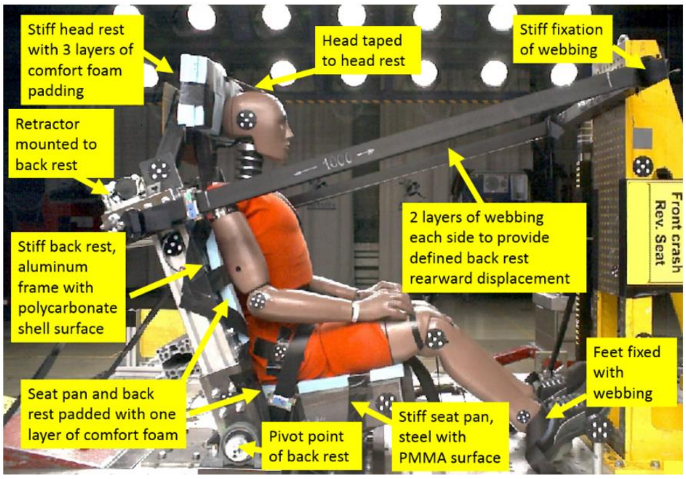


Figure 1. Generic seat in its final version

TEST SETUP

In test series 1, the standard production seat was used. In the first four tests, Δv was increased from 17 km/h as given in FMVSS 202a [12] to 40 km/h. A standard three point belt system was used with the upper shoulder belt fixed to a stiff B-pillar mounted on the sled and the lower anchorages fixed to the seat. At a Δv of 40 km/h, the deformation of the seat back was so large that no further increase in speed was done. The dynamic rear displacement at the upper end of the back rest was with 250 mm above our target of 200 mm. In order to study influencing parameters, three more tests at Δv of 40 km/h were performed, this included the variation of the back rest angle and of seat belt parameters. To investigate the influence of the back rest angle, the back rest was set to its most upright position with otherwise identical parameters to the previous test. The influence of the belt restraint system was investigated in two further tests: One test was done with a lap belt only, the other with two crossed shoulder belts (crisscross belt without lap belt portion) attached directly to the top of the seat and to the anchor plate on the seat frame.

The second tests series was performed with the generic seat. In the first six tests, the speed was increased from a Δv of 40 km/h in 5 km/h increments to about 60 km/h and an occupant load criterion (OLC) [13] of about 36 g. A seat-integrated three-point belt system was used in the tests, mounted to the upper cross member of the back rest. The tests allowed further improvements to be made. There were among others the stiffening of the production head rest and the optimisation of the webbing parameters for the controlled back rest rearward displacement. After six tests, the target Δv of 60 km/h and OLC of 36 g was attained and two additional tests to study the influence of the restraint system were performed, cf. Table 2. The additional belt systems tested were a lap belt only system and a standard 3-point belt with additional shoulder belt at the other shoulder (crisscross belt).

The focus of test series 3 was to determine repeatability and to provide reliable data for the validation of a finite element model. In contrast to the first two series, in which the crash pulses were generated by a hydraulic brake system, the tests in series 3 were performed with a bending bar brake system. This provided a better repeatability of the crash pulses. The pulse chosen had an OLC of 31.5 g and thus was softer than the pulse used in series 3. The first two tests in this series were performed with a seat belt retractor pretensioner. The second two tests were without belt system and performed mainly for the FE model set-up. A pairwise comparison of the tests data already showed a good repeatability. Therefore, a series of four identical tests were performed with a standard three point belt system to better quantify repeatability.

TEST RESULTS

The results of test series 1 are shown in Table 1. Tests 1.1 to 1.4 were performed to access the limit of the seat. It was decided not to exceed Δv of 40 km/h and a small parameter study was done at this speed. All injury assessment values (IAV) were well below its reference values. As can be seen in test 1.5, a more upright seating position slightly reduced chest acceleration. The lumbar spine was mainly loaded in tension, in test 1.6 the dummy was belted only with a lap belt which increased lumbar spine tension, in test 1.7 the dummy was mainly restrained with a shoulder belt at each side. This decreased tension in the lumbar spine. However, the effect was not as big as expected, the main restraint of the dummy was provided by the seat itself. It is interesting to mention, that we measured not only chest deflection but also chest extension. This was possibly due to the back rest frame which pushed the dummy ribs forward. At higher Δv a part of the effect is compensated by the inertia of the ribs being pushed backwards in the crash.

Table 1.
Test series 1, test setups and injury assessment values

Test	ΔV	Backrest Angle (Torso Angle)	Belt System	Chest 3 ms / g	Chest defl. / mm	Chest ext. / mm	Lumbar spine tension / kN	Lumbar spine comp. / kN
1.1	17.3 km/h	22.1° (25°)	Normal Seat Belt	18	3	12	1.1	0.3
1.2	24 km/h	22.1° (25°)	Normal Seat Belt	27	4	14	1.4	0.8
1.3	33 km/h	22.1° (25°)	Normal Seat Belt	30	6	3	1.2	0.7
1.4	40 km/h	22.1° (25°)	Normal Seat Belt	31	0	4	1.9	0.2
1.5	40 km/h	15.6° (N/A)	Normal Seat Belt	27	1	3	1.9	0.3
1.6	40 km/h	22.1° (25°)	Lap Belt only	31	0	8	2.3	0
1.7	40 km/h	22.1° (25°)	CrissCross w/o Lap Belt	29	1	5	1.3	0.3

The test parameters of test series 2 are shown in Table 2. Injury assessment values are not given in the table, as several parameters of the seat were changed in the first six tests. In tests 6 to 8 the same belt parameters as in test series 1 were investigated.

Table 2.
Test series 2, test setups

Test	ΔV	OLC	Belt System
2.1	40 km/h	20.0 g	Seat integrated 3-point belt
2.2	45 km/h	24.7 g	Seat integrated 3-point belt
2.3	50 km/h	29.9 g	Seat integrated 3-point belt
2.4	55 km/h	28.0 g	Seat integrated 3-point belt
2.5	~ 60 km/h	33.5 g	Seat integrated 3-point belt
2.6	60 km/h	36.1 g	Lap Belt only
2.7	60 km/h	36.6 g	Seat integrated CrissCross Belt
2.8	60 km/h	35.2 g	Seat integrated 3-point belt

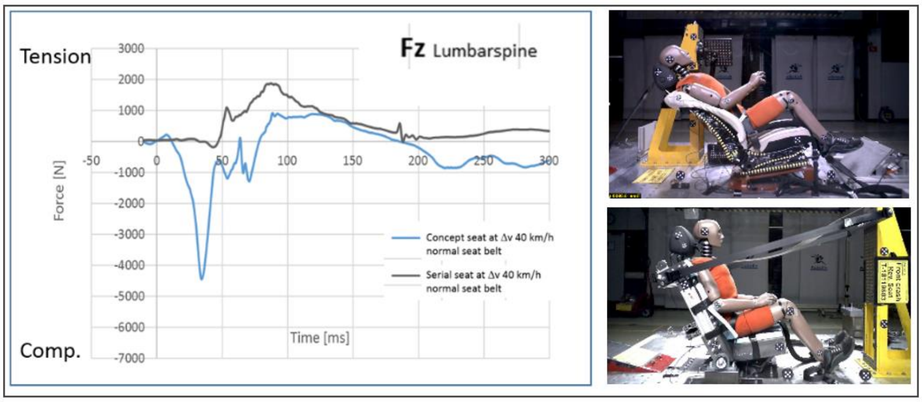


Figure 2. Comparison of lumbar spine forces of tests at Δv 40 km/h with the serial and the generic seat. The upper right picture shows the serial seat at its maximum spine tension (90 ms), the lower right picture the concept seat at its maximum compression at 34 ms

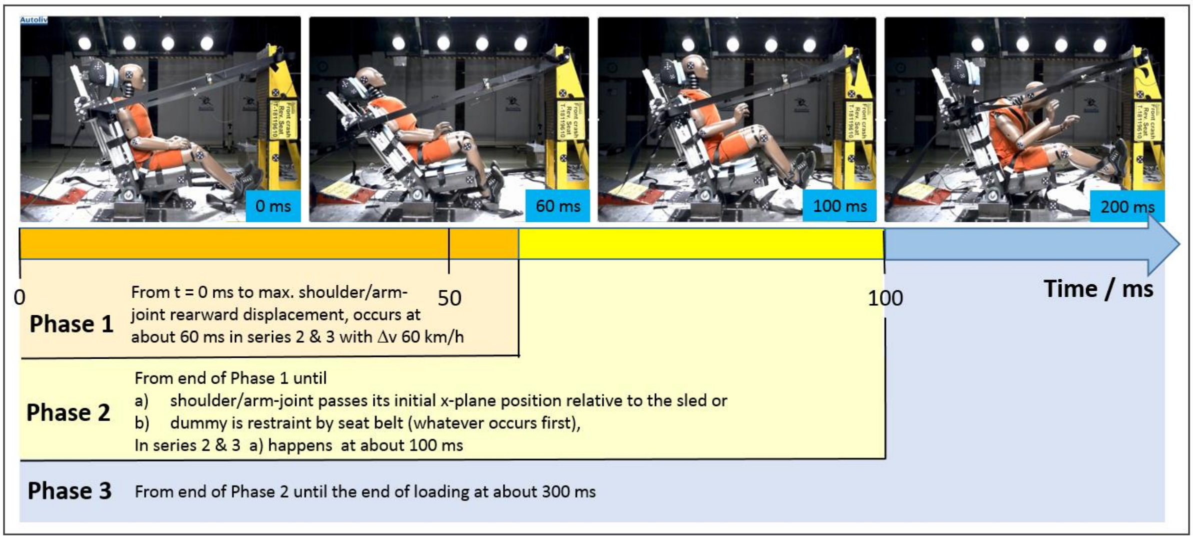
First it has to be mentioned that the dummy kinematic in the generic seat differed from that in the serial seat (Figure 2). In the serial seat the spine was mainly loaded in tension, the dummy pelvis was restrained by the seat back and the upper part of the torso could move up. The generic seat back has a plain surface and the whole body could freely move up. The pelvis pushed the torso and caused compression in the spine.

In contrast to the serial seat, the concept seat showed a considerable rebound of the back rest which is due to elasticity in the webbing and the dummy fell in to the restraint system in rebound. Therefore, it is useful to divide the crash into three phases, similar as earlier done for the low speed rear impact [14]:

Phase 1: From the beginning (t = 0 ms) to the time when the maximum shoulder/arm-joint rearward displacement occurs, this is at about 60 ms in series 2 & 3 with Δv 60 km/h.

Phase 2: From the end of Phase 1 until the shoulder/arm-joint passes its initial x-plane position (relative to the sled) or the dummy starts to be restraint by the seat belt (whatever occurs first), in series 2 & 3 the first happend at about 100 ms.

Phase 3: From end of Phase 2 until the end of the dummy loading at about 300 ms.



From t = 0 ms to max. shoulder/arm-joint rearward displacement, occurs at about 60 ms in series 2 & 3 with Δv 60 km/h

From end of Phase 1 until
a) shoulder/arm-joint passes its initial x-plane position relative to the sled or
b) dummy is restraint by seat belt (whatever occurs first),
In series 2 & 3 a) happens at about 100 ms

From end of Phase 2 until the end of loading at about 300 ms

Figure 3. The three phases of the crash

In the further discussion we will focus on injury values for Phases 1 & 2 and will mention values of Phase 3 only when appropriate. Table 3 lists the tests with Δv 60 km/h of test series 2. It is seen that chest acceleration was close to its legal limit in all three tests, lumbar spine compression came up to of 80% of its IARV of 6.4 kN. All other values were uncritical. The influence of the belt system to the injury assessment values was small. The maximum of chest deflection was reached in Phase 3. It was dependent on the seat belt and ranged from 5 mm for the lap belt and 19 mm for the crisscross belt.

Table 3.
Test series 2, injury assessment values

0 < t ≤ 100 ms			Test-No.								
			Test 2.6 Lap Belt only			Seat integrated CrissCross Belt			Test 2.8 Seat integrated 3-point belt		
Region	**Criterion**	**IARV**	**Value**	**% IARV**	**time /ms**	**Value**	**% IARV**	**time / ms**	**Value**	**% IARV**	**time / ms**
Chest	3 ms clip [g]	60	62	103	42 - 45	58	97	43 - 46	60	100	42 - 45
	Deflection [mm]	42	6	15	37	12	28	64	7	16	39
	V*C [m/s]	1	0,06	6	37	0,08	8	61	0,07	7	41
Lumbar spine	Tension $F_{L,ZT}$ [kN]	12,2	2,6	21	82	1,1	9	95	1,7	14	83
	Compression $\lvert F_{L,zc} \rvert$ [kN]	6,4	4,8	76	26	5,1	79	26	5,3	83	27

The main focus of test series 3 was to investigate repeatability and to provide realiable data for the validation of a FE model. The setups of series 3 are listed in Table 4. A total of eight tests were performed with three different belt systems. As in test series 2, the differences between the belt systems in crash Phases 1 & 2 were not very pronounced and should not be discussed here further.

Table 4.
Test series 3, test setups

Test	ΔV	OLC	Belt System
3.1	60 km/h	32.0 g	Seat integrated 3-point belt with pretensioner fired at 0 ms
3.2	60 km/h	31.5 g	Seat integrated 3-point belt with pretensioner fired at 0 ms
3.3	60 km/h	31.4 g	no belt system
3.4	60 km/h	31.8 g	no belt system
3.5	60 km/h	31.6 g	Seat integrated 3-point belt
3.6	60 km/h	32.2 g	Seat integrated 3-point belt
3.7	60 km/h	31.6 g	Seat integrated 3-point belt
3.8	60 km/h	31.2 g	Seat integrated 3-point belt

The tests with the seat integrated 3 point belt were performed four times under the same condition. The time histories of chest acceleration and lumbar spine forces showed a good repeatability, cf. Figure 4. Deviations in lumbar spine forces were slightly bigger (especially close to the peaks at about 30 ms and 60 ms) and indicated a slight “complex” behavior, which is probably due to the friction between dummy and seat back. To further illustrate repeatability, in Figure 5 all IAV are listed. As along as the IAV were above 40% of its respective IARV, the relative standard deviations were below 5% except for the lumbar spine compression.

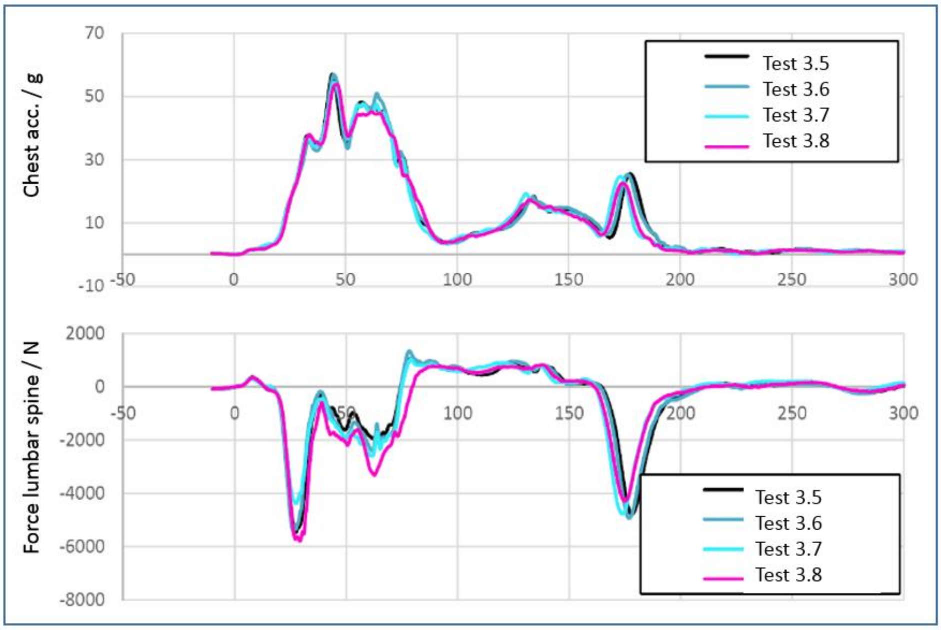


Figure 4. Time histories of chest acceleration and lumbar spine forces, 4 repeatability tests from series 3

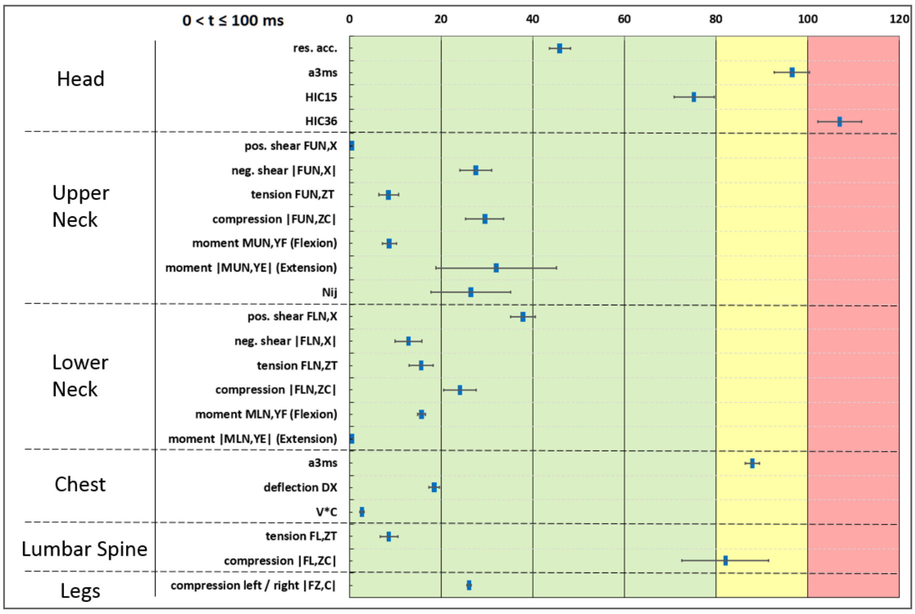


Figure 5. Test series 3, IAV in Phases 1 & 2, mean ± one standard deviation in % of IARV, four repeatability tests, the respective reference values are listed in the Appendix

DISCUSSION

One of our initial requirements to the generic test setup was, that the rearward displacement of the back rest was limited to avoid possible head contact of the occupant to the windscreen. This resulted in a relatively upright torso angle of the dummy during impact, even more upright than in the serial seat at Δv of 40 km/h, cf. Figure 6. Loading the occupant in this upright posture with such a stiff crash pulse requires further research and the dummy values can only be a rough indicator for possible injuries.

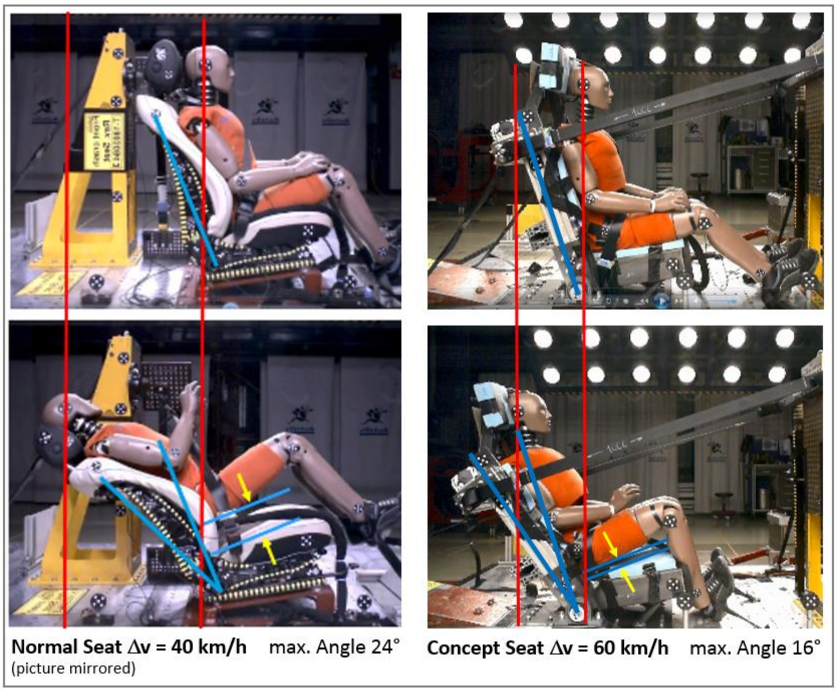


Figure 6. Comparison of the serial seat (left) and the generic (right) seat at maximum dummy rearward displacement

With the slightly stiffer crash pulse of test series 2, injury assessment values for chest acceleration and lumbar spine compression were close to its limits. With the slightly softer pulse of series 3, they reached about 80% to 90% of the limits, cf. Figure 5. It is also shown that injury values for the head were close to its respective reference values, but it again has to be mentioned that the dummy head is not validated for this impact direction. As we used an idealistic head rest without any initial gap between head and head rest, optimising the head rest for the rearward facing occupant may become a challenge. As shown in Figure 5, IAV for all other body regions were well below 40% of its limits. This is a good indicator that the generic test environment is suitable for testing, as test values are not masked by hard impacts of dummy parts to the seat. Chest deflection reached its maximum in Phase 3 and was dependent on the belt system. Values went up to 19 mm and were in good distance to its IARV. It is interesting to mention, that chest deflection in Phase 1 and 2 (0 ms to 100 ms) was mainly due to the inertia of the dummy ribcage, cf. Figure 6. The deflection went up to 7 mm and is the same for the tests with or without seat belt. A simple spring damper simulation with parameters for the thorax and ribcage from literature [15] yielded similar results.

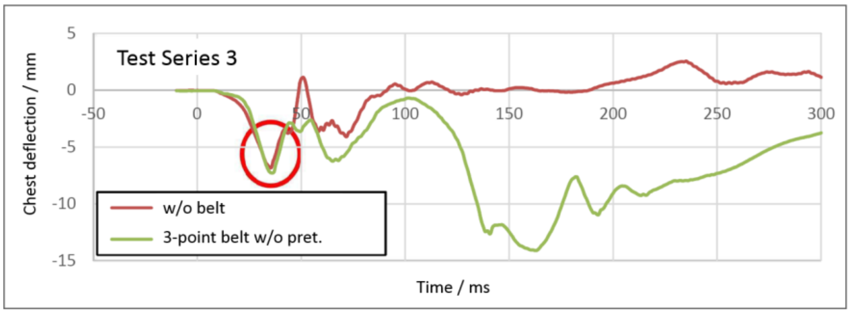


Figure 6. Test series 3, chest deflection with and without seat belt

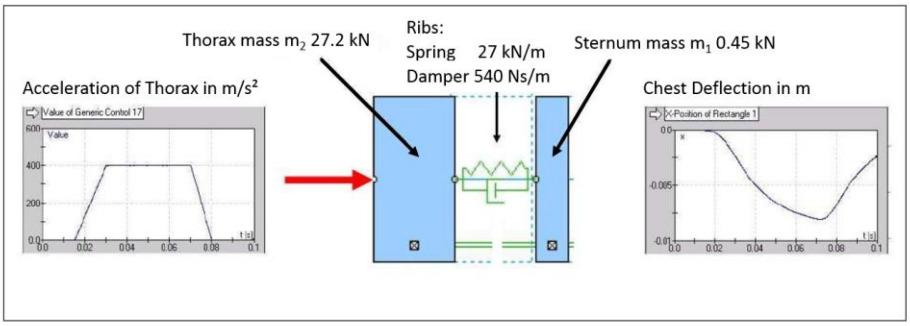


Figure 7. Spring damper model of dummy chest, parameters taken from [15]

As a next step in our investigation it is planned to build up and validate a finite element model of the generic test environment. In addition to the Hybrid III, response of a THOR 50th percentile male dummy and the THUMS human model should be investigated. Following steps using the FE models would include the study of the influence of back rest force to deflection characteristics both in impact as well in rebound. This should be optimised for dummy kinematics and loading. As described before, the influence of the seat belt system in Phases 1 & 2 is small. This is mainly due to a considerable amount of belt slack which is generated in the lap belt portion by initial dummy movement towards the seat back. A seat belt pretensioner at the anchor plate and buckle could eliminate this slack and the lap belt could properly restrain the dummy pelvis and prevent the whole dummy torso to move upwards during impact. This may also help to reduce lumbar spine compression. In the following step, the seat belt system restraint performance in Phase 3 may be optimised.

It has to be pointed out here that there is a need of reliable IARV for this loading direction and a common agreement on which dummy or human model to be used to evaluate the occupant protection.

As limitation of our study it should be mentioned that only full frontal loading directions were studied, dummy kinematics of oblique impact direction, simulating e.g. ±30° angled impacts to the barrier, were not included. As the head rest was not in focus of our investigation, the head was fixed with tape to the head rest without any gap in between.

CONCLUSION

A generic sled test and simulation environment for vehicle frontal impacts at a Δv of up to 60 km/h with occupants on rearward facing seats was developed and evaluated. The repeatability was investigated in four repeated tests, the relative standard deviations showed to be mostly below 5% of the repective injury assessment value and can be considered as good. The injury assessment value closest to its reference value showed to be chest acceleration, second was lumbar spine compression with about 80% of its limit. Peak chest deflection occurred in rebound and was below 20 mm.

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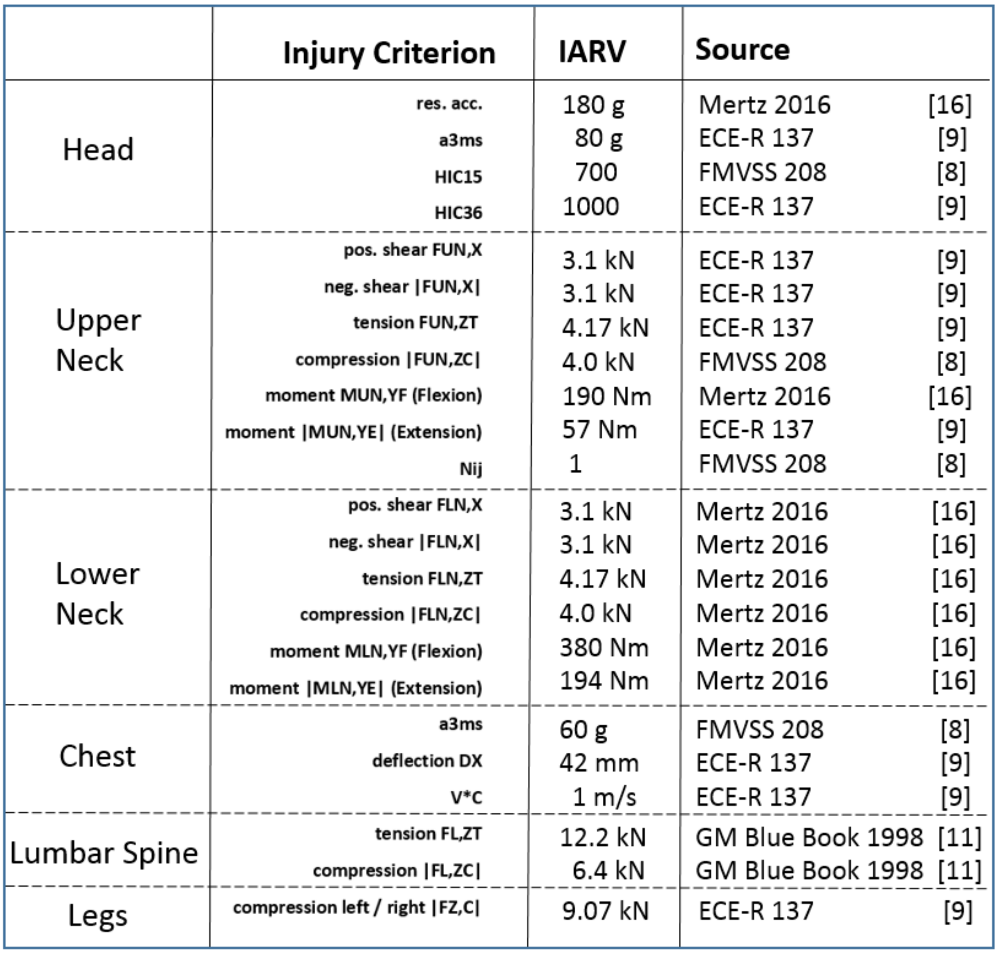
APPENDIX

Injury assessment reference values (IARV) used for the rating of repeatability



	Injury Criterion	IARV	Source
Head	res. acc.	180 g	Mertz 2016 [16]
	a3ms	80 g	ECE-R 137 [9]
	HIC15	700	FMVSS 208 [8]
	HIC36	1000	ECE-R 137 [9]
Upper Neck	pos. shear FUN,X	3.1 kN	ECE-R 137 [9]
	neg. shear |FUN,X|	3.1 kN	ECE-R 137 [9]
	tension FUN,ZT	4.17 kN	ECE-R 137 [9]
	compression |FUN,ZC|	4.0 kN	FMVSS 208 [8]
	moment MUN,YF (Flexion)	190 Nm	Mertz 2016 [16]
	moment |MUN,YE| (Extension)	57 Nm	ECE-R 137 [9]
	Nij	1	FMVSS 208 [8]
Lower Neck	pos. shear FLN,X	3.1 kN	Mertz 2016 [16]
	neg. shear |FLN,X|	3.1 kN	Mertz 2016 [16]
	tension FLN,ZT	4.17 kN	Mertz 2016 [16]
	compression |FLN,ZC|	4.0 kN	Mertz 2016 [16]
	moment MLN,YF (Flexion)	380 Nm	Mertz 2016 [16]
	moment |MLN,YE| (Extension)	194 Nm	Mertz 2016 [16]
Chest	a3ms	60 g	FMVSS 208 [8]
	deflection DX	42 mm	ECE-R 137 [9]
	V*C	1 m/s	ECE-R 137 [9]
Lumbar Spine	tension FL,ZT	12.2 kN	GM Blue Book 1998 [11]
	compression |FL,ZC|	6.4 kN	GM Blue Book 1998 [11]
Legs	compression left / right |FZ,C|	9.07 kN	ECE-R 137 [9]