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FE ANALYSES OF THE LAP BELT INTERACTIONS WITH THE PELVIS FOR DIVERSE OCCUPANTS IN VARIOUS SITTING POSTURES

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Paper Number 23-0092

ABSTRACT

Passengers of different body shapes and sizes such as male, female, obese, and lean can sit in a car seat assuming various postures. This study aims to understand the interaction of the lap belt with the pelvis in a vehicle frontal impact scenario for occupants of various shapes, sizes, and sitting postures.

A mid-size male Total HUman Model for Safety (THUMS) was morphed to develop a high and a low body mass index (BMI) human model using computer tomography (CT) images of sitting participants wearing a lap belt. Frontal impact finite element (FE) simulations were conducted for various occupant models (THUMS high-BMI, AM50, low-BMI, AF05, and Hybrid III AM50, AF05) under standard, reclined, and slouched sitting postures in the rear seat. The lap belt interactions with the anterior superior iliac spine (ASIS) were compared using the belt-pelvis angle and the overlap of the lap belt with the ASIS in the lap belt direction (belt-ASIS overlap).

From FE simulations, submarining occurred more in the reclined and slouched postures than in the standard posture because of the large initial rearward pelvis tilt. Submarining occurred in fewer cases in the high-BMI model due to smaller pelvis rotation and larger belt-ASIS overlap than in other models. In the THUMS AF05, even though the belt-ASIS overlap was comparable, the pelvis began to rotate earlier and rotated more than in male models. The pelvis of Hybrid III showed a small initial tilt and rotation angle, resulting in fewer submarine occurrences than human body models. Submarining occurred in more cases in the slouched posture than in the reclined posture. This is because the belt-ASIS overlap was smaller in the slouched posture due to the shallow belt angle.

In this study, a new parameter, the belt-ASIS overlap in the lap belt direction, was proposed to evaluate the belt engagement with the ASIS. The occurrence of submarining in various occupants and postures could be examined by using the lap belt-pelvis angle and the lap belt-ASIS overlap. These two parameters will be useful in designing a restraint system to interact with the pelvis in various conditions.

INTRODUCTION

A seat belt is a key element of the restraint system for occupant protection. During vehicle frontal impacts, the lap belt should engage the anterior edge of the pelvis. Submarining is defined as the lap belt slipping over the pelvis toward the abdomen and can cause serious abdominal injuries [1]. Leung [2] and Horsch [3] proposed a submarining model in which the lap belt starts to slip when the tangential force of the lap belt on the anterior edge of the pelvis exceeds the maximum friction force in the superior direction. Thus, the angle of the lap belt relative to the pelvis is a critical parameter for predicting submarining. Countermeasures for preventing submarining (e.g., occupant position, posture, lap belt anchorage position, seat belt pretensioner, and seat pan design) have been investigated in many studies [4-6].
Reed et al. [7] measured the lap belt location and surface landmark of human subjects sitting on the vehicle seat to investigate the lap belt path around the pelvis. The body mass index (BMI) had a great influence on the belt fit, and the lap belt of obese occupants was located further away from the anterior superior iliac spine (ASIS) in the

anterosuperior directions. Tanaka et al. [8] measured the lap belt fit in the upright and reclined posture using computed tomography (CT). They found that the overlap of the lap belt with the ASIS in the vertical direction depends on the thigh diameter and abdominal shape, and the belt-ASIS overlap was large for females due to a small thigh diameter. Kim et al. [9] have shown that interactions between the lap belt and the pelvis highly depend on the initial location and the initial angle of the lap belt. They demonstrated that the lap belt was likely to intrude into the abdomen when it was positioned high above the ASIS.

In the real world, occupants adopt various postures when sitting in vehicle seats. Especially for seats with limited recline angle, occupants may sit in the slouched posture, moving their hip forward from the normal posture. In future autonomous vehicles, occupants are likely to sit in extreme postures, e.g., highly reclined postures. Hence, the demand for understanding the safety of occupants in various postures is increasing. Reed et al. [10] have shown that the pelvis angle is inclined rearward when assuming a reclined posture. The PMHS tests by Uriot et al. [11] have shown that in the slouched posture, the pelvis tilts backwards and increases the risk of submarining. FE analyses have been conducted for occupants in reclined sitting postures, and the results showed that the pelvis rotated rearward with a large forward excursion, and the lap belt slid over the ASIS [12-14]. The postures of the pelvis and the lap belt fit in the reclined sitting postures are significant parameters in these simulations, but the available information for these parameters on various occupants is still not sufficient.

The purpose of this study is to understand the interaction of the lap belt with the pelvis in a frontal impact for various occupants and sitting postures. The THUMS low-BMI and high-BMI models were developed with morphing based on the CT image of participants. The FE simulations were conducted for THUMS low-BMI, AM50, high-BMI and AF05 as well as Hybrid III AM50 and AF05 seated in the standard, reclined, and slouched postures, and interaction between the lap belt and the pelvis was analyzed.

METHODS

FE Human Model Morphing

THUMS AM50 V4.01 (THUMS AM50) was selected as the baseline model. Tanaka et al. [8] measured 10 male participants wearing a lap belt and sitting upright in a rigid seat using standing CT. The CT images of two participants with BMIs of 33.4 and 17.6 were used to develop the high and low BMI models (THUMS high-BMI and THUMS low-BMI). From these CT images, the shapes of bones and soft tissues were converted to three-dimensional FE models consisting of bones and outer surfaces. The nodes of soft tissue around the pelvis of THUMS AM50 were morphed to have the same outer surface as the referenced models. In THUMS high-BMI, a deep valley shape was formed between the abdomen and the thigh based on the CT image. The soft tissues of the abdomen, the buttock, and the thigh were morphed, but the bones, internal organs, head, upper extremity, and lower legs were not changed.

Sled Tests

Sled tests were conducted using the Hybrid III AF05 in the standard, reclined, and slouched postures to examine the relationship between sitting posture and submarining. The dummy was seated in the rear seat of a mini car body wearing a seat belt without pretensioners and load limiters. For the slouched posture, the hip point was moved forward by 100 mm from the standard posture. The seat back angle was 26°, 29°, 26°, and the pelvis angle was 19.9°, 24.6°, 37.1° in the standard, reclined, and slouched postures, respectively. A crash pulse was based on a full frontal impact test of a minicar at 50 km/h.

FE Simulations

Simulations were conducted using a seat model that represents the environment of the sled tests. A total of 6 models, THUMS high-BMI, THUMS AM50, THUMS low-BMI, THUMS V4.10 AF05 (THUMS AF05), Hybrid III AM50, and Hybrid III AF05, were used in the simulations. The torso of the human and dummy FE model in the standard and slouched postures was rotated to match the pelvis angle with the dummy in the sled tests in the standard and slouched sitting posture, respectively. The pelvis angle in the reclined posture was matched to that in the slouched posture to compare these two postures in the same pelvis angle. The seatback angle was 26° in the standard and slouched posture, and 43° in the reclined posture. Let the segment connecting the ASIS and anterior inferior iliac spine (AIIS) be the anterior edge of the pelvis, then the anterior edge angle of the pelvis (θ_{Pelvis}) is defined as the angle between the horizontal plane and the line that is perpendicular to the anterior edge of the pelvis in the lateral view (Figure 1(a)). The θ_{Pelvis} for THUMS male models, THUMS AF05, Hybrid III AM50, and Hybrid III AF05 were 27.5°, 27.4°, 13.8°, 15.0° in the standard posture and 44.5°, 44.4°, 30.8°, 32.0° in the reclined and slouched postures, respectively. Note that the θ_{Pelvis} defined for Hybrid III AF05 in the FE simulations was smaller than the pelvis angle defined in the sled tests by 5°. The seat and seat belt models were validated by comparing FE simulations with sled tests using Hybrid III and matching the acceleration of each part of the dummy [15].

Submarining Assessment

The occurrence of submarining was evaluated based on the relative angle between the pelvis and the lap belt as introduced by Horsch and Herring [3] (Figure 1(a)). Under high loadings, the lap belt fully compresses the abdominal soft tissue, and the lap belt follows the shape of the anterior edge of the pelvis. Considering that submarining is defined as when the lap belt slips over from the anterior edge of the pelvis toward the abdomen, submarining occurrences depend on the angle between the anterior edge of the pelvis and the direction of the lap belt tension. Assuming a two-dimensional problem in the lateral plane, the equilibrium of forces can be expressed as:

$$T\cos\theta_{PB} = T_n\,, \qquad T\sin\theta_{PB} = T_t \qquad (1)$$

where T is the force component of lap belt tension projected to the lateral plane, T_n is the normal force acting on the pelvis, T_t is the tangential force acting on the pelvis. The pelvis-belt angle, θ_{PB} $(= \theta_{Pelvis} - \theta_{Belt})$ is the difference between the pelvis angle (θ_{Pelvis}) and the angle of the direction of lap belt tension from the horizontal plane (θ_{Belt}).

Let the maximum static friction coefficient between the lap belt and the skin be μ_s, then the maximum tangential force T_t is $\mu_s T_n$. For the lap belt to engage the pelvis without slipping, the following equation should be satisfied:

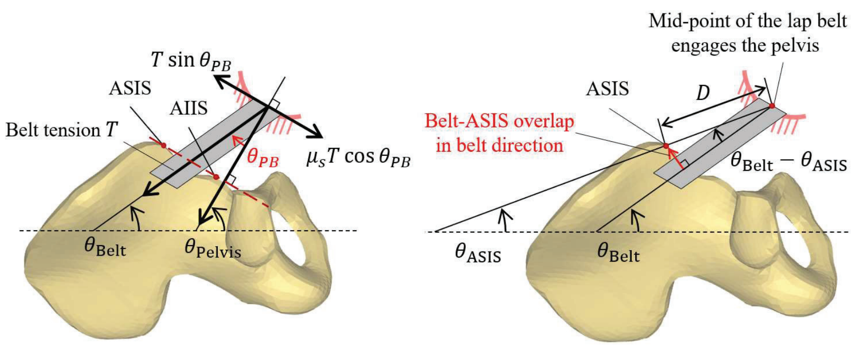
$$\mu_s T\cos\theta_{PB} > T\sin\theta_{PB} \qquad (2)$$
$$\tan\theta_{PB} < \mu_s \qquad (3)$$

The belt can slip on the anterior edge of the pelvis when the belt force is in the superior direction ($\theta_{PB} > 0$). If θ_{PB} exceed θ_{crit} $(= \tan^{-1}\mu_s)$, submarining can occur.

The lap belt overlap with the ASIS can be another parameter to evaluate the submarining occurrence. The lap belt applies force on the pelvis in the direction of the lap belt toward the anchorage. When the lap belt tension is applied to the pelvis closer to the ASIS, the possibility of submarining can be higher. Hence, we defined the belt-ASIS overlap as the distance from the ASIS to the lap belt in the sagittal plane (Figure 1(b)). The belt-ASIS overlap is expressed as:

$$\text{Belt-ASIS overlap } = D\sin(\theta_{Belt} - \theta_{ASIS}) \qquad (4)$$

where D is the distance between the mid-point of the lap belt and ASIS in the sagittal plane that goes across the ASIS, and θ_{ASIS} is the angle of the line connecting the lap belt and ASIS from the horizontal plane. This belt-ASIS overlap is a measure of an effective interaction of the lap belt force with the anterior edge of the pelvis. When the belt applies force over the ASIS (Belt-ASIS overlap < 0), submarining can occur.



(a) Pelvis-belt angle (θ_{PB}) (b) Belt-ASIS overlap in belt direction

Figure 1. Definition of submarining assessment parameters.

RESULTS

Table 1 presents the occurrence of submarining in sled tests and FE simulations. Submarining occurrences were classified into the following: no-submarining (the lap belt engaged the pelvis the whole time), the lap belt slipped over the pelvis after the pelvis and the sled had a common velocity, and submarining (lap belt slipped over the pelvis before the beginning of rebound phase). As shown in Table 1, submarining tends to occur in the reclined and slouching posture. Submarining was more prone to occur in THUMS models than in Hybrid III dummy models.

Table 1.
Submarining occurrence of sled tests and FE simulations: "++" indicates no submarining occurrence, "+" indicates the lap belt slip over during the rebound phase, and "−" indicates submarine occurrence.

	FE simulation						Sled test
Posture	THUMS high BMI	THUMS AM50	THUMS low BMI	THUMS AF05	Hybrid III AM50	Hybrid III AF05	Hybrid III AF05
Standard	++	+	+	+	++	++	++
Reclined	++	–	–	–	++	++	++
Slouching	–	–	–	–	++	–	–

Sled Tests
The dummy kinematics during the impact is shown in Figure 2. In the standard and reclined postures, submarining did not occur, and the pelvis moved downward into the seat cushion while the tibia contacted the lower frame of the front seat. The torso pitched slightly forward in these two postures. On the other hand, submarining occurred in the slouched posture. The pelvis fell from the seat cushion due to the large pelvis excursion, and the torso tilted rearwards and the shoulder belt interacted with the neck.

0 ms	50 ms	80 ms

Figure 2. Kinematic behavior of Hybrid III AF05 in the sled tests: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

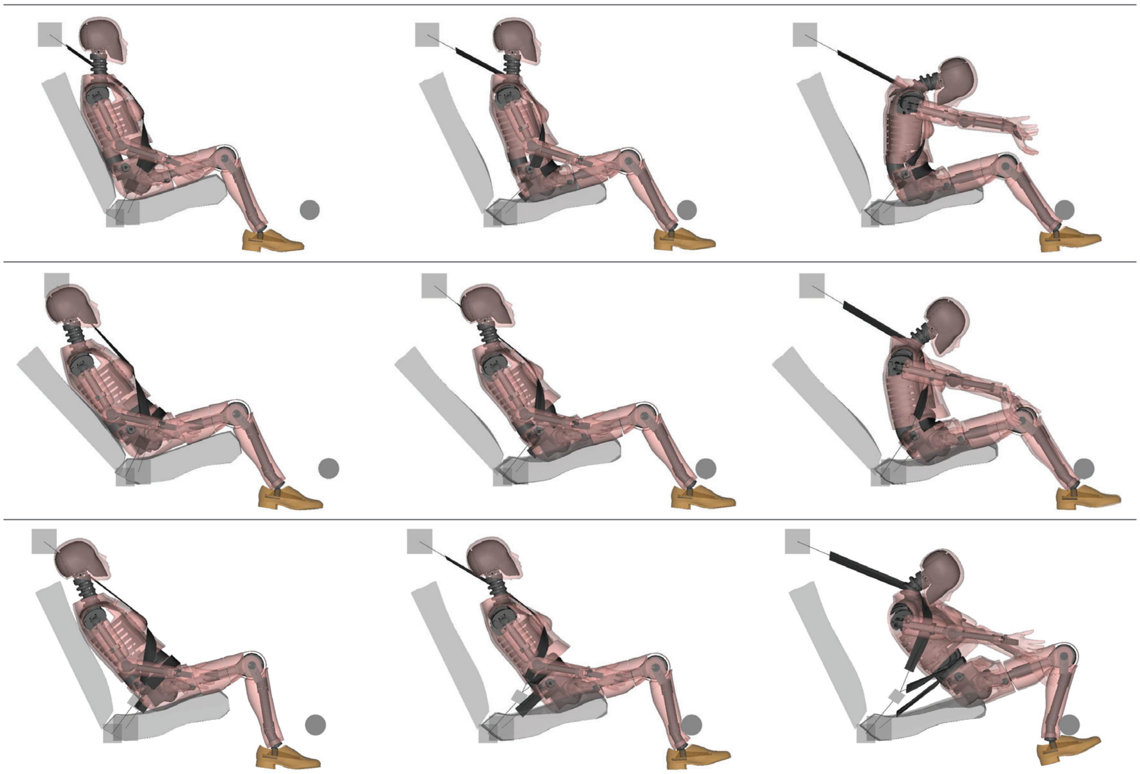
The belt connecting the inboard anchorage to the buckle was initially bent because this connecting belt went through a gap in the seat cushion. A time lag occurred before the bending was removed and tension was generated in the initial stages of the impact. This caused a time delay in increasing the belt tension of the lap belt, resulting in a large pelvis excursion.

FE Simulations

Figures 2, 3, A1, A2, A3, and A4 show the kinematic behavior of models in the standard, reclined, and slouched posture. In the standard posture, submarining did not occur for all models. Note that in this standard posture, for THUMS low-BMI, THUMS AM50, and THUMS AF05, the lap belt slipped from the pelvis during unloading. In the reclined posture, submarining occurred in THUMS low-BMI, THUMS AM50, and THUMS AF05. In the slouched posture, submarining occurred in all models except for the Hybrid III AM50.

Figure 4 shows the trajectories of the head, chest, hip joint, and knee joint for THUMS AM50 and AF05, as well as Hybrid III AM50 and AF05 in the standard posture. The pelvis excursion of the Hybrid III AM50 and AF05 was smaller than THUMS in all postures. The knee excursion, pelvis excursion and rotation were large for THUMS male models. The pelvis, chest, and knee excursion of the THUMS AF05 was smaller with a shorter loading time than THUMS male models. THUMS high BMI showed a larger pelvis and knee excursion than other THUMS male models because the pelvis mass was large, and the lap belt penetrated the valley-shaped gap of the abdomen and compressed the thick soft tissue before the lap belt engaged the pelvis (Figure A1). Due to this large pelvis excursion, the torso of the THUMS high-BMI pitched less than other THUMS models. For THUMS high-BMI in the slouched posture, the pelvis fell from the seat cushion because the initial pelvis position was further forward than in the other postures. In the submarining cases of reclined posture (THUMS AM50, low-BMI, and AF05), the torso of the models tilted rearward.

The pelvis rotated rearward after the lap belt began to apply the restraint force to the pelvis (Figure B1). THUMS models tend to show larger pelvis rotation than Hybrid III, especially in the models with thin abdominal soft tissue (THUMS AF05 and THUMS low-BMI).



0 ms 50 ms 80 ms

Figure 2. Kinematic behavior of Hybrid III AF05: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

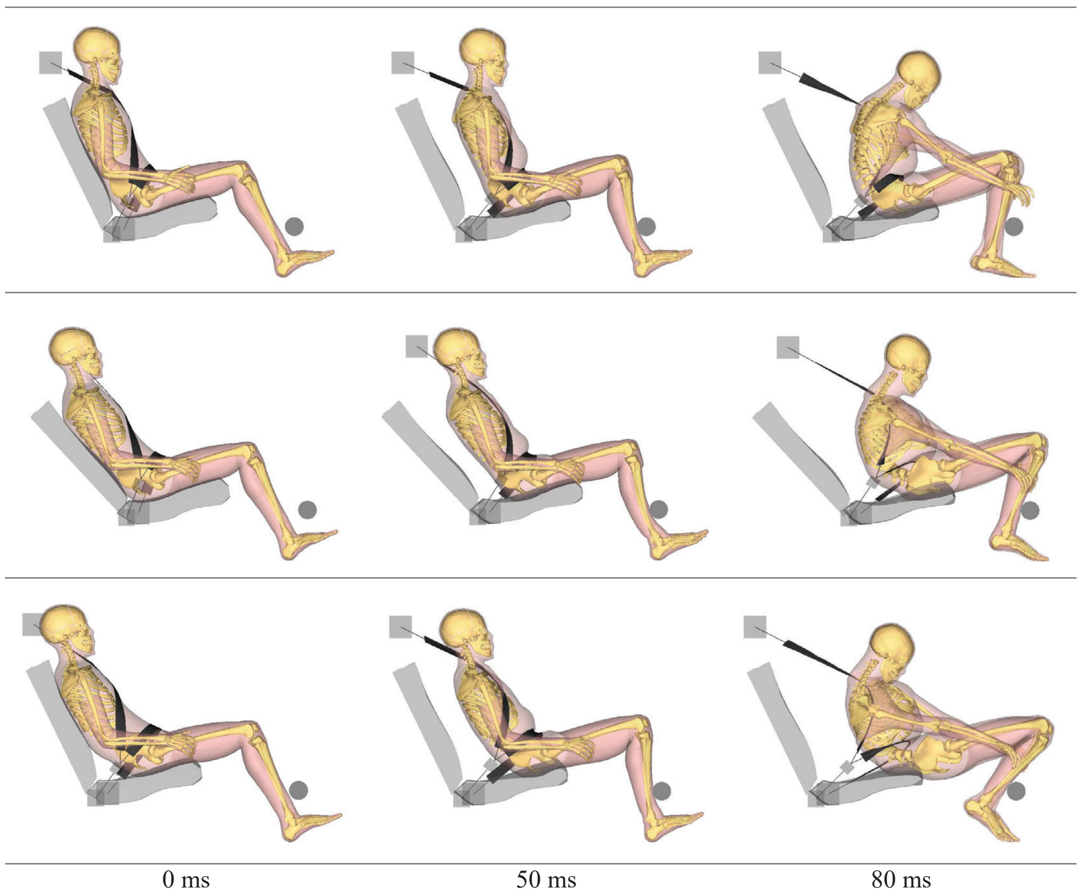


Figure 3. Kinematic behavior of THUMS AM50: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

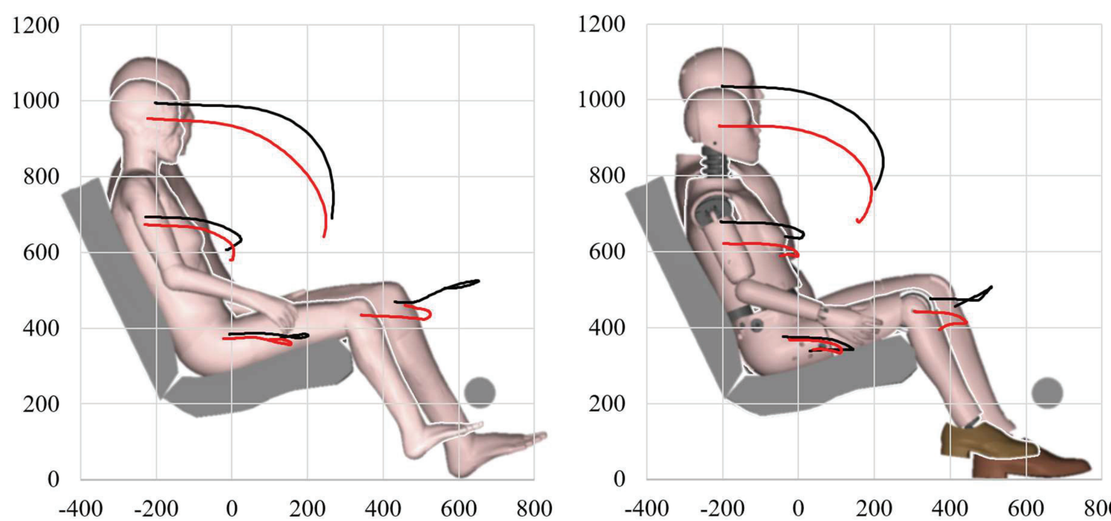
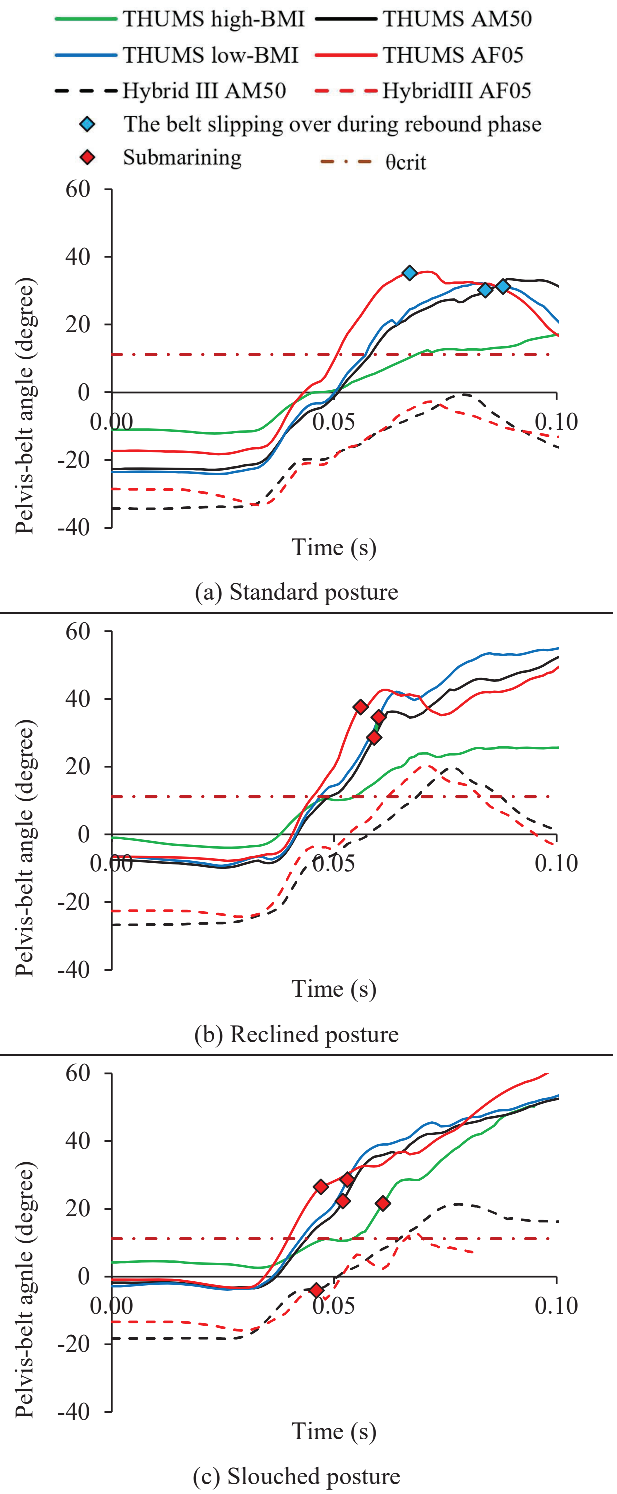


Figure 4. Trajectories of the head, chest (T8), hip joint, and knee joint for THUMS AM50 and AM05 (left), and Hybrid III AM50 and AF05 (right) in the standard posture. Trajectories of male models are shown in black, and those of female models are shown in red.

Figure 5 shows the pelvis-belt angle (θ_{PB}) with time. The time of the occurrence of submarining (the lap belt started to slip over the pelvis), as well as the time of the lap belt slipping over the pelvis during the rebound phase are also indicated in the graph. The maximum static coefficient of friction between the lap belt and skin was set to 0.2, then $\theta_{crit} = 11.2°$ is drawn as a dotted line.



(a) Standard posture

(b) Reclined posture

(c) Slouched posture

Figure 5. Pelvis-belt angle (θ_{PB}).

In general, the pelvis rotates with time, and the pelvis-belt angle θ_{PB} becomes large with higher submarining risk. The pelvis-belt angle θ_{PB} does not change until the lap belt interacts with the pelvis, then θ_{PB} increases as the lap belt engage the pelvis and the pelvis rotates rearward (see Figure B1). In the standard posture (Figure 5(a)), the initial θ_{PB} of THUMS is larger than that of Hybrid III due to the large initial pelvis angle. Despite THUMS male models having the same initial pelvis angle (θ_{Pelvis}), THUMS high-BMI has a large initial θ_{PB} due to the shallow angle of the lap belt fit (θ_{Belt}). In the reclined posture (Figure 5(b)), the initial θ_{PB} was larger than in the standard posture by 10.9° on average in all models because the initial pelvis angle was rotated rearward (+17°), whereas the initial lap belt angle θ_{Belt} was steep (+6.1°). In this reclined posture, submarining occurred in the three models (THUMS low-BMI, AM50, and AF05) when θ_{PB} reached around 29° to 38°. In the slouched posture (Figure 5(c)), the initial θ_{PB} was larger than in the reclined posture, because the initial lap belt angle was shallow. Submarining occurred in all THUMS when θ_{PB} reached around 21° to 29°, which was smaller than θ_{PB} at submarining in the reclined posture. In this posture, submarining occurred in Hybrid III AF05 before θ_{PB} reached θ_{crit}.

The thin ASIS flesh margin of THUMS low-BMI and AF05 was fully compressed by the lap belt in the initial stage of restraint, and the pelvis began to rotate earlier. THUMS high-BMI, which has thick abdominal soft tissue, showed fewer submarining occurrences than other THUMS. The thick abdominal soft tissue distributed the force from the lap belt to a wide area of the pelvis (Figure C1) and decreased the pelvis rotation moment. For Hybrid III in the three postures, the initial pelvis angle and the pelvis rotation during loading were small, which led to fewer submarining cases.

Figure 5(b) and Figure 5(c) also suggest that submarining occurred at smaller θ_{PB} in the slouched posture than in the reclined posture. This may have been due to a larger initial θ_{PB} in the slouched posture; however, this may not be the only cause because θ_{PB} of THUMS high-BMI and Hybrid III AF05 at 40 – 50 ms were comparable between the slouched and the reclined postures. This result implies that other parameters are necessary to evaluate the risk of submarining.

Figure 6 shows the lap belt overlap with the ASIS in the lap belt direction (Figure 1(b)). In the standard posture (Figure 6(a)), the belt-ASIS overlap of the THUMS high-BMI is larger than THUMS AM50 and THUMS low-BMI even though the lap belt was fitted in an upper location relative to the ASIS due to the large thigh diameter. Comparing Figure 6(b) and Figure 6(c), the initial belt-ASIS overlap in the slouched posture is smaller than that in the reclined posture due to the shallow lap belt angle in the slouched posture. Submarining occurred when the belt-ASIS overlap reached around -12 to 0 mm in all postures and models.

In the belt-ASIS overlap in the standard posture, three phases of the overlap decrease were observed (Figure 7). In Figure 6(a), phase 1 of the overlap decrease (30 - 40 ms) is caused by soft tissue compression as the occupant moves forward before the lap belt engages the pelvis. Then the lap belt engaged the pelvis (phase 2), and the overlap reaches a plateau. After 50 ms, the overlap decreased again after θ_{PB} exceeds θ_{crit} because the lap belt slid up on the pelvis (phase 3). When the belt-ASIS overlap is negative, submarining occurred. In THUMS AF05, the overlap does not have a plateau because θ_{PB} exceeds θ_{crit} earlier than in other models. In the reclined posture (Figure 6(b)), phase 1 of the overlap decrease was large because the lap belt slid over the skin before the engagement with the pelvis. In the submarining cases, phase 3 of the overlap decrease began earlier after the small plateau area (phase 2). In the slouched posture (Figure 6(c)), phase 3 began even earlier, and there are no plateau areas (phase 2) except for Hybrid III AM50 without submarining.

In THUMS high-BMI, submarining occurred only in the slouched posture whereas it did not occur in the reclined posture. Comparing Figure 6(b) and Figure 6(c), the belt-ASIS overlap of THUMS high-BMI in the slouched posture is always smaller than that in the reclined posture, suggesting that submarining occurred because of small belt-ASIS overlap.

In the Hybrid III AF05 in the slouched posture, the lap belt slipped over the pelvis before θ_{PB} reached θ_{crit}. That suggests submarining occurred in phase 1 of the overlap decrease; in other words, the lap belt slipped over without engagement with the pelvis. Because the initial belt-ASIS overlap of Hybrid III AF05 in the slouching posture was insufficient, the belt-ASIS overlap became negative during phase 1, and submarining occurred (Figure 6(c)).

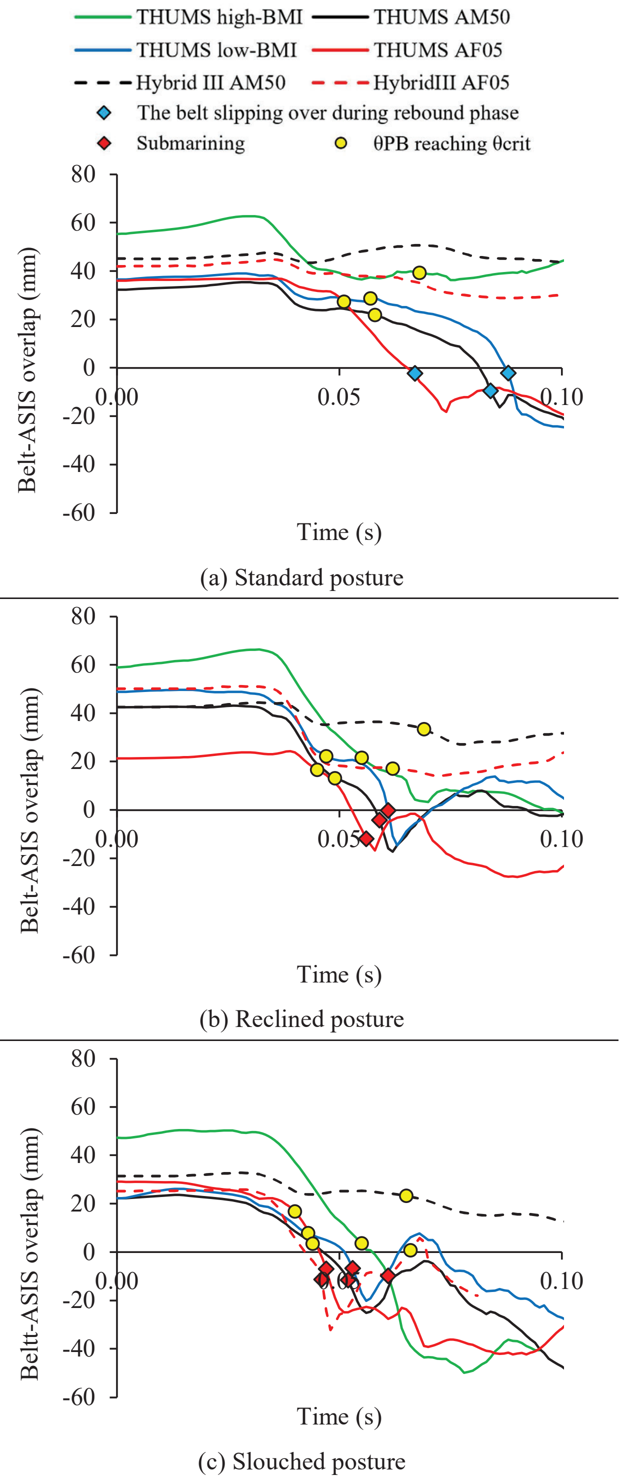
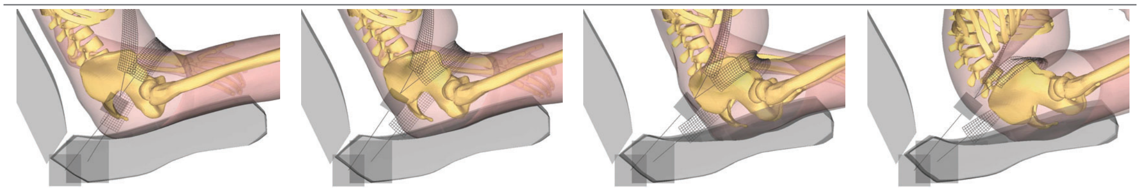


Figure 6. Belt-ASIS overlap in the belt direction.



Phase 1 start (33 ms)	Phase 2 start (45 ms)	Phase 3 start (57 ms)	Lap belt slipped over (84 ms)

Figure 7. Interaction between the pelvis and the lap belt at each belt-ASIS overlap decrease stage (THUMS AM50, standard posture, the right arm is not displayed). Phase 1: the ASIS flesh margin is compressed, phase 2: the lap belt engages the pelvis, and phase 3: the lap belt slides up on the pelvis.

DISCUSSION

In this study, the lap belt engagement with the ASIS was examined for various occupant models in the standard, reclined, and slouched postures. The results of this study showed that in the sled tests and FE simulations, the likelihood of submarining increases in the following order: standard, reclined and slouched posture. Hybrid III dummies were less likely to submarine than THUMS.

We proposed a lap belt-ASIS overlap which is the overlap of the lap belt with the ASIS in the belt direction (Figure 1(b)). In previous studies, the position of the lap belt and ASIS of human subjects have been measured [7, 8], and the belt-ASIS overlap has been defined as the vertical distance between the lap belt and the ASIS. While the occupant mainly moves in the forward direction, the lap belt applies a force in the lap belt tension direction toward the anchorage. Hence, the overlap of the lap belt in the vertical direction may not represent the lap belt engagement with the ASIS. For example, the lap belt-ASIS overlap in the vertical direction tends to be small (or no overlap) for high BMI participants because the lap belt locates upward. However, the lap belt engaged with the pelvis for high-BMI occupants [16]. In this study, the lap belt-ASIS overlap in the lap belt direction was large in the high BMI occupant (see Figure 5), and submarining of the high BMI occupant did not occur in the standard and reclined postures. Thus, the belt-ASIS overlap in the lap belt direction is probably appropriate to evaluate the lap belt engagement with the pelvis. Based on this parameter, the layout of the lap belt can be designed to have sufficient overlap with the pelvis.

The combination of the belt-ASIS overlap in the belt direction and the pelvis-belt angle (θ_{PB}) appears to be useful in understanding the process of submarining. The process of change of these parameters with time can be described as follows:

1. The overlap decreases as the lap belt compresses the abdominal soft tissue (phase 1).
2. The overlap becomes constant when the lap belt engages the pelvis, and the pelvis begins to rotate (phase 2).
3. When θ_{PB} reaches θ_{crit}, the lap belt begins to slip on the pelvis, and the overlap begins to decrease again (phase 3). When the overlap is negative, submarining occurs.

Submarining occurred in two scenarios: 1) when the lap belt did not engage the pelvis (e.g., Hybrid III AF05 in the slouched posture), or 2) when the lap belt slips over the pelvis (e.g., THUMS low-BMI in the reclined posture).

This study showed that submarining occurrence is more likely in the reclined posture than in the standard posture. Even though the pelvis angle is the same between the reclined and the slouched postures, the lap belt angle θ_{Belt} was smaller in the slouched posture (Figure 5). Moreover, the smaller belt-ASIS overlap in the slouched posture indicates that submarining is more likely to occur than in the reclined posture (Figure 6).

Rawska et al. [13, 14, 17] have shown that submarining is more likely to occur in a small female FE model than in standard and large male models. Tanaka et al. [8] have shown small females have a large belt-ASIS overlap in the vertical direction because of a low thigh height. However, the result of this study shows that the belt-ASIS overlap in the lap belt direction in the small female model is comparable with that in the male models (see Figure 5). Additionally, due to its small flesh margin, the pelvis of THUMS AF05 began to rotate early in the restraint and rotated largely. This large pelvis rotation is a possible reason that submarining is likely to occur in small female models. Further research is necessary to identify the reasons for the large rotation of the female's pelvis.

A limitation of this study is that it is not clear whether the THUMS can correctly predict submarining. This is because elements of soft tissues around the ASIS became unstable and collapsed under large deformations in some calculations. Sun et al. [18] applied a smoothed particle Galerkin method to a belt-flesh-pelvis interaction for the evaluation of submarining occurrence. Even if submarining prediction in THUMS is not so accurate, the analytical method of the lap belt and pelvis behavior using the belt-pelvis angle and the belt-ASIS overlap proposed in this study will be useful to understand submarining occurrences.

CONCLUSIONS

In this study, sled tests and FE simulations of occupant frontal impact responses were conducted in 3 seating postures. Interactions between the lap belt and pelvis were observed using belt-pelvis angle (θ_{PB}) and belt-ASIS overlap in belt direction.

- The overlap between the lap belt and ASIS in the direction of belt tension may be a better parameter than vertical or lateral overlap to evaluate the risk of submarining in occupants with various body sizes, body shapes, and seating postures.

- In reclined and slouched postures, dummy and human body models tend to show more submarining because of the initially rearward tilted pelvis. In slouched posture, the risk of submarining is higher than reclined posture because of the small belt-ASIS overlap in the belt direction.

- Hybrid III models showed fewer submarining cases because of small pelvis rotation during impact and large belt-ASIS overlap.

- Occupant with high BMI have large belt-ASIS overlap because the lap belt is located forward compared to occupants with lower BMI. The risk of submarining for occupants with high BMI is low because of large belt-ASIS overlap and small pelvis rotation.

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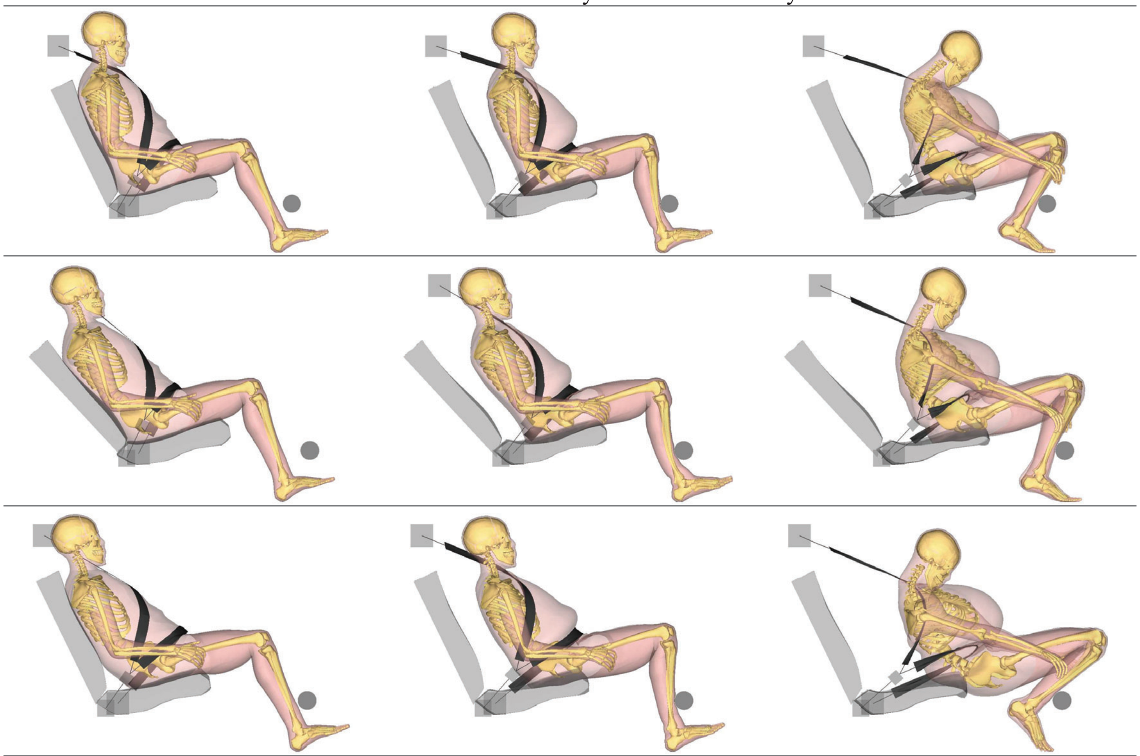
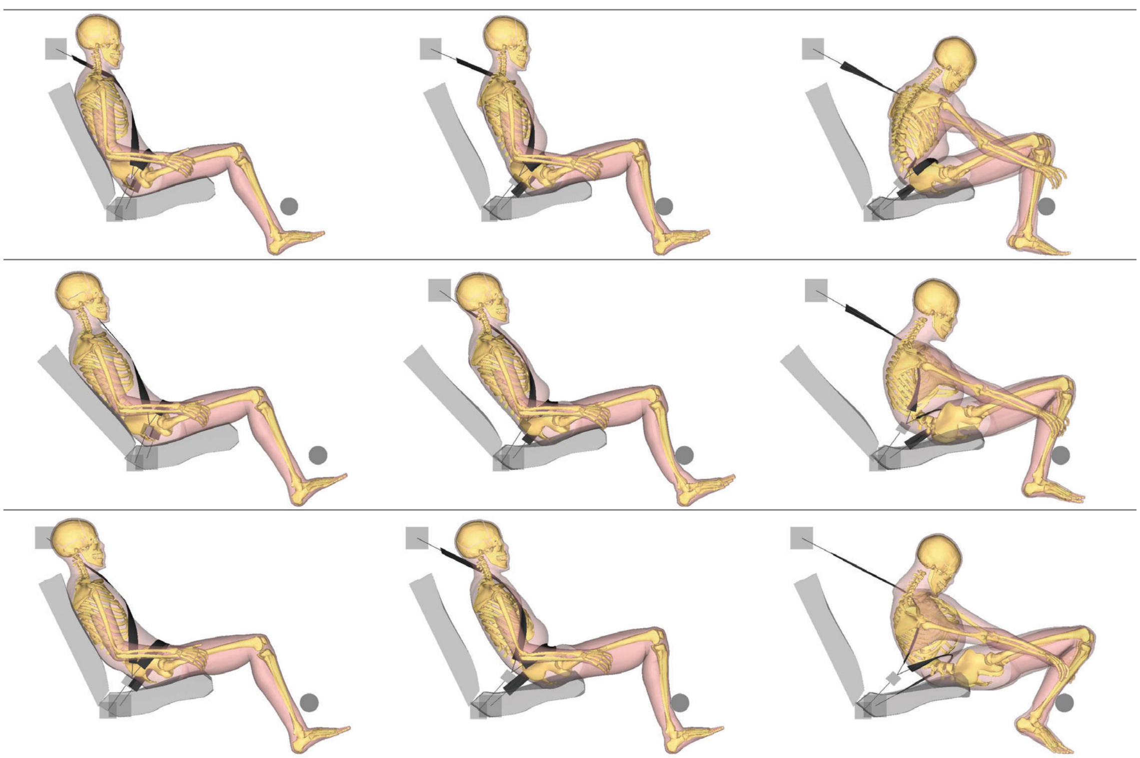
APPENDIX A Kinematic behavior of human body models and dummy models in FE simulations



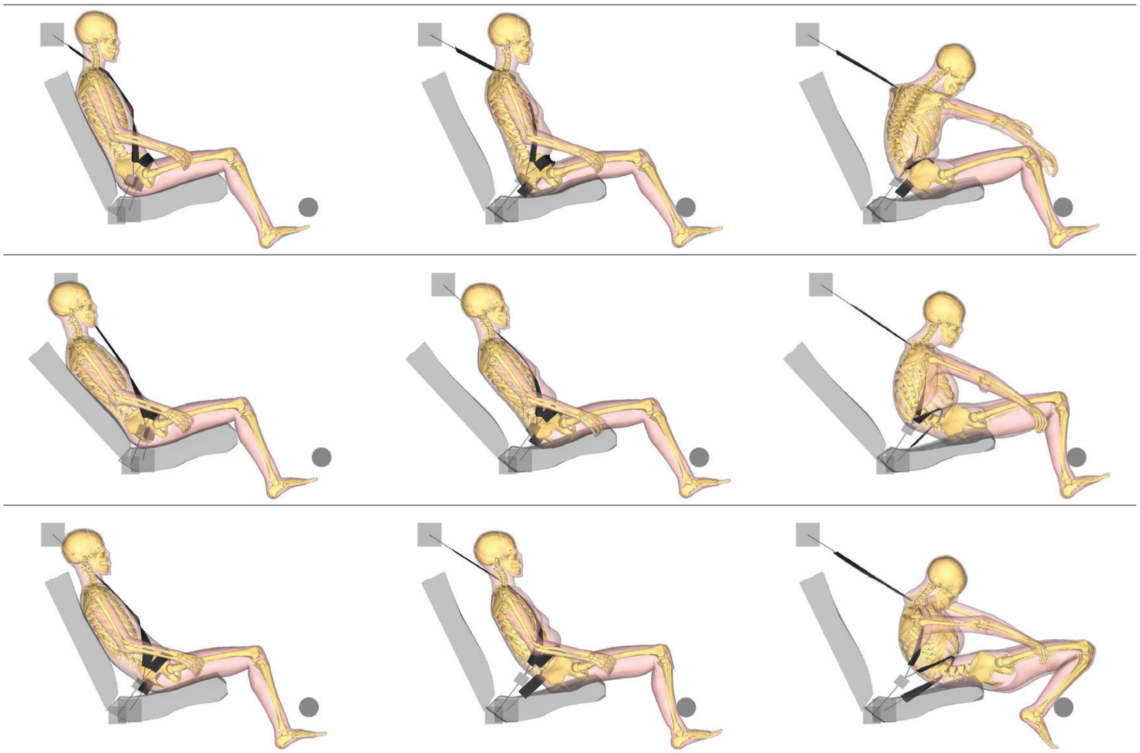
0 ms 50 ms 80 ms

Figure A1. Kinematic behavior of THUMS high-BMI: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



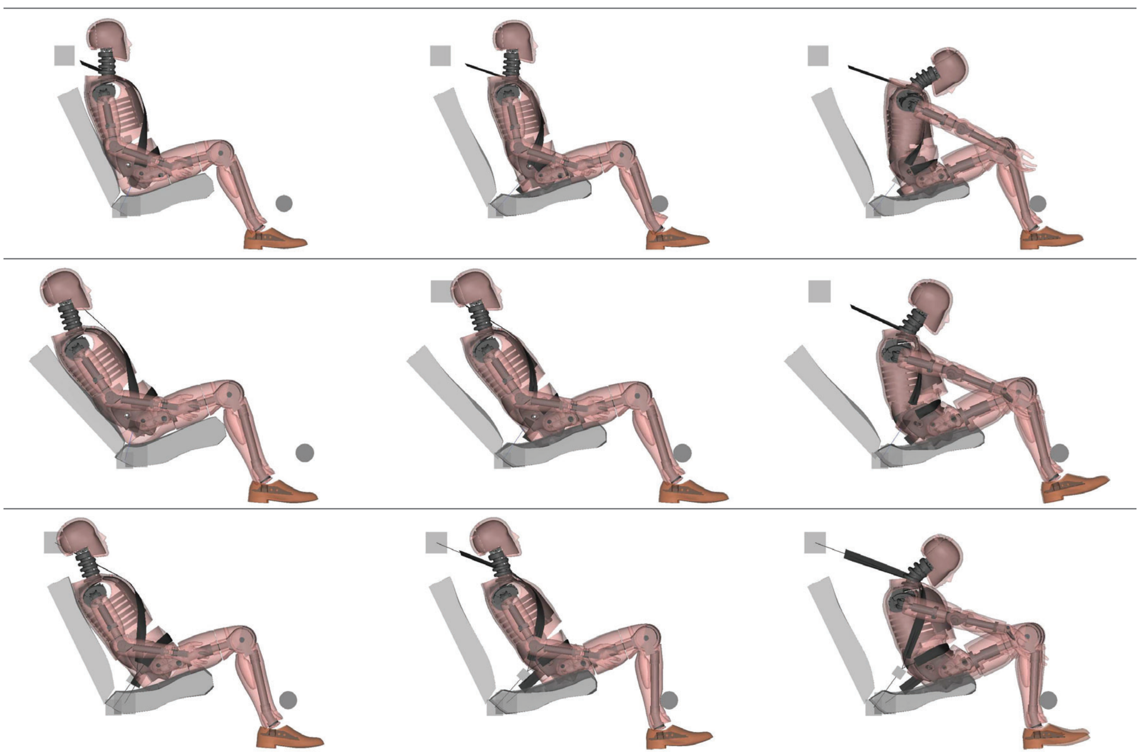
0 ms 50 ms 80 ms

Figure A2. Kinematic behavior of THUMS low-BMI: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



0 ms 50 ms 80 ms

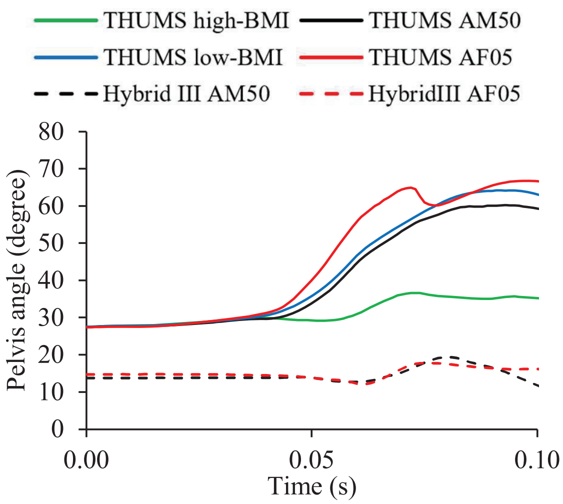
Figure A3. Kinematic behavior of THUMS AF05: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).



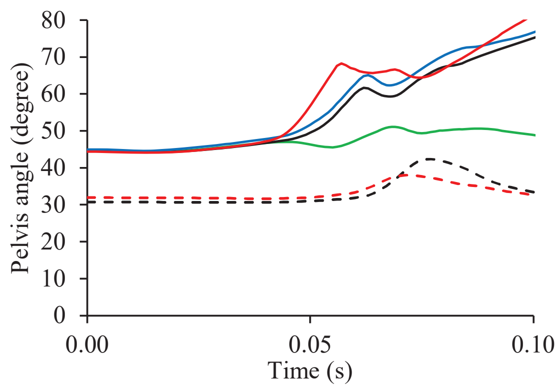
0 ms 50 ms 80 ms

Figure A4. Kinematic behavior of Hybrid III AM50: standard posture (upper row), reclined posture (middle row), slouched posture (lower row).

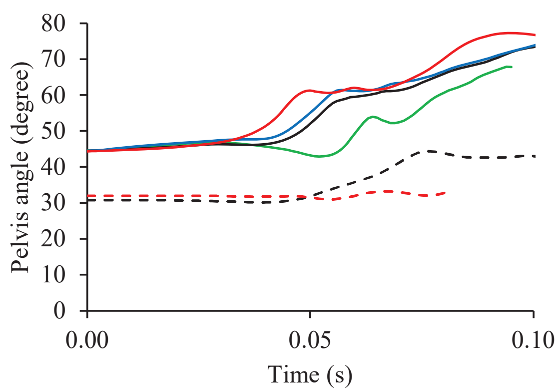
APPENDIX B Pelvis angle (θ_{Pelvis})



(a) Standard posture



(b) Reclined posture



(c) Slouched posture

Figure B1. Pelvis angle (θ_{Pelvis}).

APPENDIX C Stress distribution on the pelvis

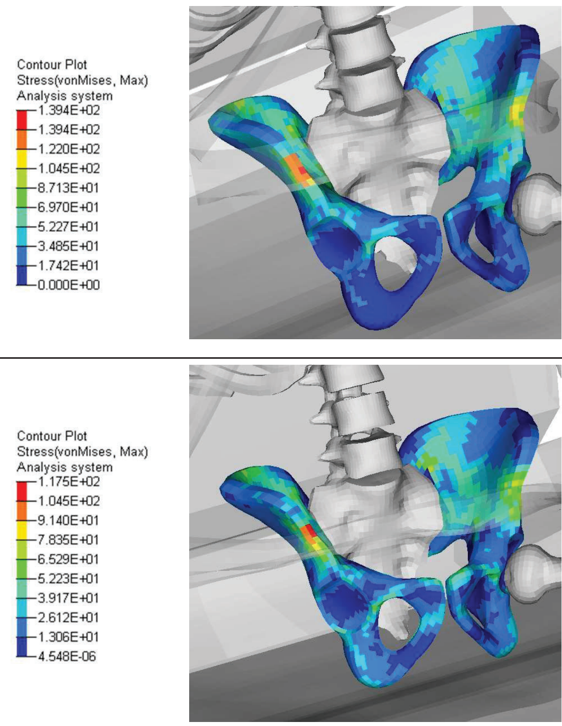


Figure C1. Stress (von Mises) distribution on the pelvis: THUMS AM50 (upper row), THUMS high-BMI (lower row), standard posture, 60 ms.

EVALUATION OF SEATBELT USE AMONG PREGNANT WOMEN IN SWEDEN

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ABSTRACT

A digital questionnaire was distributed through social media targeting women who were or had been pregnant. The primary objective was to investigate self-reported seatbelt use and misuse during pregnancy. The second objective was to study if, and to which extent, women had received information regarding seatbelt use and how to wear it during pregnancy.

The survey of 2,030 women who were or had been pregnant showed a total seatbelt wearing rate of 99%. However, 39% were wearing the seatbelt wrongly. In 35% of cases, the shoulder section of the seatbelt was incorrectly positioned, and the lap section of the seatbelt in 8% of cases. In 4% of cases, both the shoulder and lap belt parts of the seatbelt were incorrectly positioned.

The majority (66%) had not received any information regarding proper seatbelt use during pregnancy. Of the 700 women (34%) who had received information, most of them had actively sought out information about how the seatbelt should be worn during pregnancy. This subgroup had significantly lower misuse rate, although a third of the group wore the seatbelt incorrectly. Very few (6%), had received information via a health care provider.

Present data highlight the need for improved seatbelt fit for pregnant women. The result from the survey shows that misuse was lower among the women whom actively searched for information regarding how to wear the seatbelt. To reach other user groups, it should be a priority for several stakeholders to communicate information regarding proper seatbelt use during pregnancy.

Keywords Seatbelt, Pregnancy, Misuse.

INTRODUCTION

A number of studies worldwide have reported that there is a lack of knowledge among women on how to use and position the seatbelt during pregnancy; US [1,2], Japan [3,4], UK [5,6], France [7], and Iran [8]. In the Japan survey by Hanahara et al. [3], involving 680 belted pregnant drivers, 13% used the seatbelt incorrectly. The most common misuse was placing the lap belt across the abdomen (7%) or the thighs (3%). According to the UK survey by Acar et al. [5], which included 1,931 pregnant women from around the world, only a very small proportion (4%) indicated completely correct placement of the seatbelt (i.e. both the hip and diagonal parts of the belt correctly positioned). The most common misuse involved placing the seatbelt *'across abdomen'* (lap part: 45%; diagonal part: 18%) or '*not using the seatbelt at all'* (lap part: 12%; diagonal part: 9%). In the French survey by Auriault et al. [7], involving 135 pregnant women, 20% indicated that they placed the hip belt above/on the abdomen, 13% that they kept the diagonal belt behind their shoulder and about 10% that they did not use the belt all the time. In addition, 35–40% considered/thought that the belt was a potential danger to the foetus.

The need for information regarding correct seatbelt use for pregnant women has been strongly highlighted in several studies [1,2,3,4,5,6,7,8]. For example, Acar et al. [5] recommend that media, the medical community, and automotive industry should provide targeted information regarding correct seatbelt use during pregnancy.

Women's safety while driving and travelling in cars must be studied to a higher extent. The aim of this study was to investigate self-reported seatbelt use and misuse among pregnant women in Sweden. An additional aim was to study, if and to which extent, women had received any information regarding seatbelt use and how to wear the seatbelt during pregnancy.

METHOD

A digital questionnaire was distributed through social media to evaluate seatbelt use and misuse of during pregnancy. To spread the survey and increase the number of women responding, it was distributed among Folksam Insurance Groups (Folksam) costumers holding a family policy who had a registered e-mail address. In total 31,598 costumers received an e-mail from Folksam, of which 8,209 (26.0%) opened the e-mail and 1,025 (3.2%) clicked on the link to the survey. Furthermore, the survey was distributed by Folksam using sponsored posts (€3,500) on Facebook and Instagram.

The target audience were women in Sweden within the age range 23-44 and mothers of children aged newborn to five years of age. The number of reached people amounted to 182,800 and 1,549 had clicked on the link. The survey was also distributed by the blog "Baking Babies", Facebook group "Mammor United", "Mammagrupp med högt i tak", "Professional Womens Group in Gothenburg", Folksam's and the authors' LinkedIn networks.

The web-based survey began with the question *'Are you or have you ever been pregnant?*', and the survey was terminated for anyone responding with a 'no'. Other respondents continued to complete the entire survey, which included 22 questions on the following topics:

1) Personal data: Number of pregnancies, length, country of birth, driver's license, etc.
2) Car use: Access to car, type of use/travel, car brand, position in the car, etc.
3) Seatbelt use: Questions regarding seatbelt positions were categorised in two categories describing the hip and diagonal parts of the seatbelt separately. Position, safety concerns, discomfort, etc.
4) Information: Received information about correct seatbelt use during pregnancy, source, whether the information was sufficient, etc.

Further information regarding the correct use of seatbelts was not provided in connection with the questionnaire. Estimated time to answer the questionnaire was 10-15 minutes, based on a test by a group of colleagues. Furthermore, an expert group with significant experience of both real-life crashes and car safety was assembled and given the opportunity to comment and adjust the questionnaire. The design of the images/figures describing correct or incorrect use was considered crucial. Therefore, a professional art designer was consulted to create graphical representations of likely seatbelt positions to minimise any misunderstandings. In total, six likely positions of the shoulder section of the seatbelt, and four different positions of the lap belt, were illustrated and supported by verbal descriptions.

The final version of the questionnaire was available online in Swedish, English and Arabic. The Swedish version was used to prepare the English and Arabic version. The translations were made by native speakers of each language. The responses from all versions were combined.

RESULTS

In total, 2,069 responded to the survey, out of which 2,034 (98%) were, or had been, pregnant. The 35 (2%), who stated that they had not been pregnant were excluded, leaving a study population of 2,034 individuals. The vast majority responded to the Swedish version of the digital questionnaire; 2,006 (98.6%) in Swedish, 24 (1.2%) English and 4 (0.2%) Arabic.

Personal data

The majority of the women were or had been pregnant during the past five years (96%). In total 594 (29%) were pregnant at the time of the survey. Most were raised in the Nordic countries (97%). The majority (92%), held a driving license, most of whom had passed the test in the 2000s (89%), in a Nordic country (98%). The majority had taken their driving license in Sweden (96%).

Car use

Among those who responded, 84% used the car every day or at least a couple of times every week. The vast majority (96%) had access to a car, either a private/company car (90%) or through carpool/renting/borrowing (6%). Family logistics (74%), was the most common reason for travelling by car, followed by sorting things out for the home (64%), vacation/travel (49%) and needing it for work (37%). The environments travelled in were relatively evenly distributed over urban areas (86%), rural areas (78%) and larger cities/centres (70%). The most common car make was Volvo (24%), followed by Volkswagen (16%), Skoda (8%) and Toyota (7%).

Seatbelt use

In total, 99% stated that they always wear the seatbelt. Based on self-reported seatbelt use 39% were wearing the seatbelt incorrectly (***Figure 1***). The shoulder seatbelt was incorrectly positioned in 35% of cases, and the lap section of the seatbelt in 8% of cases. In 4% of cases, both the shoulder and lap belt parts of the seatbelt were incorrectly positioned. When asked why they were wearing the seatbelt, 96% of the women indicated that they were wearing a seatbelt to protect themselves. Only 68% answered that the seatbelt would help protect the foetus in the event of a crash.

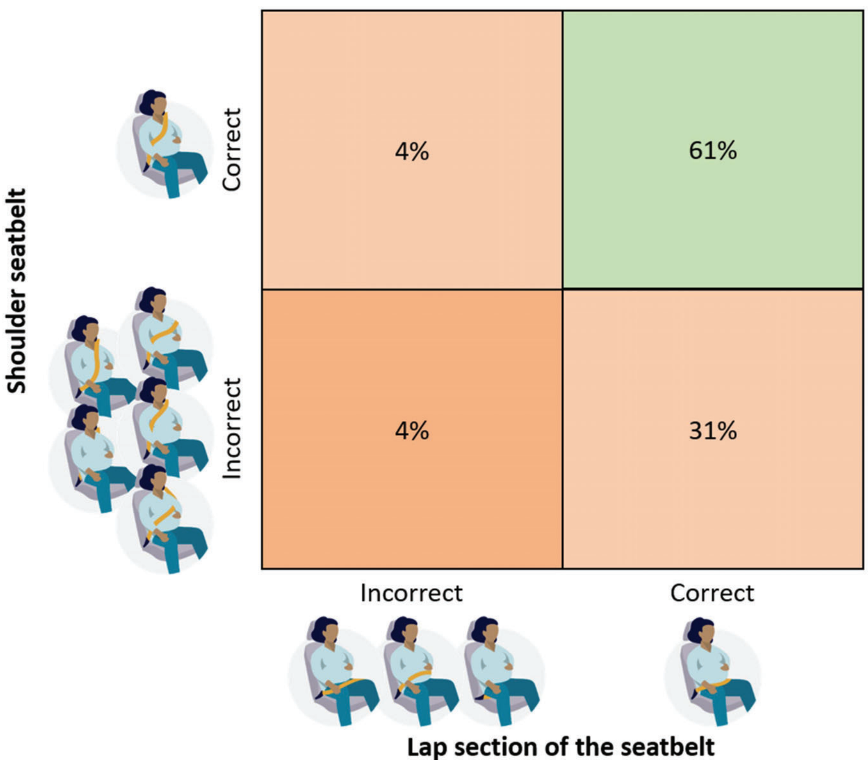

Figure 1. Responds to the questions 'How do you use 1) the diagonal part, and 2) the lap section of the seatbelt?'. (N = 2,034).

Information

The majority (66%), had not received any information regarding proper seatbelt use during pregnancy (***Figure 2***). Only 6% had received information via the Maternity Clinic (MC) (5%) or via some other health care provider (1%). A total of 700 women (34%) stated that they had received, or actively sought, information about how the seatbelt should be worn. Yet, a third of this group wore the seatbelt incorrectly. However, the misuse was significantly higher (42%), in the group that had not received any information at all.

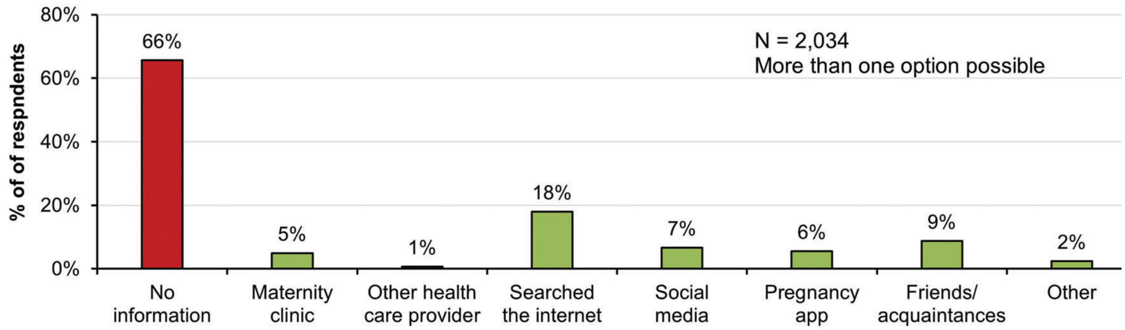

Figure 2. Responses to the question 'From whom did you receive the information of how to wear the seatbelt during pregnancy?' (N = 2,034; more than one option possible).

Of the 700 women who had received information, more than half had actively searched the internet, and a quarter had received the information through friends and acquaintances (***Figure 2***).

When asking '*from whom they would expect/like to receive information regarding how to wear seatbelts during pregnancy*', 93% responded '*maternity clinic*', followed by '*parenting classes*' (39%), '*insurance company*' (39%), and '*government agency*' (28%).

DISCUSSION

Women will experience a wide variety of physical changes during the pregnancy that may affect seatbelt use. In this study, investigating self-reported seatbelt use during pregnancy among 2,034 women, we identified that 99% were wearing the seatbelt. However, only 61% indicated correct positioning of the seatbelt, which is in line with previous findings (68% [2]; 87% [3]; 48% [6]). Incorrect seatbelt use may expose the women and the foetus to an elevated risk, since the forces during an impact will not be optimally distributed over the body. Compared to Acar et al. [5] the misuse proportion of the lap belt was significantly lower. Furthermore, the seatbelt use was somewhat higher in the present study (99%) compared to [1] (95%), [3] (98%), [5] (92%), and [7] ("more than 90%").

The misuse was significantly lower among individuals that had received some information about how to use the seatbelt while pregnant. Similar findings have been reported by [2,3,6]. Education interventions have been shown to increase the correct usage [9]. For example, a short 1–2 minute instruction film can provide significant improvements in belt use [2]. Other factors that have been shown to affect the seatbelt use include whether the belt is perceived to be (un)comfortable, level of education or social group affiliation, if the pregnant woman believes that the seatbelt protects the foetus, age, legislation, the seat position in the car, and the length of the journey [1,2,4,6].

However, information provided by healthcare providers to pregnant women regarding belt use, seems to be very limited [1,2,4]. Studies have also pointed to ignorance within the healthcare system regarding belt use for pregnant women [10]. Only 6% in the present study had received relevant information from their maternity clinic, although 93% stated that they would have liked to be informed by their maternity clinic. This issue highlights that the women's expectation has not been fulfilled. Car crashes are one of the main causes of accidental death, disability, and placental abruption in pregnancy [11]. Therefore, it is recommended that healthcare providers take greater responsibility with regard to seatbelt use guidelines for pregnant women.

The final version of the questionnaire was available online in Swedish, English and Arabic. The majority responded in Swedish (94%), only four women responded in Arabic. Although, the survey was available for anyone on the internet, the response rates indicate it therefore can be assumed that the results reflect the Swedish population. Hence, the results might not be applicable for other countries with other cultural backgrounds.

Furthermore, the results may also reflect a population that are more safety-conscious since the respondents actively/voluntarily agreed on participate.

CONCLUSION

The overall seatbelt use during pregnancy was as high as 99%. However, misuse during pregnancy was common. Present data highlight the need for improved seatbelt fit for pregnant women. The results of the questionnaire shows that the misuse was lower among the women whom actively searched for information regarding how to wear the seatbelt. To reach other user groups it should be a priority for several stakeholders to communicate information regarding proper seatbelt use during pregnancy.

ACKNOWLEDGEMENTS

This study was financially supported by the Swedish Transport Administration and Folksam Insurance Group. The authors wish to express theirs thanks to the women whom participated in this research by completing the questionnaire.

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COMPARISON OF THE IMPACT KINEMATICS OF AN ELDERLY FEMALE, THE HIII 50TH MALE AND THE HIII 5TH FEMALE DUMMIES AS DRIVERS, FRONT PASSENGERS AND REAR PASSENGERS IN FULL-WIDTH FRONTAL IMPACTS

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Paper Number 23-0176

ABSTRACT

The objectives of this study were to analyse and compare the impact kinematics of an early prototype version of an Elderly Female, the HIII 50th Male, and the HIII 5th Female dummies as drivers, front passengers, and rear passengers in full-width frontal impacts.
Three full-width frontal impact tests were conducted with a popular midsize station wagon based on Regulation UN R137 – except for the front passenger seat, which was adjusted in its longitudinal mid-position instead – in which the different ATDs were either placed in the driver, front passenger, or right back seats.
The measured loads indicate that second-row seats offer less protection than first-row seats. The HIII 50th Male dummy experienced the greatest torso forward rotation on all seats, with changes in the forward leaning angle of both the Elderly Female and HIII 5th Female dummies dependent on their respective seat positions.
More research into the biofidelity of the Elderly Female Dummy is necessary to improve ATD design and to develop injury assessment reference values and injury risk functions.

INTRODUCTION

Aside from being the only age group with an increase in road deaths since 2010, the elderly are also more susceptible to trauma [1-3]. Simultaneously, accident investigations have shown that women are more at risk of being seriously injured than men [4-7], while analyses of crash data of passenger vehicles of model years 2007 and newer show that rear occupants are exposed to a greater relative fatality risk than front occupants [8-9]. Occupant protection systems should therefore better account for female and senior occupants as well as seating positions outside of regulations to reduce the risk of sustaining serious or fatal injuries [10-11]. This highlights the necessity for Anthropomorphic Test Devices (ATDs) that not only better represent females, but also the elderly.
To address this need, Humanetics is currently developing the Elderly Female Dummy, an ATD representative of a 70-years-old female car occupant [12-13].
DEKRA conducted three full-width frontal impact tests with an early prototype version of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies being either seated on the driver, front passenger, or right back seat. We have chosen the full-width frontal impact test based on Regulation UN R137 for being the toughest load case regarding restraint kinematics.
In a previous study [14], we have already investigated the thorax and head/neck dynamics of the three ATDs being seated on the front passenger seat. This seat position allowed us to use the same seat adjustments for every ATD, while the seatbelts were equipped with a pre-tensioner and load limiter – which are not installed in the rear – and thus to directly compare dummy behaviour. As the seat adjustments chosen differed from Regulation UN R137, we have observed changes in the HIII 5th Female dummy's kinematics. Moreover, the Elderly Female Dummy's thorax was the only one being reclined at time of airbag contact.
This study continues the previous research by analysing and comparing the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies as drivers, front passengers, and rear passengers.

METHODS

Elderly Female Dummy

Clinical data of 80 women aged 67 – 73 were used to derive the anthropometry of the Elderly Female Dummy, resulting in a height of 1.61 m, a mass of 73 kg, and a Body Mass Index (BMI) of 28. Especially the mass distribution over the height represents much better the body shape of elderly females. The head and neck are those of the WorldSID Small Female, while the lower arms, hands, knees, and feet stem from the HIII 5th Female [12]. The remaining body parts were specially developed for this ATD. They comprise a new structure – which does not exist in current ATDs – to better address potential internal injuries. The supporting structure of the Elderly Female Dummy consists of a flexible spine, a movable rib cage and floating shoulders, while organ sacs representing the liver and spleen are placed in the abdomen. The stratified body flesh is mimicked by a representative fat layer covering the entire torso. Magnetic Resonance Imaging (MRI) scans were used to determine rib cage shape, flesh thickness, organ size and organ placement. The Statistical Body Shape Models of the University of Michigan Transportation Research Institute were used to derive the shape of the Elderly Female Dummy. The so-called Multi-Directional Measurement Thorax (MDMT) is equipped with four infra-red telescoping rods for the assessment of chest compression (IR-TRACCs) to measure chest deflection in both the x- and y-direction, enabling the ATD to be used in frontal and lateral impact tests.
The Elderly Female Dummy is manufactured by using new technologies such as 3D-printing, allowing for a greater freedom of design. However, more research is necessary before this ATD can be commercialised.
"The next steps in the industrialisation process are to: 1) conduct biofidelity component testing under both frontal and lateral impact conditions to advance thoracic and abdominal biofidelity; 2) perform tests for response and corridor validations; and 3) develop injury assessment reference values (IARVs), regulation limits, and injury risk functions" [14].

Test Setup

Three full-width frontal impact tests against a rigid barrier at 50 km/h were conducted at the DEKRA Crash Test Center in Neumünster, Germany as shown in Figure 1. The tests were based on Regulation UN R137 except for the front passenger seat position, where the seat was adjusted to its longitudinal mid-position instead (see sub-section "seating position"). We used identical models of a popular midsize station wagon which had similar specifications and were of model years 2009 – 2013, resulting in comparable acceleration pulses (Figure 2). The Elderly Female, the HIII 50th Male and the HIII 5th Female dummies were either positioned on the driver, front passenger, or right back seat. In a previous study [14], we already focused on the front passenger seat, as we wanted to analyse the influence of both a standardised seating position and a restraint system with double pre-tensioner and load limiter. In this study, we also focused on the driver and right back seat. We have removed all four doors in order to obtain an unobstructed view.

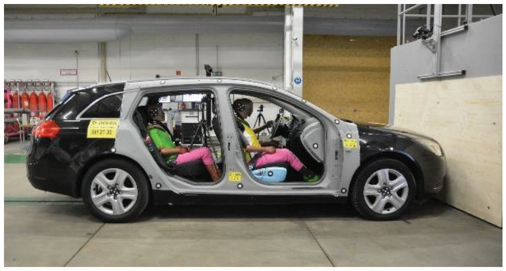

Figure 1. Test setup [14].

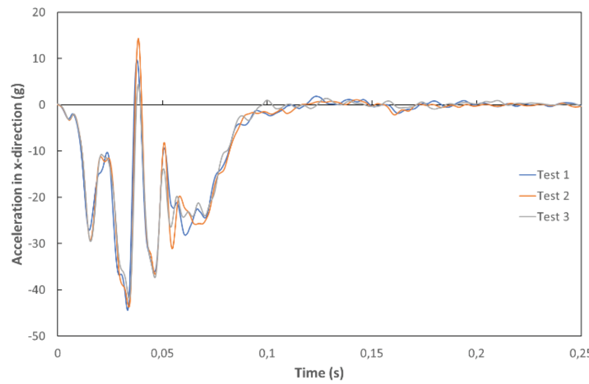

Figure 2. Acceleration pulses of the three crash tests [14].

Seating Position

Driver Seat The seat adjustments for the HIII 50th Male dummy were made according to Regulation UN R137. For the HIII 5th Female dummy, we used the European New Car Assessment Programme (Euro NCAP) frontal full-width test protocol. Thus, the driver seat was placed in its longitudinally foremost position. Currently, no regulations exist for the Elderly Female Dummy. But as its anthropometry is closer to the HIII 5th Female dummy, we have also used the Euro NCAP test protocol for the Elderly Female Dummy. However, as the Elderly Female Dummy has longer legs than the HIII 5th Female, we moved the driver seat backwards within the corridor allowed by Euro NCAP's test protocol. The seat rail overlap was 77 mm.

Front Passenger Seat While Regulation UN R137 stipulates the usage of the HIII 5th Female dummy on the front passenger seat, we wanted to use a single seating position for every ATD. Therefore, we asked ourselves what seat adjustments front passengers make. We conducted a field study and a German In-Depth Accident Study (GIDAS) analysis as previously described in [14]. These analyses yielded that the most common position was the longitudinal mid-position, which we hence chose for the crash tests.

Right Back Seat The back seats in the chosen vehicles do not allow for any adjustments. The three different ATDs were therefore simply put on the right back seat and restrained.

Measurements

While the HIII 50th Male and the HIII 5th Female dummies were equipped with a standard configuration of sensors, the prototype version of the Elderly Female Dummy had only sensors for measuring: head acceleration, thoracic spine acceleration, pelvis acceleration, and thorax compression.

Data acquisition and evaluation were performed in accordance with Regulation UN R137.

Pelvis forward displacement was determined by means of a string, while head forward displacement was determined via crash test video analysis with high-speed video software FalCon eXtra, Version 10.33.0011.

RESULTS

In order to compare the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies, measurements of restraint forces; shoulder belt extractions; dummy displacements; chest deflections; and chest, pelvis, and head accelerations are presented for the different seat positions. Still images of the three crash tests and different seat positions, which visualise the dummy kinematics, are provided in the appendix.

To aid with distinguishing between the different seat positions, the individual graphs for each seat position were created with different line types. The graphs for the driver seat were created with solid lines, the ones for the front passenger seat with dashed lines, and the ones for the right back seat with lines consisting of a dash and two dots.

Driver Seat

Figures 3 and 4 show the shoulder belt and lap belt forces of the three dummies, respectively. The shoulder belt forces were measured between the D-ring anchorage and the dummy's shoulder, while the lap belt forces were measured just above the buckle. The HIII 50th Male dummy exhibited the highest values for both the shoulder belt and lap belt forces, with around 5 kN each. Regarding the shoulder belt forces, the Elderly Female and the HIII 5th Female dummies recorded similar values at around 4 kN, though the HIII 5th Female dummy exhibited a higher peak value for lap belt forces than the Elderly Female.

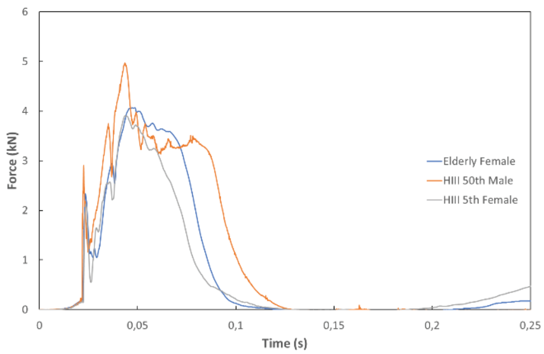

Figure 3. Shoulder belt forces driver seat.

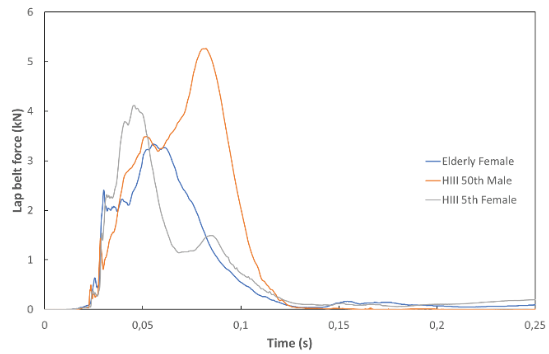

Figure 4. Lap belt forces driver seat.

The shoulder belt extractions, which are indicative of thorax forward displacement, are shown in Figure 5. Peak extraction for the HIII 50th Male occurred around 88 ms after impact and is the largest with 139 mm, with shoulder belt forces being around 3 kN at that time. The Elderly Female and HIII 5th Female dummies recorded negative peak values, meaning that the seatbelt extractions were less than the winding up of the seatbelts by the pre-tensioners.

Head forward displacements are shown in Figure 6. Like shoulder belt extractions, the HIII 50th Male dummy recorded the largest head forward displacement, which occurred around 90 ms after impact. The Elderly Female and the HIII 5th Female dummies exhibited their peak head forward displacements around 70 ms after impact.

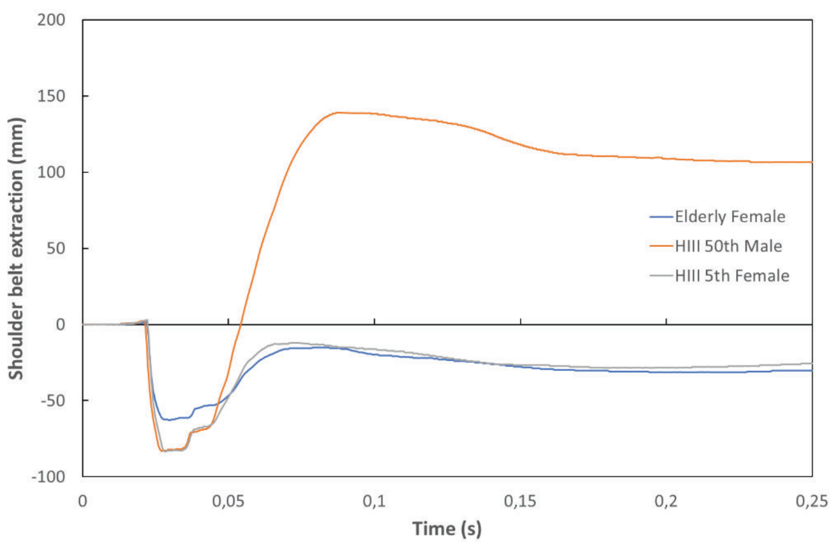

Figure 5. Shoulder belt extractions driver seat.

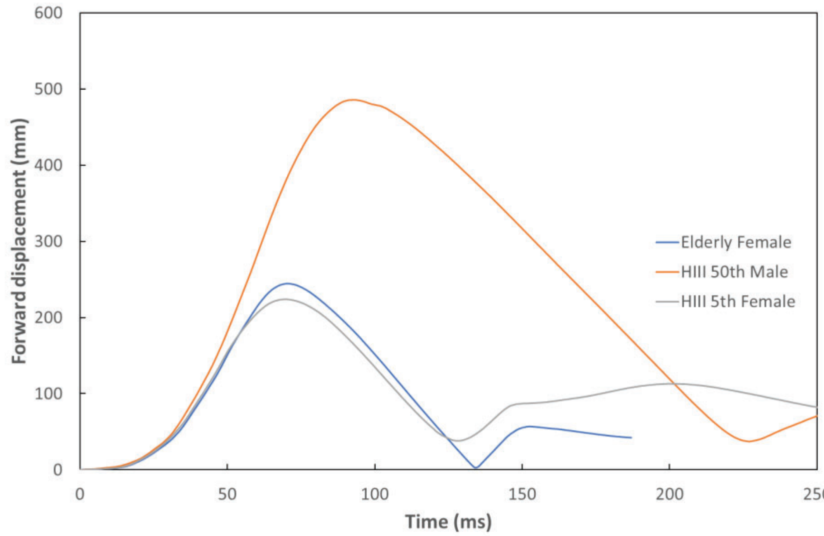

Figure 6. Head forward displacements driver seat.

Table 1 shows the peak pelvis forward displacements. Again, the HIII 50th Male dummy recorded the biggest peak value. However, the Elderly Female exhibited a larger peak pelvis forward displacement than the HIII 5th Female dummy, while both female dummies exhibited similar shoulder belt extractions.

Table 1.
Measured peak pelvis forward displacements (mm) driver seat.

Elderly Female	90
HIII 50th Male	96
HIII 5th Female	74

These differences in peak shoulder belt extraction and peak pelvis forward displacement led to different forward leaning angles at the time of airbag contact as shown in Figure 7. Both the Elderly Female and the HIII 5th Female dummies exhibited a forward leaning angle greater than 90° as measured between the thorax and the horizontal, though the torso of the HIII 5th Female dummy is nearly upright. The HIII 50th Male dummy experienced a forward leaning angle of less than 90°.

Elderly Female HIII 50th Male HIII 5th Female

Figure 7. Images of the driver seats taken 80 ms post-impact.

Pelvis accelerations are shown in Figure 8. The Elderly Female Dummy recorded the largest peak value, while both the HIII 50th Male and the HIII 5th Female dummies exhibited a similar peak value. The Elderly Female Dummy's peak value also occurred later than the ones for the HIII dummies.

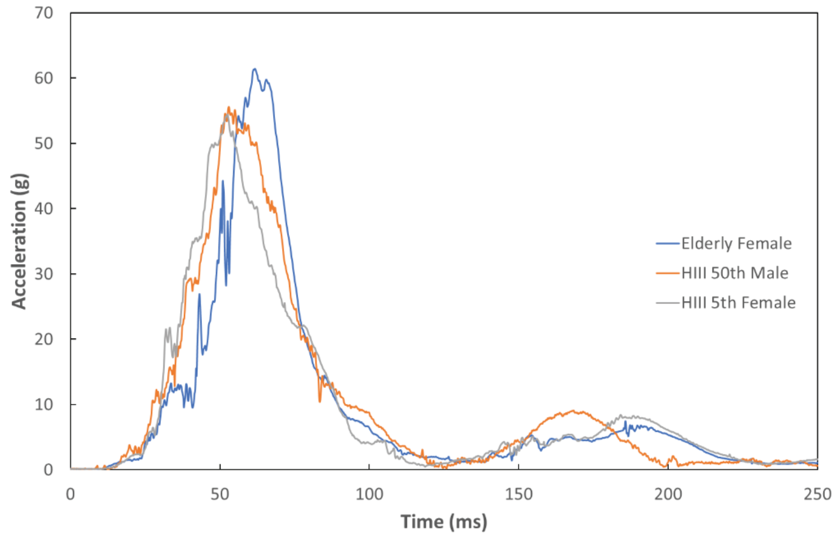

Figure 8. Pelvis accelerations driver seat.

Figures 9 and 10 show the chest accelerations and chest deflections, respectively. In contrast to the HIII dummies, the Elderly Female is equipped with two accelerometers, which are placed on vertebral bodies T1 and T12. These are also only biaxial and not triaxial as those of the HIII dummies. This is why we only evaluated the chest accelerations in the x-direction. Influences in the y- and z-direction are negligible because we conducted full-width frontal impacts. Moreover, the Elderly Female is also equipped with two chest deflection potentiometers, while the HIII dummies are only equipped with one chest deflection potentiometer each. The chest acceleration recordings in the x-direction for all three dummies are very similar. The chest deflection readings for the Elderly Female's upper measurement, the HIII 50th Male and the HIII 5th Female are very similar with 32 mm, 31 mm, and 32 mm, respectively. The Elderly Female also recorded a lower measurement reading of 42 mm. The Elderly Female Dummy's lower deflection measurement had an earlier onset than the upper deflection measurement and was at a greater rate.

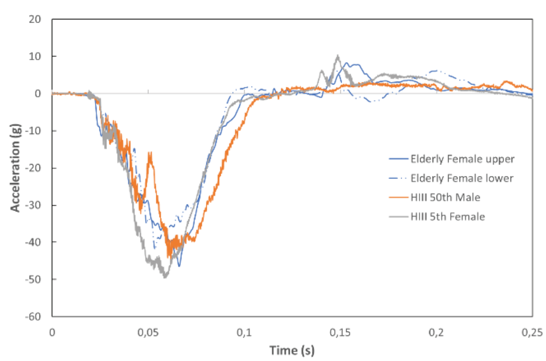

Figure 9. Chest accelerations in x-direction driver seat.

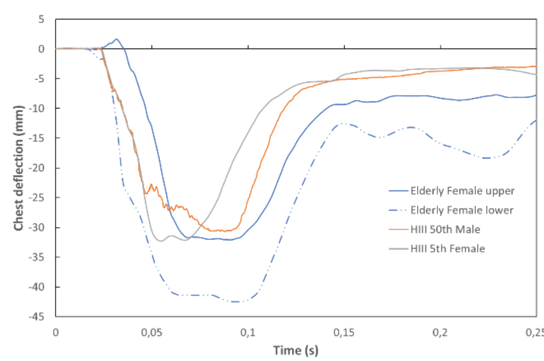

Figure 10. Chest deflections driver seat.

Figure 11 displays the head accelerations. Two distinct peaks are distinguishable. The first occurred at around 70 ms, with the second occurring around 150 ms post-impact for the female dummies, and around 230 ms for the HIII 50th Male. Regarding the first peak, the Elderly Female Dummy recorded its overall peak value of 71 g, while the HIII 50th Male dummy recorded its overall peak value of 49 g. Maximum head acceleration of the HIII 5th Female dummy is 63 g. This is lower than its overall peak value of 78 g, which occurred during the second peak at around 150 ms post-impact. This is also the largest acceleration among all three dummies.

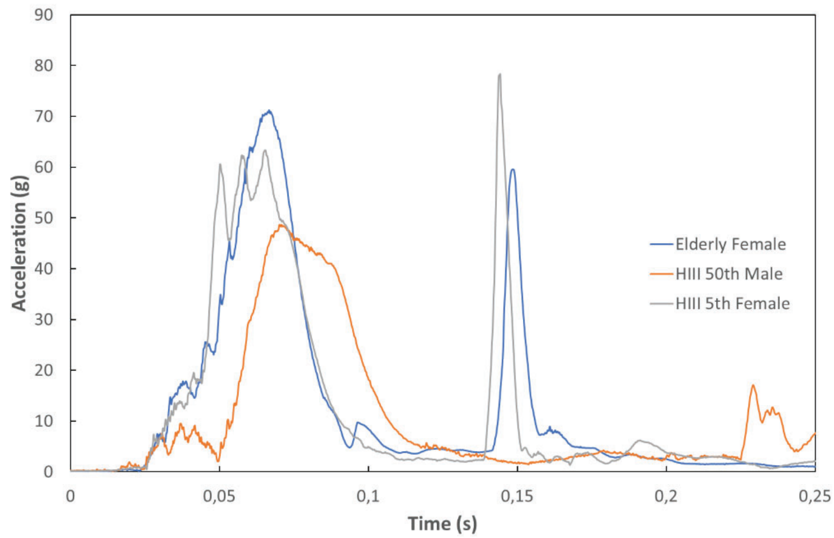

Figure 11. Head accelerations driver seat.

Table 2 shows the measured peak values to aid with comparing the results.

Table 2.
Measured peak values driver seat.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	4.06	3.34	-15^	244	90	61.44	46.49/42.03°	32/42°	71.22
HIII 50th Male	4.97	5.23	139	486	96	55.60	45.03	31	48.67
HIII 5th Female	3.90	4.11	-12^	224	74	54.42	49.63	32	78.34

° Upper/lower chest acceleration and deflection measurements.
^ The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.

Front Passenger Seat

The thorax and head/neck dynamics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies were previously analysed by us in [14]. We therefore refrain from showing the individual graphs here again, but only present the measured peak values in table 3.

Figures 12 and 13, however, show the lap belt forces and pelvis accelerations, respectively, as these were not considered in our previous research. The HIII 50th Male dummy exhibited the largest peak lap belt force, while the Elderly Female Dummy exhibited the lowest. The Elderly Female, however, recorded the largest peak pelvis acceleration, while the HIII 5th Female dummy recorded the lowest peak value. Peak acceleration for the Elderly Female Dummy also occurred later than for the HIII dummies as did peak lap belt force.

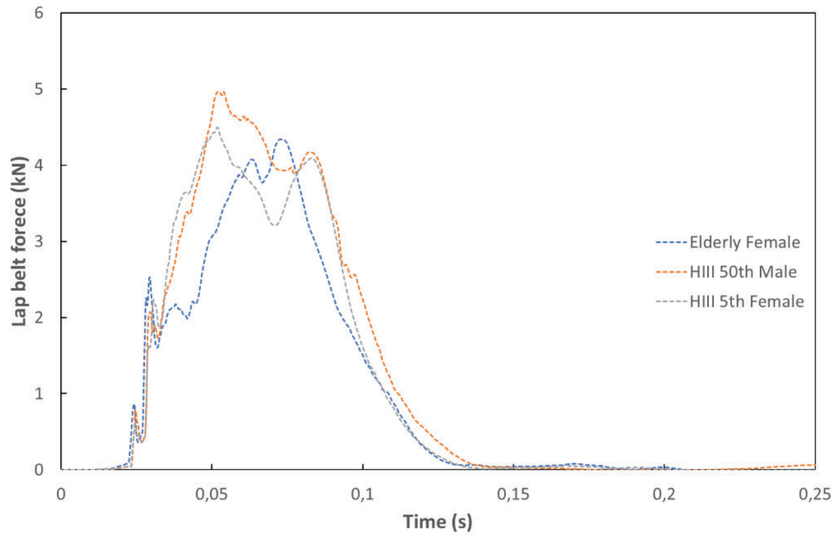

Figure 12. Lap belt forces front passenger seat.

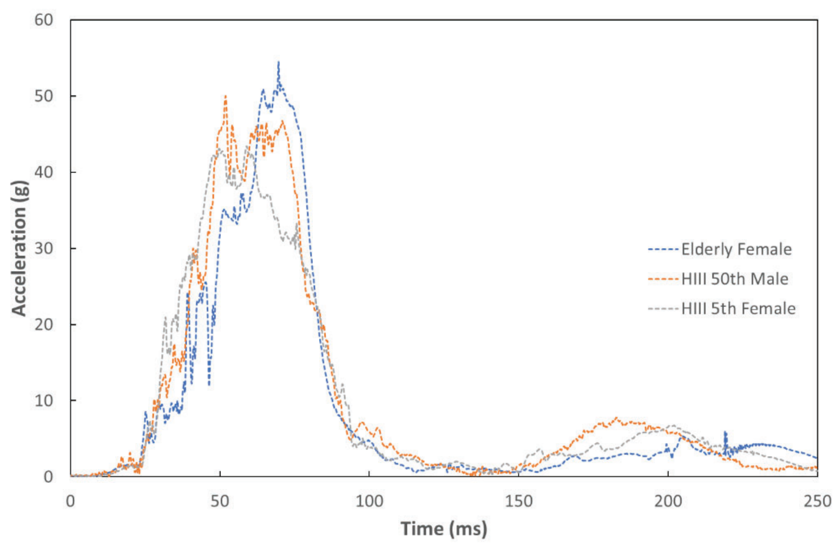

Figure 13. Pelvis accelerations front passenger seat.

Figure 14 displays the different forward leaning angles caused by the different impact kinematics of the three dummies on the front passenger seat. The Elderly Female Dummy is the only ATD with a forward leaning angle greater than 90° as measured between the thorax and the horizontal.

Elderly Female HIII 50th Male HIII 5th Female

Figure 14. Images of the front passenger seats taken 80 ms post-impact [14].

Table 3.
Measured peak values front passenger seat.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	4.59	4.34	33	387	53	54.50	40.54/33.18°	41/33°	248.49*
HIII 50th Male	5.04	4.96	206	520	91	49.99	42.97	33	54.55
HIII 5th Female	5.02	4.50	53	336	48	43.42	39.36	24	68.89

° Upper/lower chest acceleration and deflection measurements.
* The head acceleration reading for the Elderly Female is erroneous due to a cable breakage.

Right Back Seat
Figures 15 and 16 show the shoulder belt and lap belt forces, respectively. While the peak lap belt forces are very similar for all three dummies, the HIII 50th Male dummy recorded the largest peak shoulder belt force with 9.51 kN, followed by the HIII 5th Female dummy with 7.59 kN, and the Elderly Female Dummy with 5.83 kN. However, the Elderly Female's thorax and shoulder assembly were severely damaged by the seatbelt during the impact (see Figure 17). The seatbelts in the rear were not equipped with a pre-tensioner and load limiter. We assume that the shoulder belt force readings might have been affected by the collapse of the rib cage and are therefore erroneous.

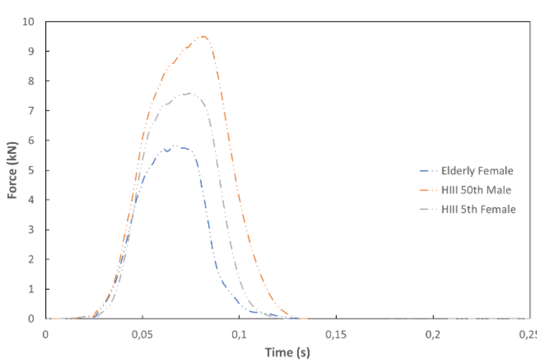

Figure 15. Shoulder belt forces right back seat.

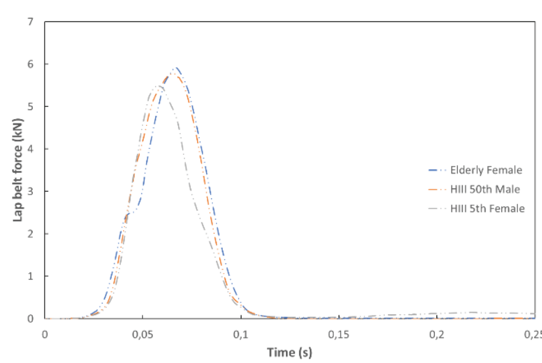

Figure 16. Lap belt forces right back seat.

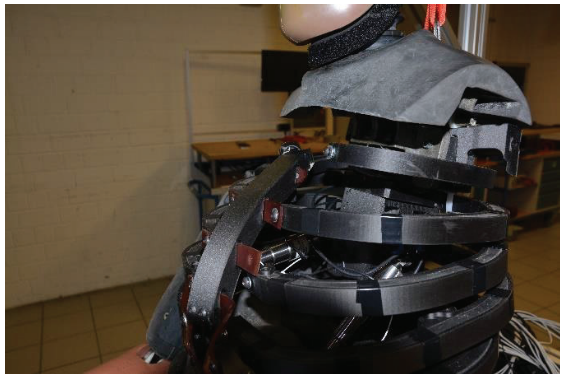

Figure 17. Damage to the thorax and shoulder assembly of the Elderly Female Dummy.

The shoulder belt extractions were not measured in the rear.
Figure 18 displays the head forward displacements as measured by crash test video analysis. Upon reaching its maximum forward displacement, the target on the Elderly Female Dummy's head, which is required to track the head's movement, became covered by the dummy's right arm and the measurement thus broke off. Peak excursion for the Elderly Female Dummy occurred around 100 ms post-impact and was the smallest. Peak excursion for the HIII 50th Male dummy occurred around the same time but was, however, the largest. The HIII 5th Female dummy recorded its peak excursion around 90 ms after impact.

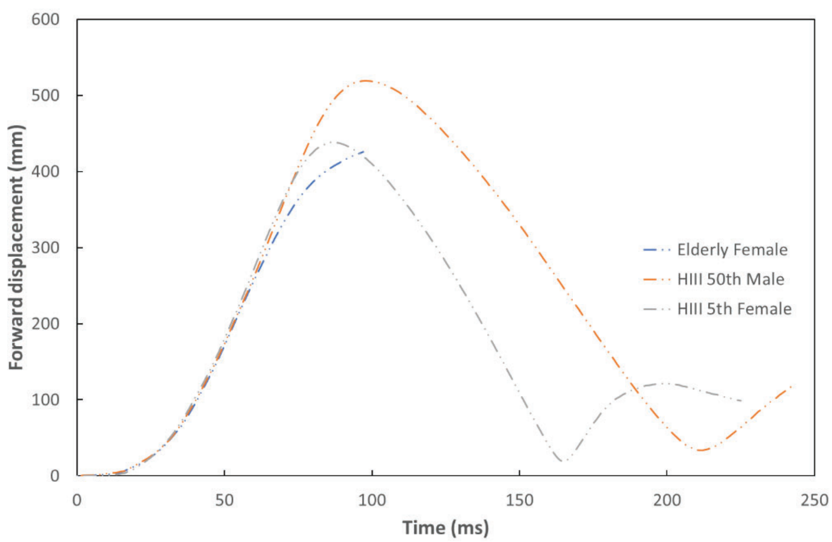

Figure 18. Head forward displacements right back seat.

The peak pelvis forward displacements, as measured by a string, are shown in Table 4. However, the measurement for the Elderly Female Dummy's pelvis forward displacement malfunctioned, which is why there is no value. The HIII dummies recorded similar forward displacements.

Table 4.
Measured peak pelvis forward displacements (mm) right back seat.

Elderly Female	-
HIII 50th Male	190
HIII 5th Female	194

These large forward displacements are shown in Figure 19. Graphical observations also indicate that the torsos of the HIII dummies' are nearly upright, while the Elderly Female Dummy exhibited a forward leaning angle greater than 90° as measured between the thorax and the horizontal.

Elderly Female HIII 50th Male HIII 5th Female

Figure 19. Images of the right back seats taken 80 ms post-impact.

The pelvis accelerations are shown in Figure 20. The Elderly Female Dummy recorded the largest peak value with 57.80 g, while the HIII 50th Male dummy recorded the lowest peak value with 53.51 g. Though acceleration onset is similar, the pelvis accelerations of the HIII dummies increase at a greater rate than the one of the Elderly Female Dummy.

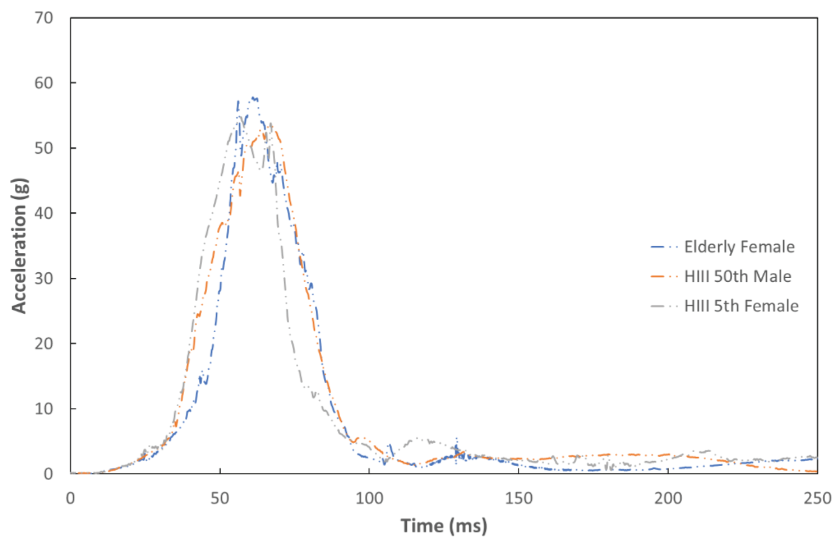

Figure 20. Pelvis accelerations right back seat.

Figures 21 and 22 display the chest accelerations and chest deflections, respectively. While the Elderly Female Dummy's lower acceleration measurement is very similar to those of the HIII dummies, its upper measurement shows an unusual peak value of 756.78 g, which we deem unrealistic. We assume that this measurement was caused by the collapse of the Elderly Female Dummy's thorax due to the high seatbelt forces. Likewise, we assume that the Elderly Female Dummy's chest deflection measurements were detrimentally affected by the dummy's damage. The HIII 50th Male dummy recorded a peak deflection of 48 mm compared to 36 mm for the HIII 5th Female dummy.

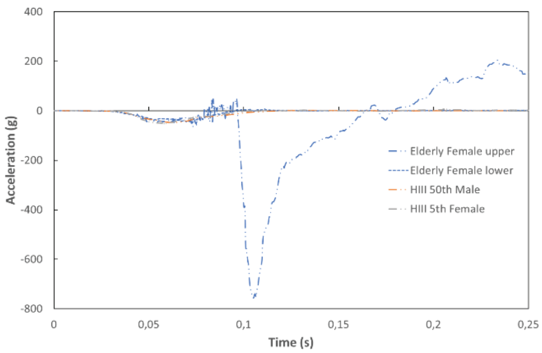

Figure 21. Chest accelerations in x-direction right back seat.

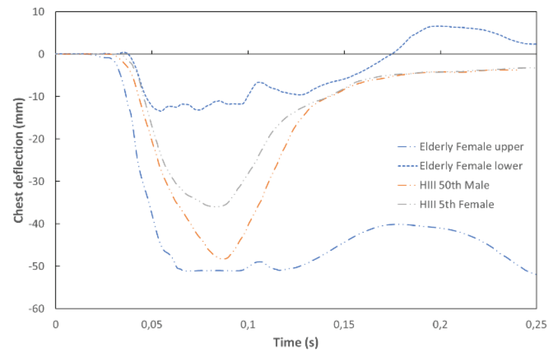

Figure 22. Chest deflections right back seat.

Head accelerations are shown in Figure 23. The HIII 5th Female dummy recorded the highest peak value of 71.45 g, as well as a significant second peak. The HIII 50th Male dummy recorded the lowest accelerations. Regarding the Elderly Female Dummy, we assume that the head acceleration was also influenced by the substantive damages to the dummy's thorax and shoulder assembly.

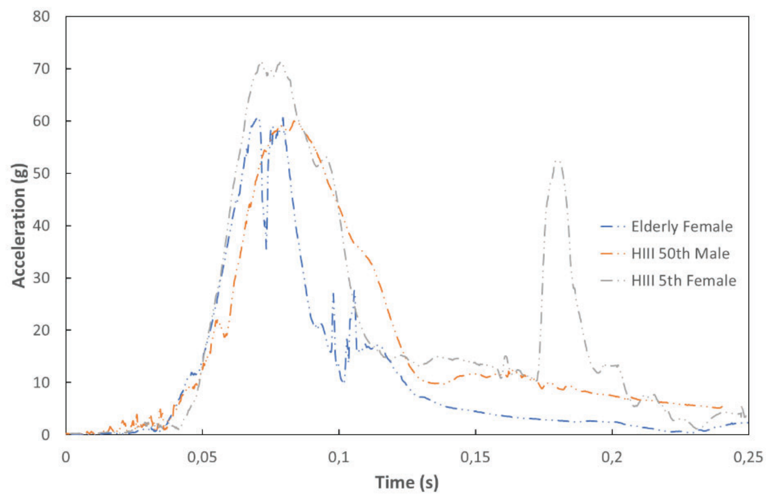

Figure 23. Head accelerations right back seat.

Table 5 shows the measured peak values.

Table 5.
Measured peak values right back seat.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Elderly Female	5.83#	5.92	-	426	-	57.80	756.78#/43.87°	53#/13#°	60.74#
HIII 50th Male	9.51	5.78	-	519	190	53.51	47.54	48	59.96
HIII 5th Female	7.59	5.50	-	439	194	54.75	52.36	36	71.45

° Upper/lower chest acceleration and deflection measurements.
We assume that this value is erroneous due to significant damage to the thorax and shoulder assembly.

Anthropomorphic Test Device

Tables 6–8 display the measured peak values for the different seat positions of each ATD. The peak value per measurement is indicated in bold, irrespective of being erroneous or not.

Table 6.
Measured peak values Elderly Female Dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	4.06	3.34	-15^	244	**90**	**61.44**	46.49/42.03°	32/**42**°	71.22
Front Passenger Seat	4.59	4.34	**33**	387	53	54.50	40.54/33.18°	41/33°	**248.49***
Right Back Seat	**5.83**#	**5.92**	-	**426**	-	57.80	**756.78**#/**43.87**°	**53**#/13#°	60.74#

° Upper/lower chest acceleration and deflection measurements.
* The head acceleration reading is erroneous due to a cable breakage.
^ The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.
# We assume that this value is erroneous due to significant damage to the thorax and shoulder assembly.

Table 7.
Measured peak values HIII 50th Male dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	4.97	5.23	139	486	96	**55.60**	45.03	31	48.67
Front Passenger Seat	5.04	4.96	**206**	**520**	91	49.99	42.97	33	54.55
Right Back Seat	**9.51**	**5.78**	-	519	**190**	53.51	**47.54**	**48**	**59.96**

Table 8.
Measured peak values HIII 5th Female dummy.

	Shoulder belt force (kN)	Lap belt force (kN)	Shoulder belt extraction (mm)	Head forward displacement (mm)	Pelvis forward displacement (mm)	Pelvis acceleration (g)	Chest acceleration (g)	Chest deflection (mm)	Head acceleration (g)
Driver Seat	3.90	4.11	-12^	224	74	54.42	49.63	32	**78.34**
Front Passenger Seat	5.02	4.50	**53**	336	48	43.42	39.36	24	54.55
Right Back Seat	**7.59**	**5.50**	-	**439**	**194**	**54.75**	**52.36**	**36**	71.45

^ The negative sign indicates that the seatbelt extraction was less than the winding up by the pre-tensioner.

DISCUSSION

Aim of this study was to compare the impact kinematics of the Elderly Female, the HIII 50th Male and the HIII 5th Female dummies as drivers, front passengers, and rear passengers in full-width frontal impacts.
It is known that the HIII dummy exhibits a restraint-system-dependent biofidelity [15]. Chest deflection of the HIII 5th Female, for example, was shown to increase when placing the front passenger seat in its longitudinal mid-position [16-17]. In our study – contrary to Regulation UN R137 – we also placed the front passenger seat in its longitudinal mid-position. Generally, ATD excursion is influenced by airbag and knee bolster contact on the front seats, while ATD excursion is primarily controlled by the seatbelt in the rear. The biofidelic requirements of the HIII 5th Female dummy were scaled down from the HIII 50th Male dummy [18], while neither injury assessment reference values (IARVs) nor regulation limits exist for the Elderly Female Dummy yet.
Figure 24 displays the injury assessments according to Regulation UN R137 for the two HIII dummies and their different seat positions. On the front seats, the HIII 50th Male dummy recorded measurements all below the respective thresholds, while chest protection was poor in the rear. For the HIII 5th Female dummy, chest protection was adequate on the driver seat with all other measurements being good. On the front passenger seat, the HIII 5th Female recorded adequate head acceleration, while head acceleration and chest protection were poor in the rear. These findings proof epidemiological data that rear seat occupants are worse protected than occupants in the front.

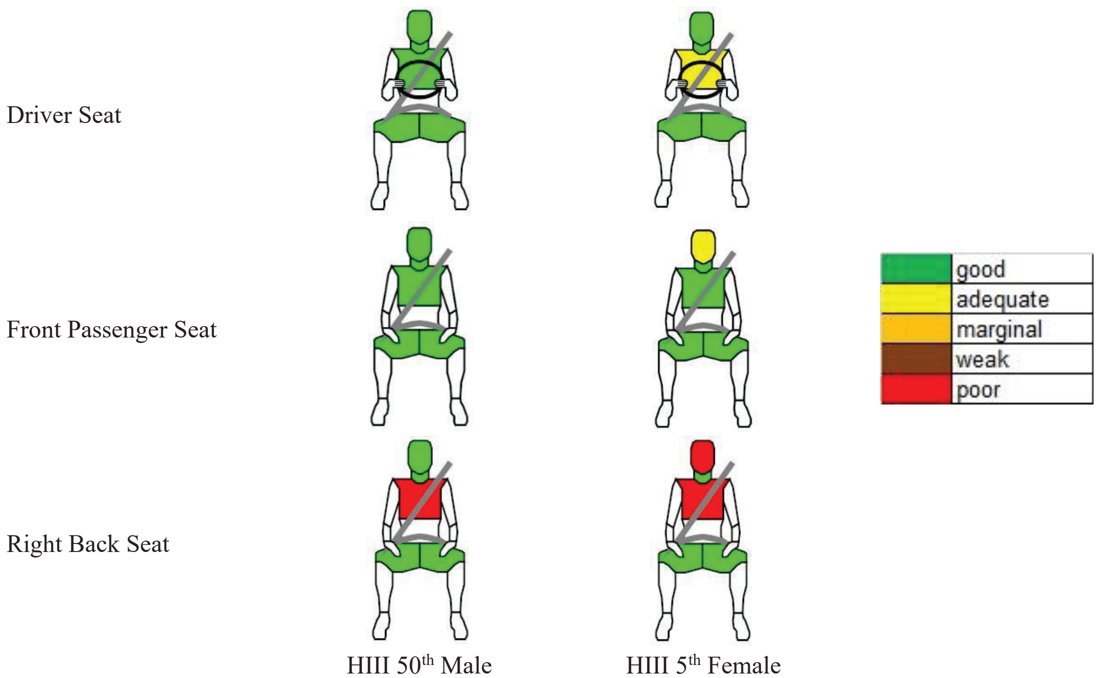

Figure 24. Injury risk assessments according to Regulation UN R137.

As previously observed on the front passenger seat [14], kinematic observations have also shown differences in ATD dynamics for the driver and rear seats. While the front seats were equipped with double pre-tensioners and load limiters, the back seats were fitted with neither.
In the front, the HIII 50th Male experienced the largest pelvis excursions and shoulder belt extractions. As we observed in our previous study for the front passenger seat, the Elderly Female Dummy also experienced a bigger pelvis displacement than the HIII 5th Female on the driver seat, while, to the contrary, shoulder belt extractions were quite similar on the driver seat. For both female dummies, the peak shoulder belt extraction value was negative, meaning that the shoulder belt was extracted less by the dummies than wound up by the respective pre-tensioner. This implies, similar to the front passenger seat, different forward leaning angles on the driver seat. These are not corroborated quantitatively, but graphic observations show that on the driver seat only the HIII 50th Male dummy experienced a forward leaning angle of less than 90° as measured between the thorax and the horizontal, while on the front passenger seat both HIII dummies experienced a forward leaning angle of less than 90° (see Figures 7 and 14). The Elderly Female Dummy, however, experienced a forward leaning angle of greater than 90° on both front seats.

The HIII 50th Male dummy experienced the biggest torso forward rotations on both front seats, while the HIII 5th Female dummy's torsos rotated minimally being nearly upright on both front seats. On the front passenger seat, such a behaviour was observed before by [19] for the HIII 5th Female when the seat was positioned in its longitudinal mid-position.

Interestingly, pelvis excursion was larger on the driver seat than on the front passenger seat for all three ATDs. Graphic observations of the Elderly Female Dummy on the driver seat show that the ATD is susceptible to submarining. Figure 25 shows still images beginning at 25 ms post-impact – the time at which the driver airbag started to deploy – and then at intervals of 10 ms. The red horizontal bar is placed at the same height in each frame. At 35 ms after impact, it can clearly be seen how the deploying driver airbag hit the Elderly Female Dummy's chest, while the head did not yet contact the airbag. Starting at roughly 45 ms post-impact, it can be seen how the thorax slid down the backrest – this can be visualised by looking at the targets placed on the ATD's upper arm and how they move below the red horizontal bar – while the pelvis continued to move forward. Simultaneously, the seat base and the backrest tilted forward. Upon inspection of the seat post-crash, we noticed that metal parts in the seat base had deformed. Regarding the HIII 5th Female on the driver seat, we observed a similar pattern, i.e., the thorax slid down the backrest, and the seat base and the backrest tilted forward, though to a lesser extent. The seat base was adjusted to its vertical uppermost position for both female dummies, while to its lowest for the HIII 50th Male. Therefore, we did not observe the seat base to tilt forward when the HIII 50th Male dummy was placed on the driver seat. We do not know in how far this is a problem with the seat design of the chosen test vehicle, or whether this is something of a general concern when the seat is adjusted to its vertical uppermost position. The fact that the driver seat tilted more when the Elderly Female Dummy was seated on it might be explained by the fact that the pelvis accounts for 18.5 % of total mass for the Elderly Female compared to only 14.5 % for the HIII 5th Female.

Like what happened on the front passenger seat, we assume that the Elderly Female Dummy experienced compression in its thoracolumbar spine on the driver seat too, caused by the torso sliding down the backrest. However, as the ATD is not equipped with respective sensors, we cannot quantify this. In sled tests with reclined occupants, [20] observed a combination of flexion and compression in the thoracolumbar spines of all five Post Mortem Human Subjects (PMHSs). Three PMHSs suffered fractures at vertebral body L1. Therefore, it needs to be investigated in how far this kinematic behaviour of the Elderly Female Dummy correlates with elderly women, as a forward leaning angle of greater than 90° seems to be potentially injurious.

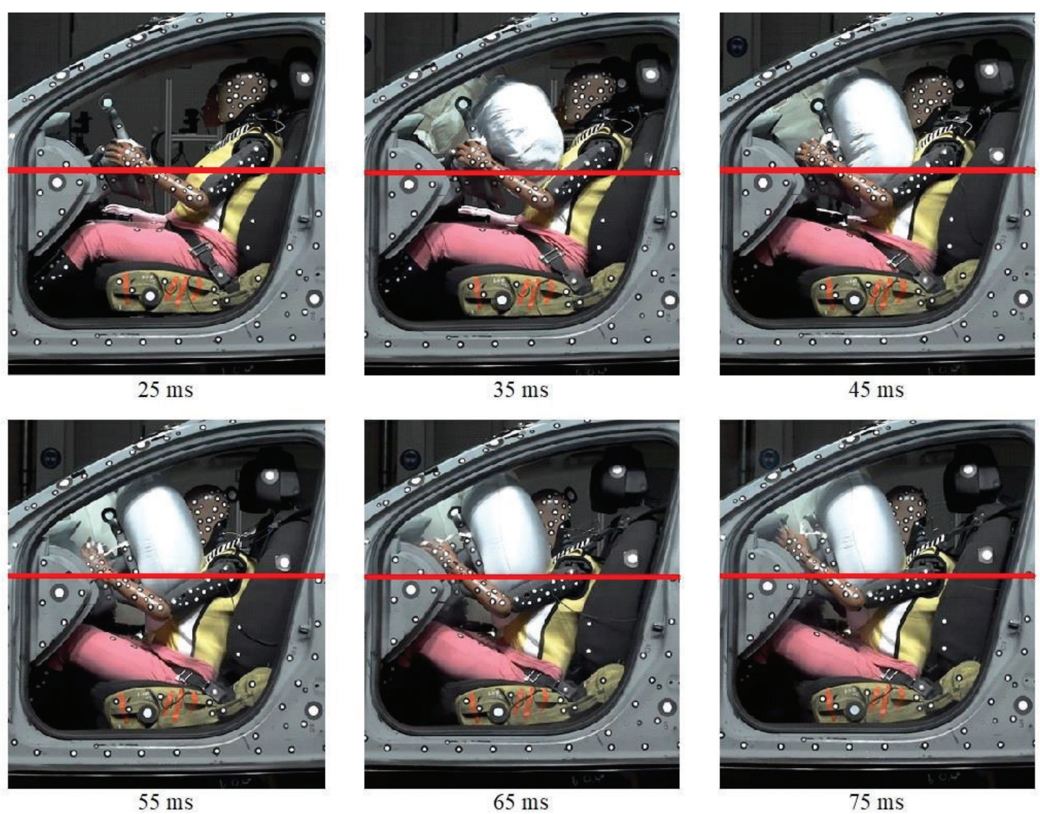

Figure 25. Still images of the Elderly Female Dummy on the driver seat.

In the rear, the HIII 5th Female exhibited a greater pelvis forward displacement than the HIII 50th Male, which is more than double as large as on the driver seat and more than threefold as on the front passenger seat. For the HIII 50th Male dummy, pelvis excursion in the rear is double that on the front seats. Unfortunately, the equipment for measuring the pelvis displacement of the Elderly Female malfunctioned in the rear. However, graphic observations show that the ATD contacted the front passenger seat with its knees, indicating substantive pelvis excursion. The torsos of the HIII dummies hardly rotated forwards with them being nearly upright, while the Elderly Female Dummy experienced – as on the front seats – again a forward leaning angle of greater than 90° as measured between the thorax and the horizontal. These observations indicate that dummy kinematics are primarily controlled by the seatbelt in the rear, whereas airbag and knee bolster contact control dummy kinematics in the front. Missing airbag and knee bolster contact may also explain why each ATD recorded both its highest shoulder belt and lap belt forces in the rear.

Considering the HIII dummies, shoulder belt forces in the rear were nearly double as large as in the front. The HIII 50th Male dummy recorded similar shoulder belt forces in the front seats, while the HIII 5th Female dummy's shoulder belt force was larger on the front passenger seat than on the driver seat. Considering the Elderly Female Dummy, we assume that the shoulder belt force recorded in the rear is erroneous due to severe damage to the ATD's thorax and shoulder assembly caused by the seatbelt. This highlights the effectiveness of pre-tensioners and load limiters to reduce chest loading. Shoulder belt extractions were not measured in the rear.

Chest deflection is the most suitable discriminator for thoracic injuries, with chest acceleration being unreliable [15][21]. On the front passenger seat, the HIII 5th Female experienced a lower peak chest deflection than on the driver seat. The HIII 50th Male, however, experienced a larger peak chest deflection on the front passenger seat than on the driver seat. For both HIII dummies, peak chest deflection was the largest in the rear. Computing the injury likelihoods according to Regulation UN R137, this translates into a peak chest deflection for the HIII 5th Female dummy of 71.2 % of the regulation limit on the front passenger seat compared to 95.5 % on the driver seat and 107.0 % in the rear, while the HIII 50th Male dummy recorded a peak chest deflection of 76.8 % of the regulation limit on the front passenger seat compared to 70.4 % on the driver seat and 112.4 % in the rear. Considering that the HIII 5th Female features a more compliant chest than the HIII 50th Male [22], and that both dummies were subjected to identical restraint systems, one would, however, assume that the HIII 5th Female generally experiences a larger chest deflection than the HIII 50th Male. On the front passenger seat, one explanation might be that the greater chest excursion of the HIII 50th Male translated into greater loading by the front passenger airbag. On the driver seat, though, the HIII 5th Female experienced greater chest loading by the front airbag as the seat was adjusted further forward. In the rear, where the seatbelts were neither equipped with a pre-tensioner and load limiter, the greater chest deflection of the HIII 50th Male might be explained by the greater mass of the ATD's thorax. Moreover, the HIII 5th Female experienced a greater pelvis forward displacement than the HIII 50th Male, which could also contribute to less chest loading. The Elderly Female Dummy features the most compliant thorax, which is also equipped with two chest deflection potentiometers. As no IARVS nor regulation limits exist yet, no injury risks can be computed. The chests were not uniformly loaded on all three seat positions, which is indicated by the differences between the upper and lower measurements. On the front passenger and right back seat, the upper chest deflection measurements were greater than the lower ones, while the lower chest deflection potentiometer recorded the larger deflection on the driver seat. These non-uniform load distributions are explained by shoulder belt loading, as the belt is routed over the sternum. On the driver seat, however, the lower chest deflection potentiometer is loaded by the deploying airbag; see Figure 25. This indicates that the driver front airbag can potentially be injurious when the driver sits close to the steering wheel. Were the regulation limit of 34 mm of the HIII 5th Female used for the Elderly Female Dummy – the Elderly Female is anthropometrically closer to the HIII 5th Female than the HIII 50th Male – the limit would have been exceeded for the lower measurement on the driver seat and for the upper measurement on the front passenger seat, indicating a potential risk of thoracic injuries. On the right back seat, the Elderly Female Dummy's thorax was severely damaged by the seatbelt, which is why we do not know in how far the chest deflection measurements are correct. Nonetheless, the damage by its own does already highlight that the chest has been subjected to potentially injurious loads. A 40 – 50 % risk of suffering Abbreviated Injury Scale (AIS) 3+ thoracic injuries is linked to HIII 50th Male sternal deflections of 50 mm [23]. Respective scaling factors have been established for the HIII 5th Female [22]. The measured peak values of both HIII dummies were below these thresholds on any seat position. In the rear, however, the recorded peak deflection values were not far below these thresholds. Were the same scaling factors as for the HIII 5th Female used for the Elderly Female Dummy, the lower chest deflection on the driver seat and the upper deflections on the front passenger and right back seat would exceed the threshold.

Given that the mechanical properties of bone get worse due to ageing, the elderly are more susceptible to trauma [24-27]. Moreover, human thoraces are more compliant than HIII dummy thoraces under seatbelt loading [28]. As the Elderly Female Dummy's thorax is a new design, more research is required to correlate ATD chest deflection to injury risk for senior women under seatbelt loading.

The damages to the Elderly Female Dummy also highlight challenges in using new advanced manufacturing technologies such as 3D-printing. Certain components of the Elderly Female Dummy failed due to delamination,

as the fibres have been aligned perpendicularly to the load direction. Changing the printing direction by 90° – so that fibre alignment would be along the load direction in frontal impacts – would, however, complicate the printing process by requiring more support material.
All three ATDs recorded two head acceleration peaks, the first one caused by airbag contact during impact and the second one caused by headrest contact during rebound. The HIII 5th Female dummy was the only ATD, whose second peak was larger than the first one. This phenomenon, however, was only observed on the driver seat. We assume that these differences between the ATDs are explained by the different masses of the heads, with the lighter head being decelerated more by the headrest. The HIII 5th Female dummy's head is lighter than the HIII 50th Male dummy's head. The Elderly Female Dummy's head is the lightest, but stems, as its neck, from the WorldSID Small Female, a side impact ATD. Using the WorldSID Small Female's head in this early prototype version of the Elderly Female Dummy was considered to be a good first step in the development process, since the Elderly Female is designed to be omnidirectional. Research is currently being conducted to investigate whether the WorldSID Small Female's head and neck assembly is more representative of the neck kinematics of elderly women than the HIII 5th Female's design. The Elderly Female Dummy's head acceleration measurements on the front passenger seat are erroneous due to a cable breakage, and we also assume that the measurements on the right back seat were affected by the severe damage to the ATD's thorax and shoulder assembly.
Graphic observations also show that, on the front passenger seat, the Elderly Female Dummy's chin contacted its thorax shortly after airbag contact. Such a behaviour was not observed on the driver seat. Neither HIII dummy experienced chin contact in the front seats. In the right back seat, all ATDs experienced chin contact, indicating large neck flexion, which might be injurious. While the front airbags cushion the head and counteract neck flexion, such a safety device is not installed in the rear. Research shows that HIII 50th Male neck response is stiffer than PMHS neck responses [29].
The HIII 5th Female Dummy does not properly represent senior women anthropometrically based on anthropometric data from the International Center of Automotive Medicine (ICAM) and the University of Michigan Transportation Research Institute (UMTRI). Pelvis design, for example, is simply scaled down from the HIII 50th Male dummy [30]. The Elderly Female Dummy, on the other hand, is being designed based specifically on the anthropometry of elderly women. However, more research is necessary to determine whether the Elderly Female Dummy's biofidelity is more representative of senior women than the HIII 5th Female.

CONCLUSIONS

The three full-width frontal impact tests have shown that second-row seats offer less protection than first-row seats. Moreover, restraint systems should be adaptive to account for passengers of different sexes, sizes, ages, weight distributions, and postures. Using another seating position on the front passenger side than stipulated by Regulation UN R137, led to changes in impact dynamics of the HIII 5th Female dummy. This was already observed in previous studies. The HIII 50th Male dummy experienced the greatest torso forward rotation on all seats, with changes in the forward leaning angle of both the Elderly Female and HIII 5th Female dummies dependent on their respective seat positions. More research into the biofidelity of the Elderly Female Dummy is necessary to improve ATD design and to develop IARVs and injury risk functions.
The damages to the Elderly Female Dummy highlight the challenges in using new advanced manufacturing technologies such as 3D-printing.

DISCLAIMER

The Elderly Female Dummy is still in its early prototype stage and continuously being developed further, which is why the presented results should not be construed as the final performance of this ATD.

ACKNOWLEDGEMENT

We would like to express our gratitude to all personnel at the DEKRA Crash Test Center in Neumünster, Germany who have been involved in designing and executing the crash tests. Further thanks go to Humanetics for supporting this research project by providing the prototype version of the Elderly Female Dummy.

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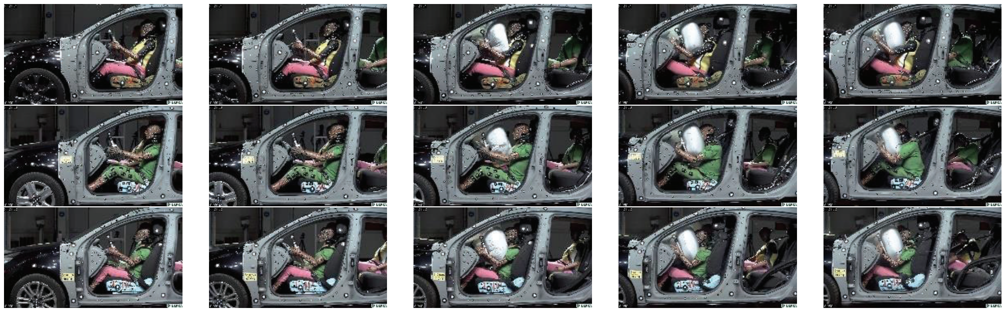
APPENDIX

Elderly Female

HIII 50th Male

HIII 5th Female



Time (ms) 0 20 40 60 80

Figure AI. Still images of the driver seats in the three crash tests.

Elderly Female

HIII 50th Male

HIII 5th Female

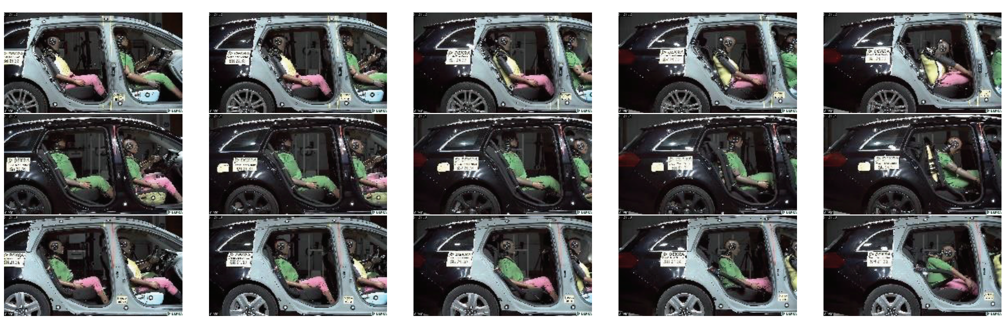
Time (ms) 0 20 40 60 80

Figure AII. Still images of the front passenger seats in the three crash tests [14].

Elderly Female

HIII 50th Male

HIII 5th Female



Time (ms) 0 20 40 60 80

Figure AIII. Still images of the right back seats in the three crash tests.

ASSESSMENT OF PASSENGER SAFETY IN FUTURE CARS - IDENTIFYING THE REAL-WORLD NEEDS TOWARDS SAFETY SYSTEM DEVELOPMENT

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Paper Number 23-0186

ABSTRACT

Future cars will likely include further collision mitigation systems, seat positions and seating configurations compared to current cars, in addition to an increased degree of shared mobility solutions. At the same time the population is becoming older and the diversity in car passenger dimensions is growing. This calls for assessment tools and evaluation methods beyond the current standardized crash test methods. This paper summarizes the results of a Swedish research project on how to assess the protection of the heterogeneous population of passengers (i.e., non-drivers) in future car crashes, focusing on restraint interaction. With the overall purpose of further improving passenger protection, the specific aims were to achieve method developments based on the enhancement of tools (physical and virtual human substitutes) as well as to create knowledge on passenger protection needs.

This comprehensive research project combined multiple competencies and international collaborations, and a large number of studies have been performed using different methods. The applied methods include real-world crash data analyses to identify scenarios and situations, crash testing and simulation, and additionally user-studies conducted in cars to evaluate sitting posture, beltfit, kinematics, comfort, experiences and attitudes. Furthermore, the project included studies on crash test dummies (ATDs) and Human Body Models (HBM). Moreover, adult morphed HBMs were developed in various sizes, ages and sexes, for investigating various protection principles.

In novel studies, crash interventions strategies were applied to predicted residual crash configurations. User-studies provided evidence of self-selected passenger postures in real car settings and, thus, deviations from standardized ATD positions. The importance of body shape was highlighted in a beltfit user-study including older adults. Essential booster design parameters were identified for children in upright and reclined seat positions. Restraint principles were investigated for adults in reclined seat positions and with the seat in rearward positions, away from the frontal airbag and knee bolster, along with an evaluation of the capabilities of the assessment tools.

The adult HBM morphed to various sizes, ages and sexes were validated for prediction of in-crash kinematics in different impact scenarios, and provided enhanced insights in passenger protection assessment compared to the three standardized sizes of ATDs. Simulations with PIPER6y, a child-sized HBM, emphasized the importance of vehicle-booster-user system interaction.

The results from the research project provided input to safety system development, ATD/HBM design, assessment methods development, and a number of identified research challenges for future work. Specifically, there is a need to further explore car passenger interaction with the restraint system in terms of seat positions and variations in body sizes, shapes and postures. The inclusions of the heterogeneous population into more advanced tools such as HBMs are essential, acknowledging that when moving closer to “zero injuries”, the situations to address are more unique and specific. Although a large range of studies using different methods was conducted, many challenges still remain to cover the entire scope of passenger safety in future cars.

INTRODUCTION

Assessing protection for passengers in cars is of increased importance moving towards automated driving (AD) and a higher degree of car and ride sharing (Jakobsson et al., 2019). In unsupervised AD, the driver becomes a passenger. Car sharing and increased use of taxis and other ride sharing, call for effective, comfortable, and safe protection systems, customized for a wide range of ages and sizes as well as a wider range of seat positions and seating configurations. In addition, the advanced driver-assistance systems (ADAS) will influence the crash frequency, as well as the pre-crash dynamics and the crash configurations, when activated and altering but not avoiding the crash.

It is expected that future passengers will choose their seat position and sitting posture with even more freedom than today, presenting a larger spread in real-world postures in crashes compared to today. For example, passengers may choose more reclined seat positions. This poses the challenge of assessing safety for novel sitting postures and seat positions where current tools (physical and virtual human substitutes) may not be biofidelic, nor the sitting postures and beltfit are understood.

The position of the shoulder and lap-belt over the body (beltfit) is highly related to the seat position and the occupant's posture, shape, and anthropometry. The aging population is growing, and beside their fragility and frailty, there are challenges with respect to the lap-belt position (Fong et al., 2016). Similar challenges are also seen for obese passengers, for whom their abdomen size influences lap-belt position, (Reed et al., 2012, Park et al., 2016). A high positioned lap-belt increases the risk for submarining (Howes et al., 2015).

Many passengers are children. Children have specific needs due to their body shape and development, which will remain in future cars. The smallest children are optimally protected using rearward facing child seats, while children from approximately 4 years of age can use the car's seat belt (Jakobsson et al., 2005). However, these older children need to use belt-positioning boosters to adapt to the seat belt (Reed et al., 2008). Specifically, the increased usage of transportation modes such as car sharing and ride sharing will require for children flexible and easy-to-use solutions in order to maintain high utilization and protection.

To enable future mobility services (such as AD and shared mobility) and to ensure the protection of a heterogeneous passenger population, safety assessment methods and tools need to be evaluated and where applicable be developed or updated. Tools for car passenger protection assessment are mainly crash test dummies (ATDs) and virtual human body models (HBMs). ATDs are available as physical tools as well as virtual counterparts. They are available in a limited number of sizes and do not reflect the variety of body shapes. HBMs, being more anatomically similar to humans, have greater potential to be omni-directional, representing human kinematics in all impact directions. In addition, they are representing a wider range of anthropometries for both sexes. They also have the potential to predict injury risk at the organ or tissue level and to recreate more humanlike interactions, e.g., detailed shoulder to shoulder-belt interaction. However, as for ATDs, the HBMs need to be validated for new sitting postures as well as for the injury risk predictions in focus.

This paper summarizes the results of a Swedish research project on how to assess the protection of the heterogeneous population of passengers in future car crashes, focusing on restraint interaction. Future car crash challenges include, among others, the influence of ADAS, potential novel seating in future unsupervised AD, increased use of shared mobility, and injury prediction when moving towards "zero injuries". Using various methodologies of applied research, the objectives of the project were to investigate variations in passengers' seating and perceptions, to address and develop assessment methods and tools for evaluating protection principles, and to contribute to identifying future research and development needs. The following research questions were formulated:

- What are the challenging passenger protection needs in current and future passenger cars?
- What do passengers' sitting postures and beltfit look like in today's cars and what are their seating preferences in future car usage?
- How can existing tools help to address the real-world needs for passenger safety assessment?
- Can morphed versions of existing HBMs represent a larger portion of the population and how do we choose the target population?

The project considered passengers of age 4 years and older in passenger cars. Younger children who are not using the car's seat belt as part of their protection were excluded. Only passengers were included as they are free to choose a greater variation of seat adjustments, seat positions and sitting postures, which results in more interesting learnings than for drivers. Passengers are also a more relevant population for future car safety challenges.

The research effort combined expertise from industry and academia, involving senior researchers as well as doctoral and master students. The project started in 2017 and the structure and way of working followed prior research projects (mainly addressing child car passengers) presented at the 22nd and the 25th ESV conferences (Jakobsson et al., 2011 and 2017). In total 25 publications, 13 academic theses and some insights from unpublished studies are briefly summarized in four chapters. The chapter **Real-world data** covers methodologies ranging from crash data analysis and occupant preference predicting, to user-studies on postures and beltfit. The chapter on **Tools** includes studies on the development of a heterogeneous population of HBMs and assessment of ATDs, while the chapter **Assessment of protection principles** covers physical sled tests and virtual simulations applying the HBMs and the ATDs. The chapter **International outreach** demonstrates a method for international multidisciplinary exchange.

REAL-WORLD DATA

Real-world crash data was analyzed to identify scenarios relevant for future crashes. User-studies of various kind were executed to investigate seating preferences in future travel modes, as well as passengers' sitting postures, movements, beltfit and comfort experiences in current passenger cars.

Predicting future crash scenarios

Crash data was used as input to determine future safety-critical scenarios. Lubbe et al. (2018) and Östling et al. (2019a and 2019b) used the German In-depth Accident Study (GIDAS) data and National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) data from USA, respectively, to identify future unavoidable crash scenarios for ADAS equipped cars and what crashes fully automated vehicles will be exposed to in mixed traffic analysis. The unavoidable crashes identified in the NASS-CDS data were further analyzed to identify remaining injuries (Östling et al., 2018). Analyses of crash data also served the purpose to derive statistics about passenger car seat occupancy and occupant age, sex, height, and weight. A comparison between Sweden, Germany and USA was performed using crash data from each of these countries. Front passenger seat occupancy ranged from 24% in the US data, 26% in the German data to 37% in the Swedish data. A relatively higher share of children in the front passenger seat was seen in the two European datasets compared to the US data.

An example of results from one of the studies looking at predicted future crash scenarios is shown in Figure 1. An estimation of most frequent remaining crash scenarios was derived using real-world data involving modern passenger cars virtually equipped with 15 different ADAS (Östling et al., 2019a). As a result, about 90% of the remaining crashes involving moderate to fatal injuries were assigned to four of the crash scenarios (Figure 1). Three of them are intersection related, representing together three quarters of all remaining crash scenarios, while the fourth is the 'Opposite Direction - Head-On crash scenario'.

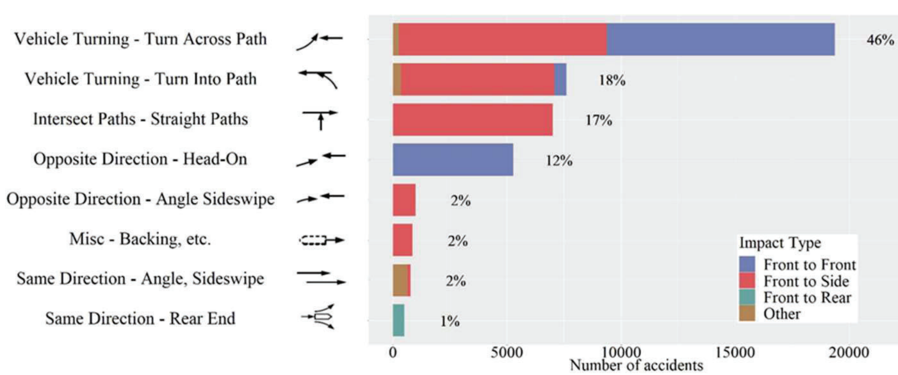


Figure 1. Prediction of unavoidable crash scenarios, after applying 15 ADAS, example from the NASS CDS database in USA (Östling et al., 2019a).

Exploring users' preferences in future transportation

Studies investigating preferences in future transportation were executed using different methods, addressing either AD or passenger cars in shared mobility services.

Hagberg and Jodlovsky (2017) investigated preferred reclined seat positions in potential unsupervised AD, with a comfort and safety approach using volunteers in a test-rig equipped with a production passenger car seat including a leg support (Figure 2a). It was found that the preference to sit reclined increased when the seat was equipped with the leg support compared to without. In addition to that, the reclined positions often led to a lap-belt position above the pelvis. Another important finding was that most of the respondents did not consider crash safety when selecting their seat positions.

An experimental setup was developed to assess drivers' experiences of the reclined sitting posture and the human machine interfaces (HMI) for transitions between upright and reclined modes and between manual and automated driving modes (Makris, 2020, Makris and Osvalder, 2022). The experimental setup consisted of four steps: practicalities, preparations, execution, and data collection methods. Six aspects were identified as important when assessing user experiences in a dynamic test: (1) recruiting appropriate participants, (2) providing consistent tasks, (3) providing adequate time constraints, (4) avoiding social influences, (5) utilizing appropriate data collections methods, and (6) carrying out a pilot study.

Figure 2a. Reclined seat with a leg support in the study by Hagberg and Jodlovsky (2017).

Figure 2b. Investigating future expectations of future automated passenger car interiors (Östling and Larsson, 2019).

Two studies, one in Vårgårda Sweden, and one in Shanghai China, were executed using the method "setting the stage" (Pettersson and Karlsson, 2015) to predict adults' and children's perception on seating configurations in different trip scenarios unsupervised AD (Jorlöv et al., 2017, Östling, 2018, Östling and Larsson, 2019). The participants explored seating configurations in a stationary test setup (Figure 2b), guided through different trip scenarios by the test leader. This qualitative experimental approach was used to explore users' expectations of future products using a minimalistic test setup design and interviews, allowing the participants to take on a more dynamic role than purely being an informant. Although in different continents, the user expectations in Sweden (Jorlöv et al., 2017) and in China (Östling and Larsson, 2019) were similar. In both studies the volunteers expected unsupervised AD to offer reclined seat positions, versions of a living room setup especially when several passengers would be travelling together, and more comfortable seats with screens and tables for various activities. Children showed a more positive attitude than adults, when asked if they would accept extra restraints if that would allow them to use new seating configurations (Jorlöv et al., 2017).

Focusing on booster-seated children in shared mobility, the users' needs on child restraints for car sharing services were studied by interviews and online questionnaire surveys in Sweden (Simmons and Johansson, 2020, Jakobsson et al., 2020). It was found that the majority of respondents had no experience with car sharing services, and they stated that one of the reasons not to use such services was the difficulties with child restraints. Portability, size, and weight were stated as important design features for boosters to be used in shared mobility services. 72% of the participant would use a booster if available in the car, instead of bringing their own.

Sitting postures and beltfit

User-studies were executed to explore and document real-world sitting postures, passenger movements and beltfit of passengers in current cars. A variety of individual differences (such as gender, age and body constitution) and differences in types of travels were explored with the purpose of learning from current car passenger seating. The aim was to identify how passenger characteristics and driving situations can influence sitting posture and beltfit, as input for further work on how occupant to restraint interaction can be addressed in future protection strategies. Some studies also included the development of methods for collection and analyses.

A number of the user-studies focused on older adults and their beltfit and comfort as front seat passengers in stationary cars, also including a comparison to younger adults (Ankartoft and Alfredsson, 2018, Osvalder et al., 2019, Bohman et al., 2019b). In addition to comfort perspectives, insights were gained on beltfit depending on body shape; as illustrated in Figure 3a. Twenty six of the 55 participants had non-optimal beltfit, including poor lap or shoulder-beltfit (Osvalder et al., 2019). Belt close to the neck increased the reporting of shoulder-belt discomfort. Overall, the safety awareness was low among the older adults compared to younger adults. Although not evaluated, it was estimated that most of the non-optimal beltfit could have been avoided, if the participant had used the adjustments possibilities offered in the car (Bohman et al. 2019b). In both studies, it was found that participants with high BMI were more likely to have the shoulder-belt higher up on the abdomen, resulting in that the shoulder-belt was routed closer to the neck. This beltfit occurred regardless of sex or age but was related to the body shape. Women with high BMI tended to have poorer lap-beltfit compared to men with high BMI, potentially due to the fat distribution differences. (Osvalder et al., 2019, Bohman et al., 2019b).

Figure 3a. Examples of passengers with different body constitutions and their beltfit (Osvalder et al., 2019).

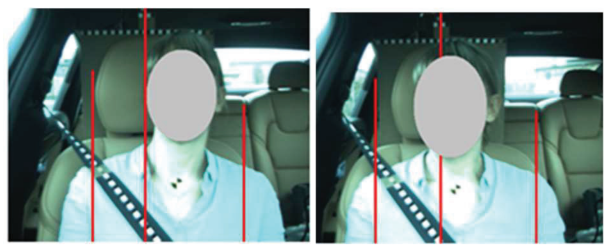


Figure 3b. Example of a front passenger prior to turn (left) and at maximum lateral position with head off the head restraint (right) (Bohman et al., 2020a).

Another user-study investigated 26 front seat passenger volunteers exposed to turns representing everyday driving. The study provided quantified data of beltfit, laterally leaning postures and lateral movement that can be used as input to simulation studies for assessing protection principles in relevant sitting postures (Olander and Andersson, 2019, Bohman et al., 2020a). An example of a passenger sitting upright and at max lateral position due to a turn is shown in Figure 3b. In the turn with highest lateral acceleration (0.3 g), the torso moved on average 45 mm from the centerline of the seat. The shoulder-belt stayed on the shoulder in all turns for all participants, but in some cases the head was positioned laterally off the head restraint (Figure 3b). The shorter participants showed a trend of greater lateral movement than the taller.

Addressing the challenging area of methods for quantifying sitting postures in cars with focus on pelvis orientation, instrumentation such as XSENS and digital measurements of body landmarks were explored using 27 volunteers in six setups (Janson and Wedmark, 2018). Both methods provided similar results, although the pelvis angle was more easily captured by XSENS. The pelvis angle changed on average 15˚ when the seatback was changed from upright (22˚) to reclined (45˚). This study served as inspiration for a follow-up driving study with the focus on pelvis rotation, in addition to slouching of front seat passengers, changes during the ride (Hansson and Lysén, 2019). It was found that pelvis rearward rotation and slouching forward increased over time with an average rearward pelvis rotation of 10° and 30 mm forward for the 20 participants.

User-studies were conducted with child volunteers who have advanced from child restraints but are yet not adults. With the aim of to understanding how the children's activities affect their experience, comfort and safety as car passengers, Gereben and Swenson (2020) investigated the behaviours of children aged 10 to 17 years old. The methods included interviews, a UX diary study and focus group sessions with the families at their home. Figure 4a shows a concept of a rear seat entertainment system with adjustable touch screen and a safe wireless phone charging place enabling the smart phone to be used as a control, developed as an example of how to nudge safe sitting posture and beltfit (Gereben and Swenson, 2020).

Figure 4a. Concept of rear seat entertainment system for study on child passenger aged 10 to 17 years old (Gereben and Swenson, 2020).

Figure 4b. Two children trying out the booster prototype in Jakobsson et al. (2020). The shoulder-belt is routed under the belt guide for the 6-year-old (left), while over the belt guide for the 11-year-old (right).

A user-study, limited to three children, was included in a study on belt-positioning boosters for children in which the mismatch between booster developments and the users' needs for shared mobility was in focus (Jakobsson et al., 2020). Figure 4b shows the role of the booster's belt guides as means to help guide the shoulder-belt, having an impact on comfort as well as protection in a potential crash. The 6-year-old child achieved a more optimal shoulder-belt fit when the shoulder-belt was routed below the belt guide, while the 11-year-old child benefited from a shoulder-belt routing above the belt guide. For optimal protection of booster-seated children it is essential that the car, the booster and the users are regarded as one entity.

TOOLS

Tools, including ATDs and HBMs, were assessed to explore their abilities to serve as substitutes for car passengers in a crash. This included examples of studies evaluating varieties in versions of specific ATDs, their capabilities to adapt to different sitting postures and comparison of two generations of dummies. A special task on the development of morphed HBMs is included as well.

Adult occupant tools

Targeting a family of HBMs representing the future adult population for evaluation of restraints, Larsson (2020) summarized the literature on the occupants with increased injury risk in car crashes, to identify the future population of car passengers posing challenges to contemporary safety systems and evaluation methods. Identifying women, older adults, and obese occupants, the boundary case method, as described by Brolin et al. (2012), was used to define 27 individuals to represent a diverse population. A morphing method for the SAFER HBM was selected and implemented to enable the creation of the individuals in the diverse population. Adult passenger HBMs, representative of both women and men of a wide range of statures, weights and ages were developed using the morphing method, examples shown in Figure 5a. A validation database was created consisting of publicly available experiments with 19 post-mortem human subjects (PMHS), together representing a wide range of male and female sizes and ages. Using this database, an extensive validation study was executed, identifying strengths and limitations of the morphed HBMs (Larsson et al., 2021a). It was found that the morphed HBMs predicted the in-crash kinematics of the PMHS with corresponding age and anthropometry with good accuracy in several crash scenarios.

In addition, a new rib fracture risk function based on recently created experimental data, that can be used to estimate HBM rib fracture risk was developed (Blennow, 2020) and implemented (Larsson et al., 2021b). The new HBM rib fracture risk function was not influenced by sex, but age was identified to have a stronger contribution to rib fracture risk than represented by previous rib fracture risk functions, enabling more accurate risk estimations over the span of adult passenger ages (17-99 years), see Figure 5b. The findings contribute to the SAFER HBM injury prediction developments (Larsson et al., 2021b).

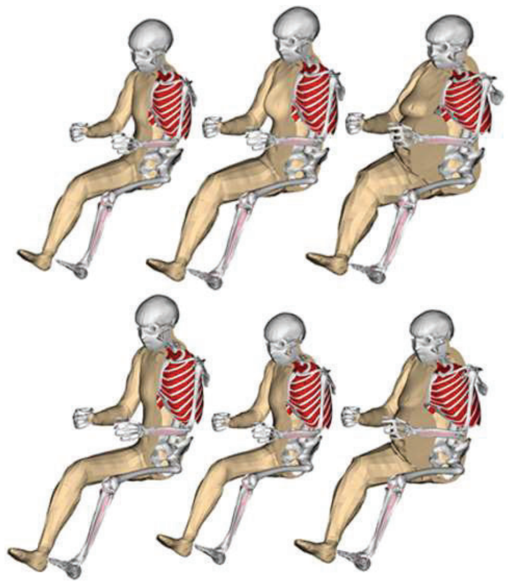


Figure 5a. Examples of morphed versions of SAFER HBM. Three female anthropometries (top row) and three male anthropometries (bottom row).

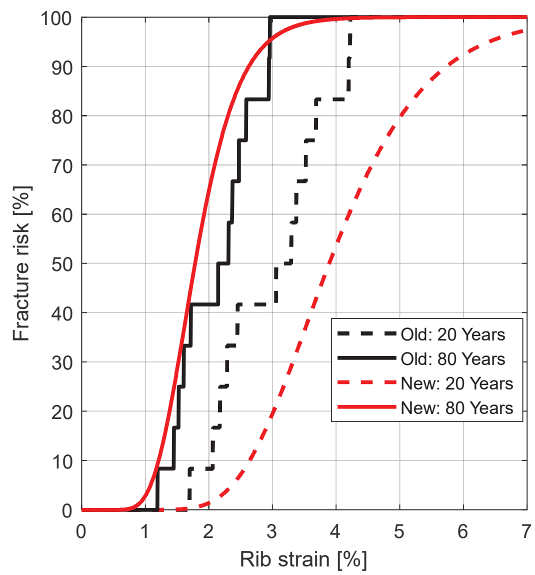


Figure 5b. New age-adjusted rib fracture risk function (red) compared to a previously existing fracture risk function (black) for 20- and 80-year-olds.

Adult-sized tools were evaluated to provide insight into their capabilities of addressing future car safety assessment needs, such as more reclined seats. The THOR-50M, a mid-sized male ATD, was evaluated in terms of kinematics and its interaction with the restraint system, exposed to frontal impacts using a generic test-rig in three different seating conditions: relaxed, reclined and upright, see Figure 6 (Östling et al., 2021). It was found that it was possible to position THOR-50M in the two reclined seat positions and the measured accelerations and forces appeared meaningful in relative comparisons even if a kinematic validation is preferred (Shin et al., 2022). As an example, the thoracic spine compression increased from 4 kN in the upright seat position to 6 kN in the two other positions. However, chest compression Rmax, measured as the maximum of the resultant value from the four IR-TRACCs, might not be meaningful in the two reclined seat positions. It was found that instead of a longitudinal compression, an angular change in vertical direction dominated the Rmax value. This might be explained by initial non-horizontal IR-TRACCs position in reclined and relaxed seat positions; the IR-TRACCs appeared to work as intended only when initially oriented horizontally as they are in the upright position (Östling et al., 2021). As a result, the Rmax indicated a higher risk of rib fractures in the two reclined seat positions despite that a lower shoulder-belt force was measured. In a following step, the mid-sized male SAFER HBM and a morphed large-sized male version were evaluated in similar conditions in a simulation study, Figure 7 (Östling et al., 2022). Similar to the sled tests with the THOR-50M, the lumbar spine compression forces of both HBMs increased in the relaxed seat position, while unlike THOR-50M, a lower risk for chest injury was predicted. However, it should be pointed out that chest injury risk is predicted by rib strain using the HBMs and chest deflection using the THOR-50.

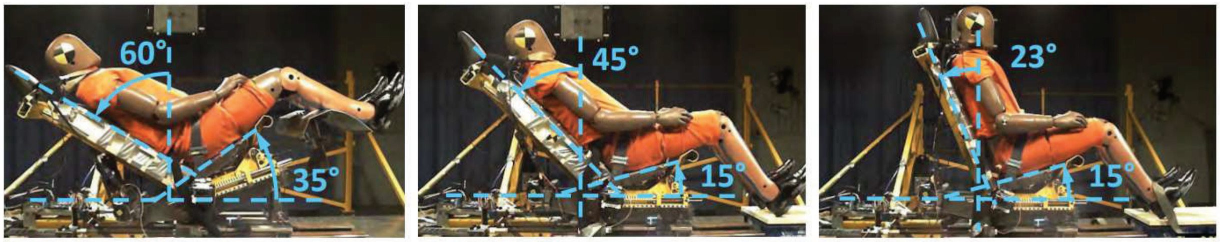


Figure 6. THOR-50M positioned on a generic seat in the relaxed, reclined and upright seating conditions (left to right), (Östling et al., 2021).

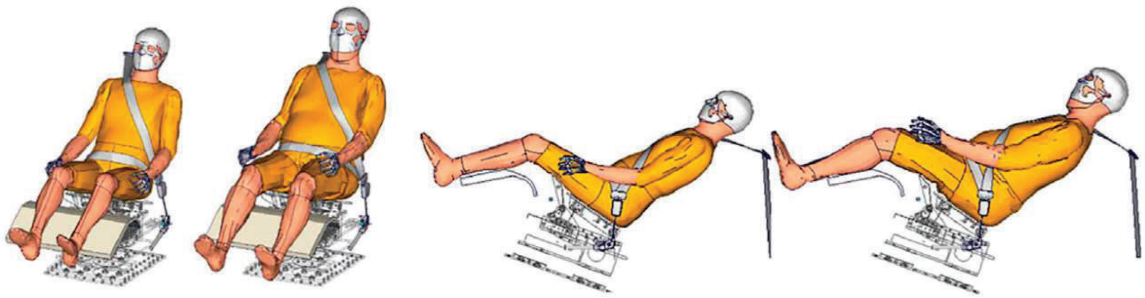


Figure 7. SAFER HBM positioned on the generic seat. Left: front views of the mid-sized male and the large-sized male. Right: side views of the mid-sized male and the large-sized male (Östling et al., 2022).

Frontal impact sled tests were run with the novel small-sized female THOR-5F ATD (Figure 8a), with comparative tests with the small-sized female HybridIII-5F (HIII-5F) ATD (Carroll et al., 2021). The SENIOR test buck (Eggers et al., 2017) was used with three different configurations: belt only at 35 km/h, belt and airbag at 35 km/h and belt and airbag at56 km/h. It was found that the two ATDs interact with the restraint system differently. The THOR-5F showed larger chest deflection and more forward pelvis excursion as compared to the HIII-5F.

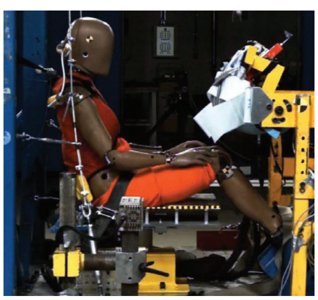


Figure 8a. The novel small-sized female ATD, THOR-5F (Carroll et al., 2021).

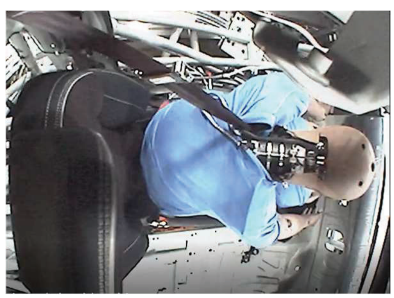


Figure 8b. Top view of shoulder-belt interaction with the original THOR-50M shoulder pad, during frontal impact.

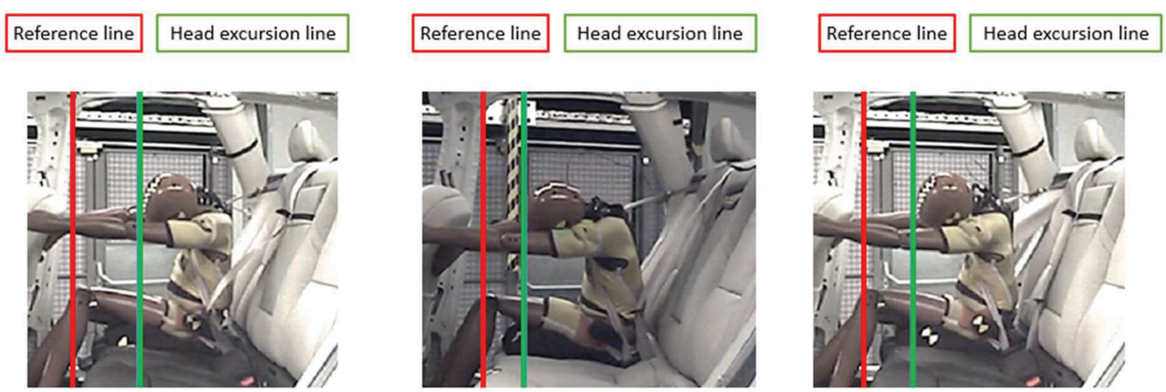
Figure 8c. Top view of shoulder-belt interaction with Humanetics updated THOR-50M shoulder pad, during frontal impact.

A sled test series was performed investigating THOR-50M's shoulder to shoulder-belt interaction, when exposed to a Euro NCAP Mobile Progressive Deformable Barrier (MPDB) frontal impact crash. The original shoulder pad was compared to update versions from two different suppliers, Kistler and Humanetics, respectively. Tylko et al. (2018) observed that with the original shoulder pad design, the shoulder-belt may slip over the shoulder pad collar into a gap between the neck and the shoulder pad. This gap is a dummy artifact and is not representative of humans. The updated versions were developed to prevent this shoulder-belt entrapment (Wang et al., 2019). In the sled test series, the shoulder-belt slipped off the shoulder pad collar into the gap in the tests with the original shoulder pad (Figure 8b), as well as with the updated shoulder pad by Kistler. While the shoulder-belt stayed on the shoulder in the tests with the updated shoulder pad by Humanetics (Figure 8c). The differences in shoulder-belt interaction influenced the dummy responses. The chest criterion Rmax was 33% higher, and the neck shear force was 27%, higher, when the shoulder-belt stayed on the shoulder. This study is an example of the importance of understanding the dummy design's influence on shoulder-belt interaction during a crash, improving the assessment methods towards more human and real-world like.

Child occupant tools

The open-source 6-year-old sized child HBM, PIPER6y (Beillas et al., 2016), was evaluated in studies to investigate its readiness and usefulness for child passenger protection assessment in a passenger car environment (Berntsson, 2018, El-Mobader, 2018, Daouacher, 2019). It was found capable of providing relevant information regarding sensitivity for lap-belt variations from the kinematic perspective in terms of capturing kinematic offset, submarining and pelvis interaction with the lap-belt (El-Mobader, 2018). PIPER6y also showed sensitivity to variations in shoulder-belt geometry, resulting in both inboard and outboard shoulder-belt movements (Berntsson, 2018, Daouacher, 2019). At the time of these studies, PIPER6y had some issues with early termination. Over time, the robustness has improved, and PIPER6y has become a valuable tool for studies on restraint interaction and booster design properties (Bohman et al., 2020b, Bohman et al., 2022).

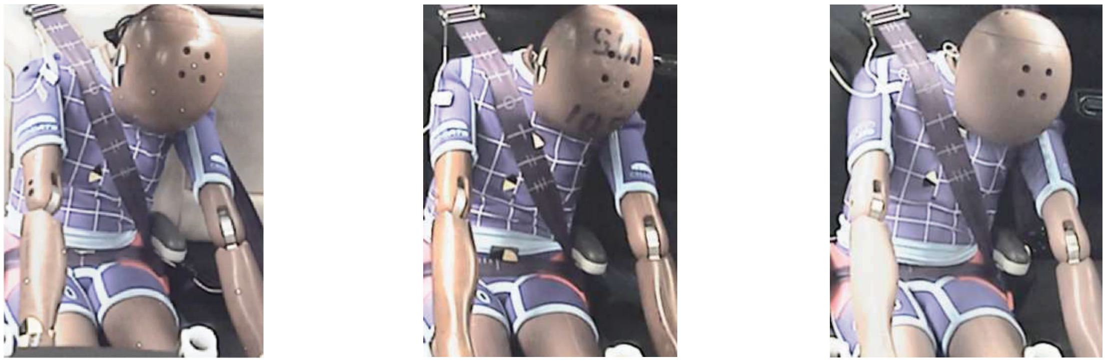
Frontal and side impact sled tests were performed comparing three different versions of the Q10, an ATD with the size of a 10-year-old child (Bohman et al., 2018 and 2019a). Q10 is used in certification rig tests (UN ECE R129) and as a rear seat passenger in consumer information testing by Euro NCAP, wherefore it is essential to understand any consequences of variation between versions. The original Q10 was compared to two modified versions, here called 'Q10update', and 'Q10light'. The 'Q10update' comprises an upgrade kit with 5 modifications, which includes changes to the shoulder joint, shoulder liner, mass redistributions, soft tissue representation at nipples and head and neck shift resulting in nose more upward rotated. The 'Q10light' includes three of those changes: the head and neck shift, shoulder liner and mass redistributions. The three versions, when exposed to the frontal impact, are shown in Figure 9. The two modified Q10 showed greater head excursion and more upper torso tilt, than the original Q10, due to the mass distribution differences. This kinematics was anticipated to be more biofidelic. The 'Q10upgrade' showed limited sensitivity to shoulder-belt position, while 'Q10light' showed sensitivity to shoulder-belt position but still had a more stable behavior than the original Q10. Following these studies, the 'Q10light' version was selected by Euro NCAP to be used in their rating program starting 2020, now called Q10 2020.



The original Q10 The modified 'Q10update' The modified 'Q10light'

Figure 9. Three Q10 versions evaluated in Bohman et al. (2019a), at time of maximum head excursion in a frontal impact.

A follow-up study was conducted to compare supplier setups of the Q10 2020, including one complete Cellbond manufactured Q10 ('Q10_Cellbond'), one complete Humanetics manufactured Q10 ('Q10_Humanetics') and one version with Humanetics Q10 base and upgrade kit by Cellbond (Q10_HU_CB). The ATDs were restrained with the seat belt and a booster cushion, positioned in the right rear seat position and exposed to a frontal impact Euro NCAP MPDB crash pulse. Upper chest deflection was 62% larger for 'Q10_Humanetics' as compared to 'Q10_HU_CB' and 'Q10_Cellbond'. The difference could not be explained by shoulder-belt interaction nor difference in kinematics, since all three versions showed similar behavior (Figure 10). The neck tension was 27% higher for 'Q10_Cellbond' compared to ‘Q10_Humanetics’. Additional tests were made by shifting the suits between ‘Q10_Humanetics’ and ‘Q10_Cellbond’. However, no differences in dummy response or kinematics were seen between those tests.



‘Q10_Humanetics’ ‘Q10_HU_CB’ ‘Q10_Cellbond’

Figure 10. The shoulder-belt to shoulder interaction of the three different versions of Q10 at the time of max forward excursion in a frontal impact.

ASSESSMENT OF PROTECTION PRINCIPLES

Physical sled tests and virtual simulations were performed to investigate principles of car passenger protection using different ATDs and HBMs. The aim was not to develop protection systems, but to develop knowledge on how the different tools could be used to assess the interaction with the lap- and shoulder-belt in the variety of configurations. The studies included variations in seat position, sitting postures, seat belt routing and features, in addition to booster design when applicable. Some examples, illustrating the spread in applications, are provided.

Adult occupant protection principles

Östling et al. (2017) proposed a seat belt system that incorporated a triple belt pretensioner to avoid submarining in reclined seat position testing using a THOR-50M. When this system was evaluated in reclined PMHS tests, it was found that submarining could be avoided in four out of five tests (Richardson et al., 2020b). However, iliac wing fractures were induced by the lap-belt in two out of five tests, and lumbar spine vertebra fractures were induced by the reclined upper body (Boyle et al., 2019, Richardson et al., 2020a) in three out of five tests. Based on these findings, several sled test and simulation series were performed with the purpose to study occupant retention in novel seat positions (e.g., reclined), investigating the assessment of different restraint principles, such as lap-belt pretensioners and load limiters, lap-belt geometries, and a seat track load limiter (Östling et al., 2017, Östling et al., 2021, Östling et al. 2022, Östling and Lubbe, 2022, Östling and Eriksson, 2022).

When evaluating the effect of a seat track load limiter (i.e., reducing the crash severity by adding an energy absorbing element in the seat track) using the THOR-50M and the SAFER HBM, both tools indicated a reduced risk of lumbar spine vertebra fracture (Östling et al., 2021, Östling et al., 2022). However, whereas the SAFER HBM showed a substantial reduction in rib fracture risk, the THOR-50M indicated an increased risk of thorax injury when evaluated by the Rmax criterion. This was despite a lower shoulder-belt force. This difference supported the statement in Östling et al. (2021): “We believe HBMs with human-like design and use of rib strain as an indicator of risk of rib fractures, are likely to be more biofidelic than chest deflection to evaluate a potential increase or decrease in risk of rib fractures in reclined and relaxed positions”.

The occupant mass effect on the seat track load limiter was studied in different frontal impact crash severities utilizing the mid-sized male and large-sized male versions of the SAFER HBM (shown in Figure 7). Östling et al. (2022) showed that by adding a release mechanism in combination with an adaptable activation logic in terms of crash severity and occupant mass, the seat track load limiter protection capacity was enhanced.

Sled tests and simulations were run using the mid-sized male Hybrid III 50M (HIII-50M) ATD (Östling and Lubbe, 2022) and the SAFER HBM (Östling and Eriksson, 2022) to evaluate the influence of lap-belt load to limit the kinematics and measured injury assessment values. It was seen that the lap-belt load limiter did not only reduce the lap-belt force and thereby the risk for iliac wing fracture, but also limited forward-downwards head excursion and thereby a reduced likelihood for head-to-thigh contact, see Figure 11 for HIII-50M. Interestingly, despite fundamental different designs, both tools (ATD vs HBM) indicated similar effect on the occupant kinematics (Östling and Lubbe, 2022, Östling and Eriksson, 2022).

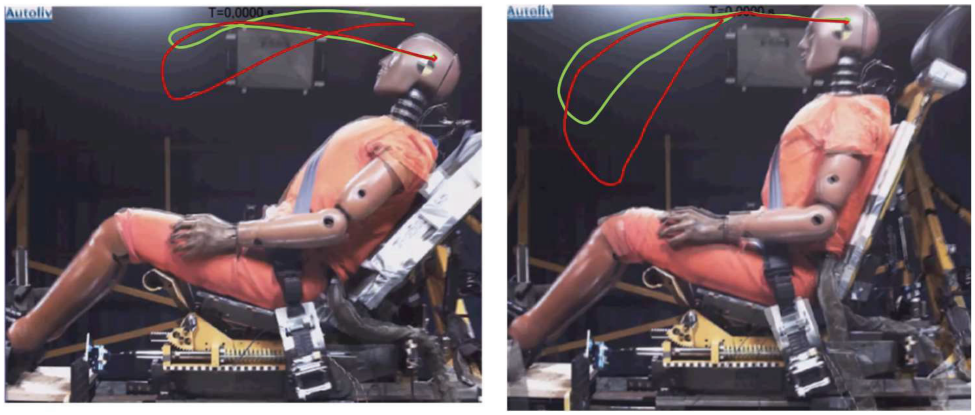


Figure 11. HIII-50M with and without double lap-belt load limiter, in reclined position (left) and upright position (right). The head trajectory was tracked during the test; red line is from test with no lap-belt load limiter and the green line is from the test with double lap-belt load limiter (Östling and Lubbe, 2022).

Another protection principle which was explored using two different tools, was conceptual air belts (Figure 12a). Frontal impact simulations with SAFER HBM were performed with two versions of conceptual air belts, a 10 liter and 18 liter airbag, respectively. Mainly focusing on kinematics, and neck and spine loads, the effect of air belt was assessed for upright seat position, and a reclined seat position. The simulations were followed-up with sled tests using THOR-50M (Figure 12b). In neither of the studies, a significant effect of the air belt was seen.

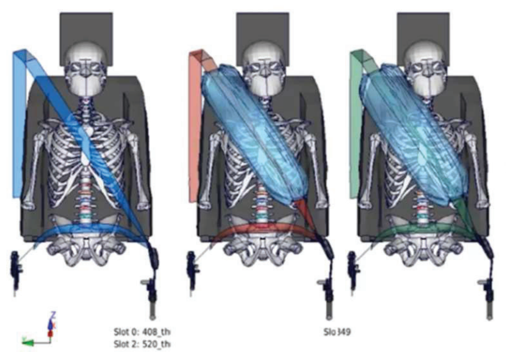


Figure 12a. SAFER HBM in the three setups; no air belt (left), air belt of 10 liters (mid) and 18 liters air belt (right).

Figure 12b. THOR-50M with a 10 liters air belt, in the sled test setup of upright (left) and reclined (right) seat position.

Child occupant protection principles

With the purpose to investigate the influence of booster cushion design on child occupant kinematics and loading; simulations using PIPER6y and sled tests using Q10 were performed, Figure 13 (Bohman et al., 2019c and 2020b). It was found that both Q10 and PIPER6y showed that though the boosters providing similar initial beltfit, the occupant responses were different during the crash. Compression of the booster cushion resulted in a delayed pelvis restraint, influencing the upper body kinematics. Furthermore, the belt guide design as well as the belt routing above or under the guide also influenced the upper body kinematics and shoulder-belt interaction (Bohman et al., 2020b).

Figure 13. PIPER6y (left) and Q10 (right) at the time of maximum head excursion restrained on three different booster cushions (Bohman et al., 2020b).

Another study used PIPER6y to explore the challenges for booster-seated children in reclined seat position and different restraint parameters (Bohman et al., 2022). Three different booster types were used in a front passenger seat with two different seatback angles. The study included variation of pretensioner activation (yes/no), attachment to the ISOFIX anchorages (yes/no) and two different shoulder-belt outlet positions. Activating the pretensioner resulted in shorter body displacement and lower head and neck responses in both seat positions compared to pretensioner non-activation. Submarining occurred only for one of the boosters, when in reclined position without pretensioner. Overall, greater pelvis displacement was observed when in reclined position as compared to upright position'. In both seat positions, greatest pelvis displacement was observed on the booster allowing a relatively more forward initial lap-belt position. Among the three included boosters, the booster providing most favorable initial lap-belt to pelvis contact and controlled vertical movement of the pelvis offered the most efficient lap-belt interaction. Furthermore, this study highlighted the importance of including the whole context of child occupant protection when investigating reclined seating, such as the interaction and compatibility of the booster, the car seat and the seat belt (Bohman et al., 2022).

Two booster cushion concepts were developed to demonstrate the needs and challenges in shared mobility, serving the purpose to illustrate and communicate the mismatch between the booster design trend and the users' needs in shared mobility (Jakobsson et al., 2020, Simmons and Johansson 2020). Booster cushion concepts were explored in order to fulfill UN ECE R129 requirements, resulting in increased height of the booster cushion and at the same time offering a portable solution suitable for ride-share and car share mobility, while still fulfilling protection principles. The foldable booster cushion, shown in Figure 14, reduced the volume by 37% in compressed state, compared to user state. Folding the belt guides as well could reduce size even further.

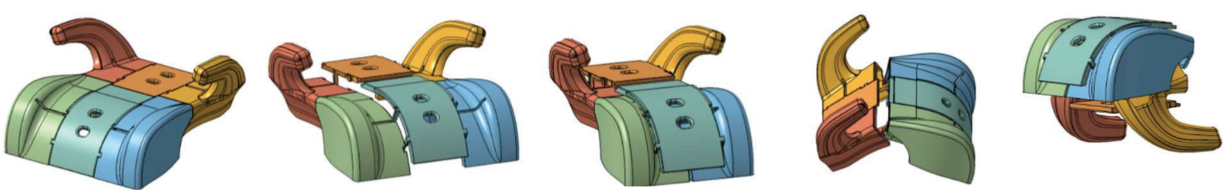


Figure 14. A sequence of pictures from user-state (left) to compressed/folded state (right) (Jakobsson et al. 2020).

INTERNATIONAL OUTREACH

Two international multidisciplinary workshops on Child Occupant Protection were held in Sweden in September 2019 and September 2022 with the purpose to identify high-priority research topics and strategize toward their implementation. The workshops were the 6th and 7th biannual workshops on this topic, and hosted by the project team and SAFER, within prior research projects over the years (Arbogast et al., 2011, 2013, 2015 and 2017). The participants of the workshops included worldwide leaders in the fields of child occupant protection, biomechanics, and automotive safety. Adjacent to the workshops, a one-day open seminar was held at SAFER in Gothenburg, Sweden, with presentations by the international researchers on current child occupant protection topics. The discussions at the workshops were summarized and presented at the International Conference Protection of Children in Cars in Munich, enabling a wider dissemination and contributing to setting the agenda of future research and development (Bolte et al., 2019; Arbogast et al., 2022).

The workshops of 2019 and 2022 followed the methodology of prior workshops with focused interaction and discussions during two-days. The first day included reflections on relevant topics on ‘pressing issues in child and adolescent occupant protection’, in addition to reviewing progress of research priorities identified during previous workshops. The second day included discussions on high priority areas, as defined based on the first day’s discussions.

The workshop in 2019 focused on the topics of what automated driving systems mean to children and youths, how new mobility may alter their behavior, and how to ensure protection of all ages of passengers when moving from a driver-centric mobility to a passenger centric mobility. Critical safety points were defined as a unified voice for all stakeholders in child safety to ensure safety for all road users as we move into a world of autonomous driving systems. The critical points highlighted that every trip is important, and special focus was put on ensuring safe trips when using shared mobility services. Furthermore, the design of the seat and restraints should promote occupant behavior allowing the individual to be both comfortable as well as safe in all types of trips. In addition, a continuous need was emphasized to improve the child-specific occupant tools (ATDs and HBMs) to address challenges in variations in sitting posture, seating configurations and pre-crash maneuvers.

In 2022, the workshop focused on what strategies are necessary to further reduce the burden of motor vehicles crash deaths and injuries for children and adolescents; and how to guide future restraint development to help protect them in shared mobility, while still ensuring protection in more traditional riding scenarios. Focusing on booster-seated children, the key safety concept that emerged from the discussions was the need to message that a booster is an adapter, not a restraint! And second, the importance to reorient the consumer to how a booster works, driving simple solutions that positively impact safety as well as the other key characteristics of accessibility and affordability. To acknowledge the real-world evidence and experience, and adhere to demonstrated protection principles, in addition to acknowledge that the car’s protection will help protect the booster-seated child as well. Hence the booster’s main purpose is to complement with the child specific needs, i.e., to elevate the child in position for the seat belt. The protective performance of a well-designed booster cushion is well established, and there is evidence that booster cushions as well as integrated boosters are relatively more used among the older child age group. Adapting these to the protection needs of booster-seated children and making them portable, focusing on size and weight while still adhering to the protection principles, will help keep children safe. It was emphasized that the journey towards increased safe shared mobility, being an enabler for a more sustainable and accessible transport system, is a collaborative task by all involved stakeholders. Vehicle manufacturers, as well as the booster manufacturers and the users, in addition to rulemaking and organizations influencing the design, such as consumer information testing, need to work together and be aligned towards the common goal of sustainable and safe transportation.

DISCUSSIONS

Assessment of passenger safety in future cars involves evaluation of protection beyond current standardized crash testing and ATDs. Real-world car passenger protection needs require knowledge on aspects important for the diverse population and tools that can reflect these aspects. It also requires abilities to assess the arise of potential injury mechanisms when introducing new seating possibilities. With increased automation and shared mobility services, capabilities are needed to consider pre-crash events as part of the occupant protection assessment, as well as understanding the context of restraint usage, passengers’ activities in the car, and the influence of potential add-on features such as boosters. The challenges are many, and the research area is wide. The foundation of this research project was to combine multiple competencies, international collaboration and a range of studies using different methods and tools. The project’s agile and knowledge-sharing way of working – by adapting parts of the research to current topics and inviting researchers in dialogues - has inspired additional research initiatives by other research groups. Although some of the research project’s studies were small in size, though pioneering within the area, they have helped to raise awareness, and to provide inspiration for, e.g., the large-scale car passenger observation study by UMTRI (Reed et al., 2020) and the world first reclined PMHS tests performed with the purpose to generate validation data to HBMs (Richardson et al., 2020b).

Challenging passenger protection needs in current and future cars include protection of the heterogenous population in new seat positions and sitting postures. This requires tools that can address the kinematics, the interaction with the restraint system, and potentially new injury mechanisms arising. In addition, the tools need to be capable of including the pre-crash event as part of the occupant protection assessment. Restraint principles for adults in reclined seat position were investigated, along with an evaluation of the capabilities of the assessment tools. The adult HBMs of varied sizes, ages and sex provided enhanced insights into passenger protection assessment compared to the limited sizes of ATDs. Novel studies predicted representative crash configurations when future crash interventions were applied, suggesting that there will likely be a large share of intersection related crash configurations whereby emphasizing the need of tools capable of omnidirectional kinematics and injury predicion. Studies with PIPER6y, with its more humanlike capabilities for real-world assessment as compared to the child ATDs, emphasized the car/booster/user entity for the protection of booster-seated children. Unfortunately, this is not how boosters are developed and assessed today. In some parts of the world, booster cushions are banned as a consequence of the regulatory test setups. In addition, booster seats are growing in size and complexity, driven by simplified test methods without taking into account the protective contribution by the car in a real-world crash. This leads to a problematic situation for children in future crashes, especially considering the users' need for easy access in shared mobility services (Jakobsson et al., 2023).

In order to gain knowledge on car passengers' sitting postures and beltfit, a number of studies were conducted using different methods. They included observation studies on car passengers in current cars, and novel methods to predict seating preferences in future cars with new seating configurations. Studying car passengers in current cars, it was obvious that passengers' self-selected postures deviated from standardized ATD positions. Several observation studies highlighted the influence of body shape on initial beltfit. There are many dimensions of body shape influence, which all should be explored further. The influence of comfort experience should also be further explored, gaining insights on favorable beltfit and sitting postures, which thereby can be used to help guide or nudge the passengers into safely designed contexts. A driving study provided insights into how shoulder-belt positions for some front seat passengers varied in everyday traffic. During turns, the passengers moved laterally, in some cases resulting in head off the head restraints. Prior studies have shown that during evasive braking events, front seat passengers (Ólafsdóttir et al., 2013) moved further forward as compared to drivers (Östh et al., 2013). The larger movements of passengers as compared to drivers is one reason to focus on car passengers. Another reason is that future car usage will include a larger share of ride sharing and eventually unsupervised AD, resulting in a larger share of non-drivers. Passenger protection also includes addressing a larger span of ages, as well as a rear seat environment. Compared to younger adults (aged 25-30), a lower safety awareness among older adult front seat passengers (aged 72-81) was observed in one of the studies. This had implications on using available adaptivity in the seat and seat belt to explore the possibilities of improved beltfit. In a rear seat study on children aged 10-17 years old, different design concepts were explored, targeting to encourage comfortable and safe sitting postures, while being engaged in various activities.

Adding to the understanding on how existing tools can help address the real-world needs for passenger safety assessment, testing and simulations studies on both adult and child ATDs and HBMs were executed. The studies on novel adult ATDs provided insights into their capabilities of representing challenges in future transportation, but also raised concerns on their biofidelity. This has triggered recent studies at University of Virginia (Shin et al., 2022) in which the HIII-50M and THOR-50M ATDs were compared to identical test conditions as the reclined PMHS test by Richardson et al. (2020b). It was concluded that both the HIII-50M and THOR-50M exhibited overall comparable responses to the PMHS. However, magnitudes and even directions of the pelvis kinematic varied between the ATDs and the PMHS. These findings have initiated new research to improve the biofidelity of THOR-50M when in reclined posture within the newly formed Research Consortium for Crashworthiness in Automated Driving Systems (RCCADS). In another test series, the novel small-sized female THOR-5F (Figure 8a) was shown to replicate the kinematics of the mid-size male counterpart THOR-50M in an upright seat position, which differed from the HIII counterparts (Carroll et al., 2021). In future passenger car interiors, such as face-to-face seating configuration, knee restraints are less likely to be included. Further studies on this topic are ongoing, partly in collaboration between project partners and universities in the USA. Such research is essential to ensure that the ATDs used for reclined seat positions are biofidelic. The study on the Q10 supplier variants provided insights in large spread in responses depending on supplier, showing the urgent need for improved and more detailed specifications of ATDs to ensure repeatability, no matter supplier.

The family of morphed HBMs that represents the population variability in body shape due to sex, height, weight, and age variations is useful in the design of future cars and safety systems targeting increased safety for all passengers. The validation of morphed SAFER HBMs showed that the morphed HBMs provided good predictions of in-crash kinematics (Larsson et al., 2021a). Crash database analyses indicated that females, elderly, and obese car occupants were at increased injury risk (Larsson, 2020). These subpopulations need further consideration in the design of crash safety features. Using morphed HBMs may have the potential to reveal injury mechanisms in a way that is not possible by only considering the standardized ATD sizes. Continued developments of morphed SAFER HBMs, as well as methods to incorporate passenger variability through morphed HBMs are ongoing. The choice of the target population to be represented by morphed HBMs was based on the height and weight variability existing for males and females in the general population. Acknowledging the extent of population variability, and also enabling representation of this variability in crash safety evaluations through morphed HBMs are important steps to enable improved crash safety for all passengers.

This comprehensive research project provided input to safety system development, ATD and HBM designs, assessment methods development, and future research challenges. Addressing the challenges of protection assessment of the heterogeneous passenger population in future car crashes requires multidisciplinary and collaborative research and a multitude of methods, such as an iterative work of user-studies and crash testing/simulations. By studying current passengers, complemented with prediction studies on future situations of crashes and passenger car interior designs, the derived results may also contribute to safety developments addressing future cars. The inclusions of the heterogeneous population into more advanced tools such as HBMs are essential, acknowledging that when moving closer to “zero injuries”, the situations to address are more unique and specific. Although a range of studies using different methods were included in this research project, many challenges still remain to cover the scope of passenger safety in future cars.

CONCLUSIONS

The importance and complexity of passenger protection in cars increase with a higher degree of automation and shared mobility. The population is becoming older, and the diversity in passenger sizes is growing. This, in addition to new seat positions, seating configurations, as well as car usage and ownership, requires assessment tools and evaluation methods beyond the current standardized crash test methods. The presented research project has contributed to advancements of assessing the protection of the heterogeneous population of passengers in future car crashes, by gathering a variety of competencies, combining different types of methods and performing international collaboration.

As examples, passenger protection needs were studied through observation studies on passenger sitting postures and beltfit in combination with simulation and sled test series. The importance of body shape was highlighted for older adults, while the influence of booster design was raised for children. Restraint principles for adults in reclined seat positions were investigated as well as evaluation of the capabilities of the assessment tools (i.e., ATDs and HBMs). Applying the protection principles to new seating configurations and seat positions is challenging and will require more advanced tools. Novel studies predicted future crash configurations and seating preferences, contributing to new insights on challenging passenger protection needs in current and future car crashes. In addition, a methodology was developed for the selection of representative individuals for crashworthiness assessment, addressing the heterogeneous population. Morphing techniques were established, and a family of morphed HBMs was created and prepared for use in car and safety system developments. HBMs of a variety of occupant sizes, ages and both sexes, used together with the knowledge on how they sit as passengers in cars, enhance the relevance of occupant protection assessment.

The way forward addressing the challenges of assessing protection of the heterogeneous passenger population in future car crashes is a collaborative work. There is a need to further explore car passenger positions and variations of sizes, shapes and postures as well as to develop means to assess real-world occupant to restraint interactions in a multitude of scenarios. A variety of methods and competencies, as well as iterative cooperation of user-studies and crash testing/simulations are required. Population heterogeneity needs to be reflected by more advanced tools, such as HBMs, to accurately assess restraint interaction – a pressing passenger protection need.

ACKNOWLEDGEMENT

This work has been carried out at SAFER- Vehicle and Traffic Safety Centre at Chalmers, Sweden and is partly financed by FFI (Strategic Vehicle research and Innovation) by VINNOVA, the Swedish Transport Administration the Swedish Energy Agency and the industrial partners within FFI.

The project partners are Volvo Cars, Autoliv Research and Chalmers University of Technology. The authors would like to acknowledge our colleagues contributing to the project, specifically; Hanna Jeppsson and Nils Lubbe at Autoliv, and Maria Wimmerstedt, Magdalena Lindman, Jacob Wass, Jonas Östh, Fredrik Heurlin, Catherine Lef and Henrik Nilsson at Volvo Cars. We would also like to acknowledge the following master students for their support Andreas Hagberg, Sandra Jodlovsky, Robin Ankartoft, Svante Alfredsson, Mathilda Janson, Jessica Wedmark, Josefine Berntsson, Sarah El-Mobader, Anna Olander, Agnes Andersson, Annika Hansson, Emma Lysén, Maria Daouacher, Sebastian Simmons, Charlie Johansson, Mio Gereben, Maia Swenson, Amanda Blennow and Melina Makris.

We also want to thank all the participants at the international workshops, listed by names in Bolte et al. (2019) and Arbogast et al. (2022).

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A Study on the Method to Reduce Thoracic Injury in Frontal Crash using Elderly Human and THOR FE Models

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ABSTRACT

In Japan, the ratio of the elderly in traffic accident fatalities has been increasing, and the thorax is the most frequently injured body region. Therefore, preventing chest injury to the elderly is one of the key issues to achieve zero fatalities. For this reason, several detailed analyses of the chest injury mechanism have been performed using elderly human body models (HBM). In a previous study, under frontal crash condition, it was observed that the forward motion of the internal organ and the forward rotation of the upper torso push up the lower ribs, potentially leading to rib fractures. In this study, a novel occupant restraint concept was devised that could reduce chest injury due to the mechanism above, and its effectiveness was verified using an elderly HBM and THOR.

On the devised restraint system, a pair of shoulder belts that pass from left and right sides of the occupant shoulder to the same sides of flank were placed. The aim of them was dispersing the restraint force applied to the thorax of an occupant. A membrane was placed wrapping the abdomen between the two shoulder belts, which aimed to reduce the protrusion of the internal organ during a frontal crash.
For the devised restraint system, a series of CAE calculation using the elderly HBM was performed in the two crash conditions of FR56K and OMDB in comparison with the conventional 3P belt, and the effect for reducing the number of fractured ribs (NFR) was confirmed. Then, another series of CAE calculation using the THOR FE model was performed in the same conditions, and several chest injury criteria such as Rmax, PC Score, TIC_NFR, and TIC_NSFR were calculated. Finally, injury probabilities for these criteria of THOR and NFR of the HBM were compared.

Comparing the devised restraint system with the 3P belt, NFRs of the elderly HBM were significantly reduced, and all chest injury criteria of THOR were reduced, under both load cases.
In the OMDB condition using the devised system and THOR, The chest deflection at inner lower was the largest, and Rmax was relatively high than other chest injury criteria. In the same condition, TIC_NSFR showed the best correlation with the NFR of the elderly HBM.

It was considered the reason why Rmax was high on OMDB was that THOR had a more protruded ribcage around the lower region than the elderly HBM, which caused higher concentrated load on this region pushed by the shoulder belt.
The reason why the TIC_NSFR on OMDB was low was considered to be that the devised system restrained the chest evenly on the left and right, and the value of the term that indicates the left-right difference of the upper chest deflection in the TIC_NSFR formula became smaller.

It was found that the devised chest restraint system could significantly reduce rib fractures of the elderly HBM in a frontal crash.
It was also found that when the devised system was evaluated with THOR, every chest injury criterion was reduced.

INTRODUCTION

In recent years, population ratio of the elderly has been increasing in such developed countries as Japan. Therefore, a lot of elderly people get involved in traffic accidents. In Japan, the number of traffic accidents has been decreasing. But the ratio of the elderly (aged 65 years old and older) in traffic accident fatalities has been increasing [1]. The thoracic injury due to rib fracture is the main factor of the death of elderly people [2] [3]. One of the reasons for this is because the density and strength of bone decrease with age [4]. Therefore, preventing chest injury to elderly people is one of the key issues to achieve zero fatalities. For this reason, a lot of detailed analyses of the chest injury mechanism have been performed, using post-mortem human surrogates (PMHS) [5] [6] [7] [8] [9] and human body models (HBM) [10] [11] [12]. In the previous study by the authors, under frontal crash condition, it was observed that the forward motion of the internal organ and the forward rotation of the upper torso pushed up the lower ribs, potentially leading to rib fractures [13]. Under frontal crash condition, the current mainstream of the chest restraint method is the so-called three-point seatbelt (3P-belt), which uses a shoulder belt placed diagonally from one shoulder to the opposite side. Shaw et al. [14] mentioned that complex deformities of the thorax affect thoracic fractures and that asymmetric thoracic restraint morphology may be a factor of the complex deformity of the thorax, based on the results of the sled tests using PMHS. In the research for safer occupant restraint methods, several studies have been conducted in the past on chest restraint methods with different types of restraint system than the 3P-belt [15] [16] [17] [18] [19] [20] [21]. For example, Östling et al. [18] analyzed the use of a 3+2 Criss Cross belt, which is a normal 3P-belt with an additional shoulder belt in the opposite diagonal direction, and reported a reduction in the risk of chest injury.

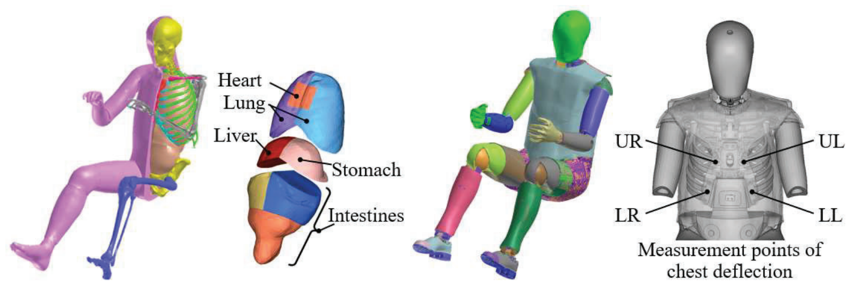
On the other hand, Test device for Human Occupant Restraint (THOR) dummy has been developed to improve the biofidelity in various body regions including the chest [22] [23], and is implemented in some crash assessments. THOR is capable of measuring the 3D thorax deflection at four locations with a kind of light reflective displacement meter called the Infrared Telescoping Rod for Assessing of Chest Compression (IR-TRACC). Several chest injury criteria for the THOR dummy have been proposed (e.g.: Rmax, PC Score, TIC_NFR), using those four deflection measurements [24] [25] [26]. However, THOR and human body have more than four ribs. Kawabuchi et al. [12] showed by the analysis using the elderly HBM that correlation between the chest injury criterion which uses deflections of all ribs and the prediction of the number of fractured ribs is improved.

The THOR dummy has been used in some studies mentioned above on the chest restraint methods, but there is no comparison of several chest injury criteria for the THOR dummy in a chest restraint configuration that could reduce the chest injury. In this study, a novel occupant restraint concept was devised that could reduce the chest injury based on the mechanism of rib fractures, and its effectiveness was verified by comparing the number of rib fractures of the elderly HBM and several chest injury criteria for the THOR dummy under frontal crash conditions.

METHODS

Occupant FE Models

In this study an elderly occupant full body FE model (Figure 1 (a)) was used which is capable of predicting rib fracture has been developed by Ito et al.[27] [4] and Dokko et al.[28] [29]. The model was designed from the results of the average anthropometric measurement of American Male 50th percentile elderly human subjects. The age of the elderly occupant FE model is defined as 75 years old. Rib fracture was represented by the elimination of the elements reaching the fracture strain. The viscera were simplified and simulated in three groups of solid elements: thoracic viscera (mainly consisting of the lung and the heart), upper abdominal viscera (mainly consisting of the liver and the stomach), and lower abdominal viscera (mainly simulating the intestines). The upper and lower abdominal viscera were defined as incompressible materials, and their density distribution was set to reproduce the center of gravity of the actual human trunk. The THOR-50th Metric Version 1.4.1 (Figure 1 (b)) developed by Humanetics Inc. was used for the THOR FE model [30]. In this study the measurement points of chest deflection at upper-left, upper-right, lower-left and lower right were respectively named as UL, UR, LL and LR. LS-DYNA (Version971 R6.1.2) was adopted as a FEM solver [31].



(a) Elderly occupant full body FE model (b) THOR-50th Metric Version 1.4.1

Figure 1. AM50 occupant FE model

As shown in Figure 2, in a full vehicle FE model, the elderly HBM and the THOR model were seated in the driver seat of a left-hand midsize sedan vehicle. As the baseline model, the vehicle model was equipped with a 3P-belt that had a force limiter, an anchor pretensioner, a retractor pretensioner, a knee airbag, and a side curtain airbag. The six-axis vehicle crash motions from the full frontal rigid barrier (FR56K) and the oblique moving deformable barrier (OMDB) tests [32] were applied. The body deformation of the vehicle was not simulated.

(a) Elderly HBM (b) THOR model

Figure 2. Occupant and Full vehicle FE model

The elderly HBM and the THOR model were both seated according to THOR seating procedure [32]. Figure 3 shows the postures of the elderly HBM and the THOR model.

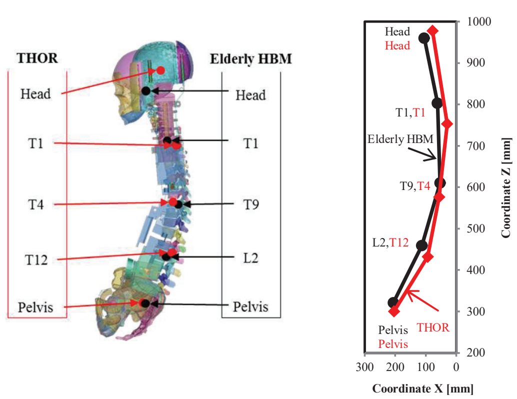


Figure 3. Posture of the elderly HBM and THOR models

Devised restraint system

Figure 4 shows the devised restraint system to reduce the chest injury. A pair of parallel shoulder belts, a membrane around the abdomen, and a 2P lap belt with an anchor pretensioner were equipped. The shoulder belts aim to disperse the restraint force applied to the occupant thorax, by restraining both sides of the occupant shoulder. Four ends of both shoulder belts were attached to the retractors with pretensioners and force limiters, and these retractors were attached to the frame of the seat back. These parts of this restraint system were named as Twin Array Shoulder restraint KIt (TASKI), which in Japanese stands for a “cord used to tuck up the sleeves of a kimono”. The aim of the membrane is reducing the protrusion of the internal organ during a frontal crash, named as Harness ARound Abdomen to Minimize Abdominal Kinetic Impact (HARAMAKI), which in Japanese stands for a “belly band”. The whole restraint system illustrated in Figure 4 was named as TASKI+HARAMAKI. To make comparison with the baseline model, TASKI+HARAMAKI was implemented by replacing with the 3P-belt system, on both the elderly HBM and the THOR model, and in both FR56K and OMDB conditions.

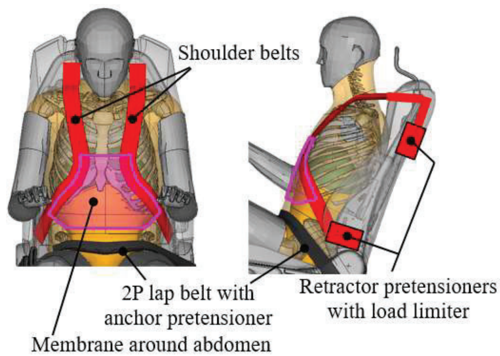


Figure 4. Schematic of the devised restraint system

Chest injury criteria for THOR dummy
In this study, Rmax, PC Score, TIC_NFR and TIC_NSFR were calculated from the results of the THOR model. Equations 1 to 4 respectively show the formulas of these chest injury criteria. Rmax is the maximum resultant deflection of the four measurements. PC Score was developed from a principal componet analysis (PCA) of a series of paird sled tests using PMHS and the THOR dummy. The formula of TIC_NFR and TIC_NSFR are consisted with a linear combination of the maximum of the four chest resultant deflections and the absolute value of the difference of the upper right and left deflections. TIC_NFR is the criterion of the number of all fractured ribs, and TIC_NSFR is that of the number of separated fractured ribs. Figure 5 shows the risk curves of AIS3+ and 65yo for these criteria. The risk curve for Rmax developed by Poplin et. al. [25] was chosen for this study.

$$R_{max} = \max\left(UL_{max}, UR_{max}, LL_{max}, LR_{max}\right)$$

where $$\left[\frac{U}{L}\middle|\frac{R}{L}\right]_{max} = \max\left(\sqrt{\left[\frac{L}{R}\right]X^2{}_{\left[\frac{U}{L}\right]S} + \left[\frac{L}{R}\right]Y^2{}_{\left[\frac{U}{L}\right]S} + \left[\frac{L}{R}\right]Z^2{}_{\left[\frac{U}{L}\right]S}}\right)$$ Equation (1)

$$PC\ Score = 0.486\left(\frac{up_{tot}}{17.439}\right) + 0.492\left(\frac{low_{tot}}{14.735}\right) + 0.496\left(\frac{up_{dif}}{9.672}\right) + 0.526\left(\frac{low_{dif}}{12.384}\right)$$

where
$up_{tot} = |UL|_{max} + |UR|_{max}$
$up_{dif} = |UL - UR|_{max}$
$low_{tot} = |LL|_{max} + |LR|_{max}$
$low_{dif} = |LL - LR|_{max}$ Equation (2)

$$TIC\_NFR = R_{max} + 1.66\ up_{dif}$$ Equation (3)

$$TIC\_NSFR = R_{max} + 3\ up_{dif}$$ Equation (4)

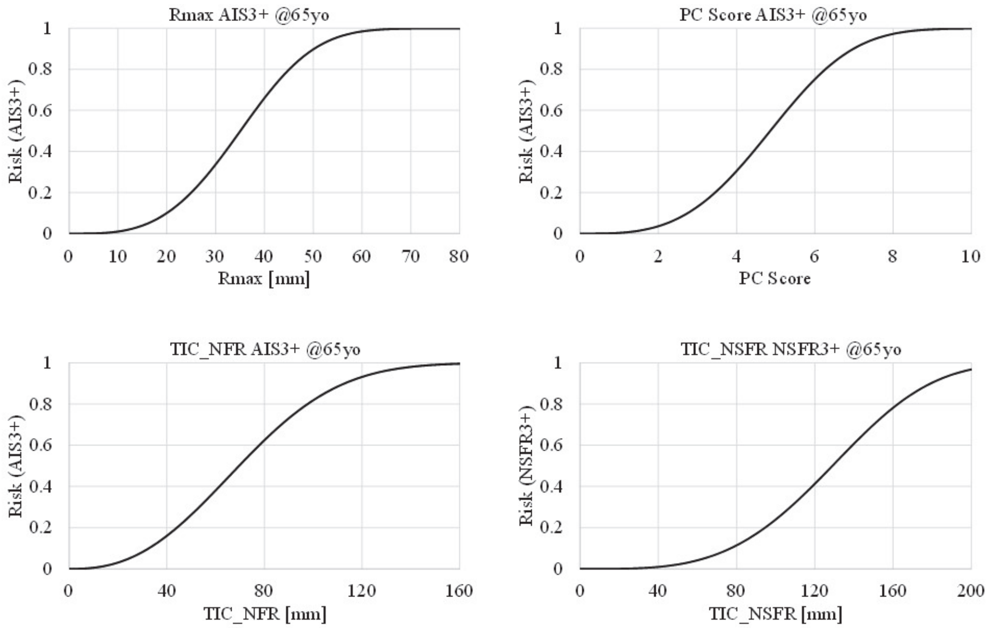


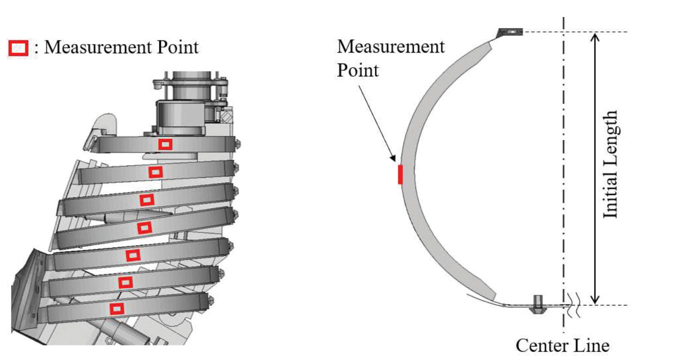
Figure 5. The risk curves of AIS3+ and 65yo of Rmax, PC Score, TIC_NFR and TIC_NSFR

Other candidates as chest injury predictor

In this study, additional two types of physical quantities were calculated as candidates of chest injury predictor. Both of them used physical quantities of all ribs, because it is considered that if fracture to each of all ribs can be taken into consideration, the number of fractures seems to be predicted more accurately.

One of them is a set of maximum rib strains of all ribs. In the case of a single rib on one side, a rib strain exceeding a certain value for the THOR dummy is considered to indicate the occurrence of a rib fracture in the human body. This concept was proposed by Davidsson et al. [33] [34]. Figure 6 shows the locations where the rib strains were measured. If a single rib of the THOR dummy is considered as a curved beam, the point of maximum bending moment is most likely to occur at the center of the curved beam. Therefore, the tensile strain along the longitudal direction at the outermost left and right sides of each rib were calculated from the THOR dummy model.

Another one is a set of normalized rib deflections of all ribs. Equation 5 shows the formula of the normalized rib deflection. The deflection of the THOR dummy is divided by the initial length of the rib, because the magnitude of the rib deflection of the THOR dummy contributing to the rib fractures in the human body is considered to depend on each size of the THOR ribs.



(a) Left View (b) Planner View of Rib #3

Figure 6. Measurement locations of rib strains on THOR dummy

$$\text{normalized rib deflection} = \frac{d_i}{L_i} \quad \text{Equation (5)}$$

where di = deflection of each rib
Li = rib initial length

Procedure for evaluating the effectiveness of chest injury reduction

Table 1 shows the matrix of model conditions calculated in this study. Calculations were first performed using the elderly HBM with the 3P-belt and the devised restraint system under FR56k and OMDB conditions. From these results, the fracture locations and the number of fractured ribs were obtained. Secondly, calculations were conducted by replacing the elderly HBM with the THOR dummy model. From these results, Rmax, PC Score, TIC_NFR and TIC_NSFR were calculated, and obtained risks of AIS3+ at 65yo were compared with the number of fractured ribs of the elderly HBM. Then, the set of maximum rib strains of all ribs and that of normalized rib deflections of all ribs were graphed and compared with the fracture locations of the elderly HBM.

Table 1. Matrix of model conditions calculated in this study

Model #	Occupant Model	Crash Condition	Restraint System
1	elderly HBM	FR56K	3P-belt
2	elderly HBM	OMDB	3P-belt
3	elderly HBM	FR56K	devised restraint system
4	elderly HBM	OMDB	devised restraint system
5	THOR model	FR56K	3P-belt
6	THOR model	OMDB	3P-belt
7	THOR model	FR56K	devised restraint system
8	THOR model	OMDB	devised restraint system

RESULTS

Rib fracture locations and number of fractured ribs on elderly HBM

Figure 7 illustrates the locations of rib fracture of the elderly HBM in FR56K and OMDB conditions. Table 2 shows the number of fractured ribs in each model. With the 3P-belt, rib fractures were located around the path of the shoulder belt in FR56K. In OMDB, the number of fractured ribs increased to 16. It was observed that the upper torso of the elderly HBM contacted with the door lining as shown in Figure 8(a). With the devised restraint system, no rib fracture was observed either FR56K or OMDB condition. In OMDB condition, occupant's contact with the door lining was mitigated as shown in Figure 8(b). Figure 9 shows the deformed shapes of rib cage and viscera in FR56K condition, with fixed view on T10 vertebra. With the 3P-belt, forward movement of the internal organ was observed, which resulted in complex deformation of the ribcage. With the devised restraint system, forward movement of the internal organ was smaller than that of the 3P-belt, which resulted in less deformation of the ribcage, in combination with the effect of the dispersion of the restraint force on the chest.

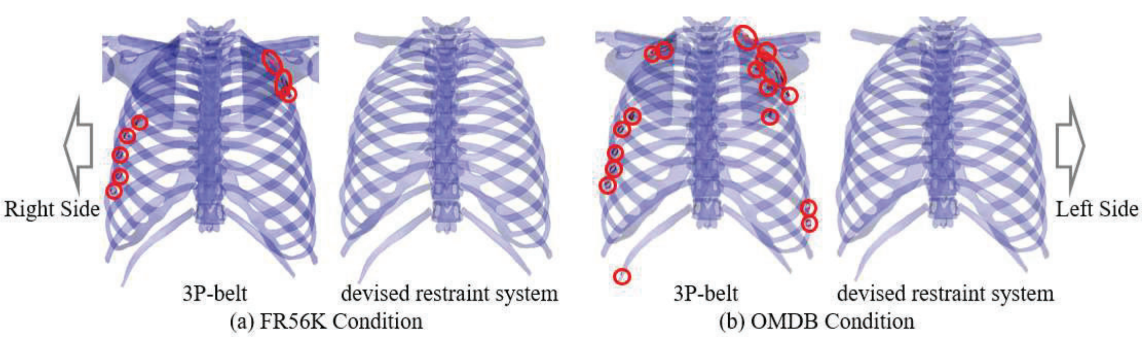
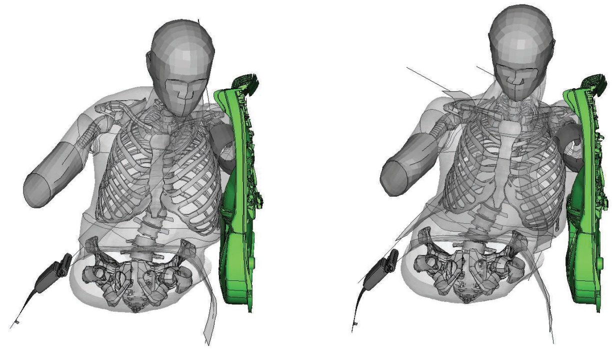


Figure 7. The locations of rib fracture of the elderly HBM in FR56K and OMDB conditions

Table 2. The number of fractured ribs of the elderly HBM in FR56K and OMDB conditions

	Number of Fractured Rib		
Model #	Left	Right	Total
1 (FR56K 3P-belt)	3	5	8
2 (OMDB 3P-belt)	8	8	16
3 (FR56K devised restraint system)	0	0	0
4 (OMDB devised restraint system)	0	0	0



(a) 3P-Belt (b) The devised restraint system

Figure 8. The deformed body shapes and the door lining from the viewpoint of the vehicle coordinate system in OMDB condition

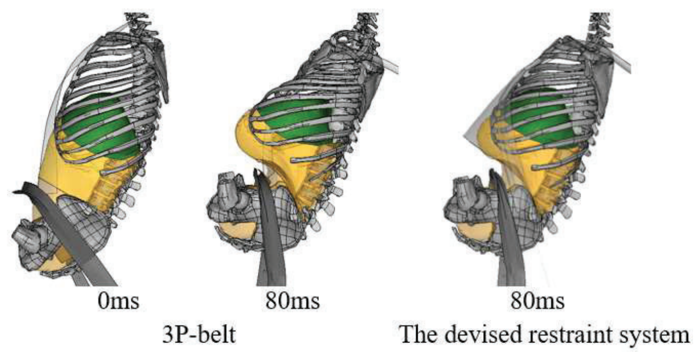


Figure 9. Left side view of deformation of rib cage and viscera (fixed view on T10 vertebra)

Chest injury criteria and risks of AIS3+ at 65yo on THOR dummy

Table 3 shows the maximum chest deflections of the four measurements on the THOR model. With the 3P-belt, the location of the highest chest deflection was obtained at UR in either FR56K or OMDB condition. With the devised restraint system, the value of the chest deflection at UR decreased in either FR56K or OMDB condition. But the deflection at LR in OMDB condition increased and became the highest of the four locations, in contrast with the result of the number of fractured ribs using the elderly HBM. Table 4 shows the chest injury criteria and the risks of AIS3+ at 65yo calculated from the results of the THOR model. For all chest injury criteria, the risks decreased between 3P-belt and the devised restraint system. But, in OMDB condition, the risks of Rmax and PC Score with the devised restraint system were greater than 50%, despite that the number of fractured ribs with the elderly HBM significantly decreased. The risks of TIC_NFR and TIC_NSFR with the devised restraint system were relatively low compared with those of Rmax and PC Score.

Table 3. The maximum chest deflections of four measurement on THOR model

Model #	UL	UR	LL	LR
5 (FR56K 3P-belt)	17.0	40.4	12.7	30.2
6 (OMDB 3P-belt)	28.8	52.2	22.8	36.4
7 (FR56K devised restraint system)	23.2	23.8	16.4	18.3
8 (OMDB devised restraint system)	25.6	33.6	30.4	42.5

Table 4. The chest injury criteria and the risks of AIS3+ at 65yo calculated from the results of THOR model

	Rmax		PC Score		TIC NFR		TIC NSFR	
Model #	Value	P(AIS3+)	Value	P(AIS3+)	Value	P(AIS3+)	Value	P(NSFR3+)
5 (FR56K 3P-belt)	40.4	67.3%	5.37	61.9%	80.8	63.4%	113.4	35.2%
6 (OMDB 3P-belt)	52.2	92.8%	7.15	91.8%	100.7	82.4%	139.9	60.7%
7 (FR56K devised restraint system)	23.8	17.2%	2.85	11.1%	29.9	8.1%	34.7	0.6%
8 (OMDB devised restraint system)	42.5	73.5%	5.10	55.8%	56.3	33.6%	67.4	6.3%

Results of other candidate as chest injury predictor

Figure 10 shows the graph of the maximum rib strains of all ribs. The vertical axis shows the rib number of the THOR dummy. The horisontal axis shows the maximum strain of each rib. For clarity, the horizontal axes on the right and left sides are reversed. In all conditions, the strain value of rib #1 of both side were higher than other ribs, and that of rib #3 and above had a tend to be higher than that of rib #4 and below.

With the 3P-belt, strain values on the right side are higher than that on the left side. Figure 11 shows the shoulder belt path of 3P-belt over the THOR dummy. The shoulder belt passes over the left rib #1 and right ribs from #2 to #7. So these ribs were pushed by the shoulder belt during crash, which resulted in relatively high strain values. The strain values of these ribs in OMDB condition are higher than that in FR55K condition.

With the devised restraint system, in both FR56K and OMDB condition, the strain values of the ribs where the shoulder belt passes over in the 3P-belt decreased, esecially with the right ribs from #4 to #7. The strain values of the left ribs from #3 to #7 increased, but remain around the same level as the opposite side.

Figure 12 shows the graph of normalized rib deflections of all ribs. These are graphed with the same manner as the maximum rib strains of all ribs. Overall, These graphs are simmiler to that of the maximum rib strains of all ribs. With the devised restraint system and in OMDB condition, however, the value of the normalized deflection of the right ribs from #5 to #7 increased, in contrast with the graph of the maximum rib strain of all ribs.

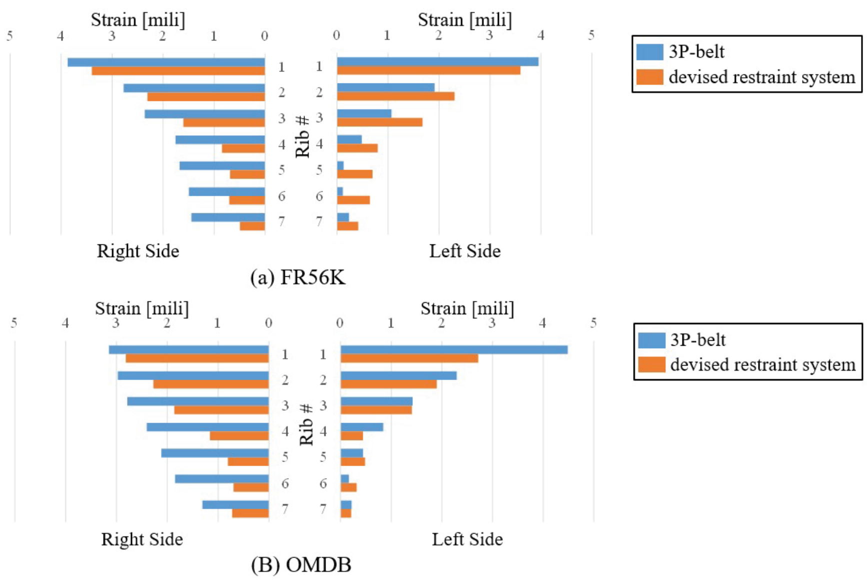


Figure 10. The graph of maximum rib strains of all ribs

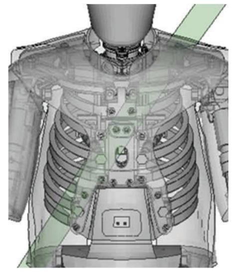


Figure 11. The shoulder belt path of 3P-belt over the THOR dummy

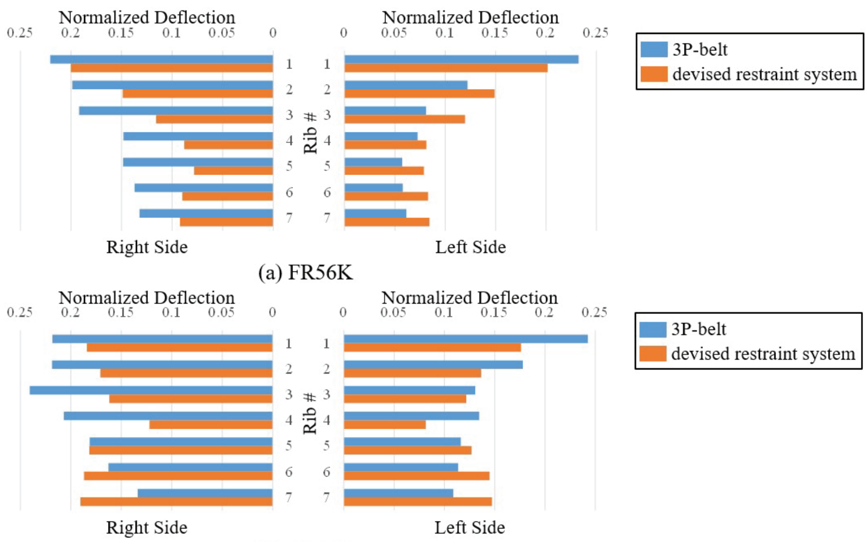


Figure 12. The graph of normalized rib deflections of all ribs

DISCUSSION

Chest deflection of lower rib on THOR dummy

With the devised restraint system, the deflection at LR in OMDB condition increased, in contrast with the result of the number of fractured ribs using the elderly HBM. Figure 13 shows the time histories of the resultant deflection and its components at LR in OMDB condition with the devised restraint system. The Z component has a positive peak which means downward. Figure 14 shows a comparison of the thorax shape of the elderly HBM and the THOR model, viewed from the right side. The lower part of the thorax of the THOR dummy protrudes forward compared to the elderly HBM. Therefore, it is thought that the protruding portion of THOR dummy is more easily pushed in by the belt than the elderly HBM. Figure 15 shows the right side view of the kinematics at 45ms and 90ms in OMDB condition with the devised restraint system. Between these times, the vehicle's floor moved downward, and the protruding portion of THOR dummy was pulled downward by the lower shoulder belts of the devised restraint system, which would cause the relatively large chest deflection with the THOR model. This tendency of the greater deflection of the lower ribs influences the results with higher risks for Rmax and PC Score in the OMDB condition. On the other hand, TIC_NFR and TIC_NSFR have lower risks. The reason for this may be that the equations of those are linear combinations of the Rmax and left-right differences in the upper deflection, and include a term that gives weight to the upper deflection value, which relatively reduces the influence of the lower rib value.

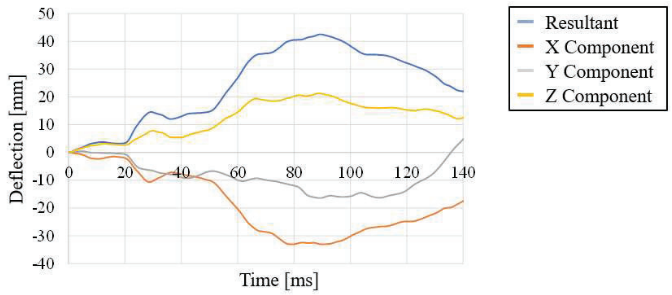


Figure 13. The time histories of the resultant deflection and its components at lower-right in OMDB condition with the devised restraint system.

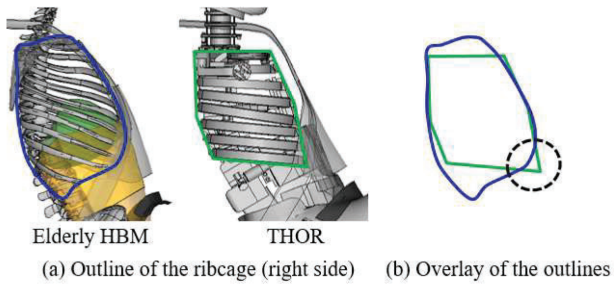


Figure 14. Illustration of a comparison of the thorax shapes of the elderly HBM and the THOR model (viewed from the right side)

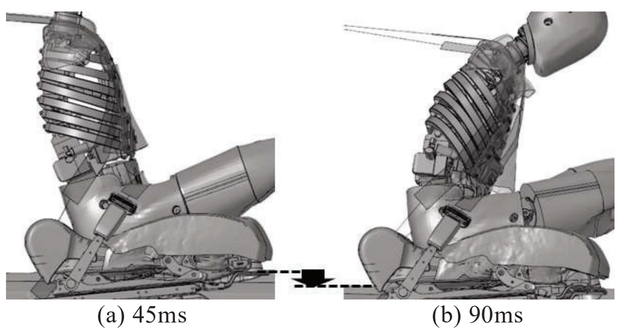


Figure 15. The right side view of the result animation in OMDB condition with the devised restraint system

Normalized cord deflections of all ribs

The graph of the maximum rib strain of all ribs seems to well represent the increase and decrease of the number of fractured ribs of the elderly HBM. On the other hand, the graph of the normalized rib deflections of all ribs has discrepancy with the number of fractured ribs of the elderly HBM with the devised restraint system and in OMDB condition. This is because of the tendency of greater deflection of the lower ribs of the THOR dummy mentioned above. Here, the structure of an actual human body around the connection between the rib and the thoracic vertebrae was considered. Figure 16 shows the schematic of costovertebral joint in a human body. This joint moves during respiration. The degree of freedom of this joint allow the anterior end of the ribs to move up and down to some extent. Therefore, the Z component of the chest deflection of the THOR dummy is expected to have little effect on the rib deformations and fractures in a human body. So, the deflection value used in that graph was exchanged from 3D deflection to cord deflection, for the purpose of reducing the influence of the Z component of the rib deflection. Figure 17 shows the illustration of the cord deflection of the THOR dummy. The cord length was measured by the distance between the anterior and posterior holes of the rib on one side. Then, the cord deflection was calculated as the change in the cord length. Figure 18 shows the graph of the normalized cord deflections of all ribs. In this graph, the maximum cord deflection was divided by the initial value of the cord length. Overall, this graph is similar to the graph of the maximum rib strain of all ribs, and with the devised restraint system and in OMDB condition, the value of the right ribs from #5 to #7 decreased, which seems to well represent the result of the elderly HBM.

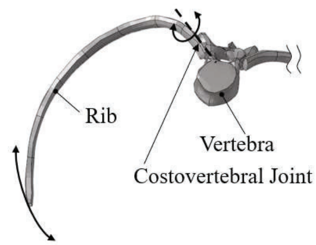


Figure 16. The schematic of costovertebral joint in the human body

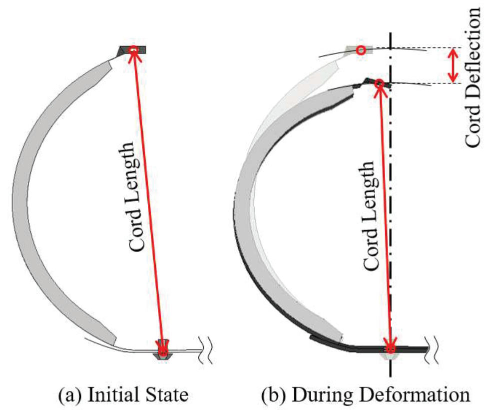


Figure 17. The illustration of the cord deflection of the THOR dummy

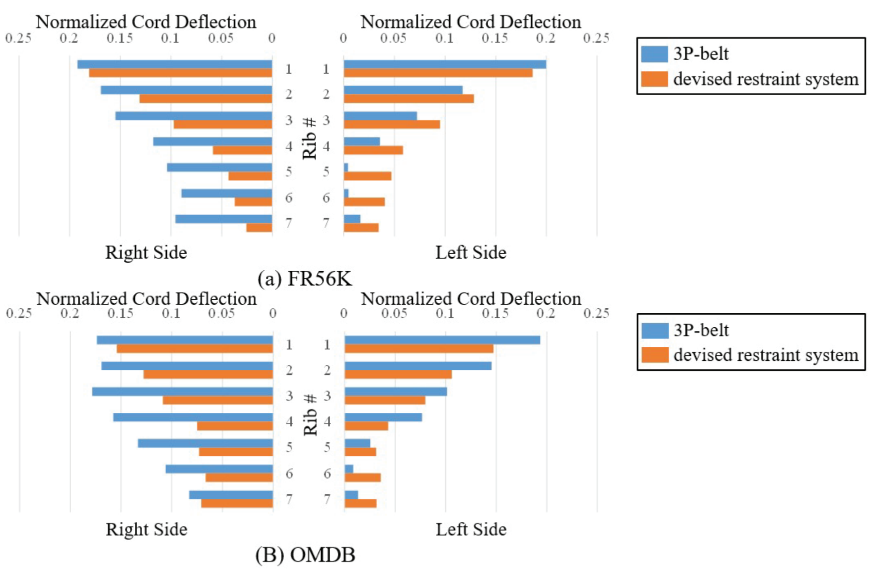


Figure 18. The graph of the normalized cord deflections of all ribs

CONCLUSION

In this study, a novel occupant restraint concept was devised that could reduce the chest injury based on the mechanism of rib fractures in FR56K and OMDB conditions, and its effectiveness was verified by comparing the number of rib fractures of the elderly HBM and several chest injury criteria for the THOR dummy. Additionally, some candidates as the chest injury predictor using all ribs of the THOR dummy were graphed and compared with the fracture locations of the elderly HBM.

As the results, the following conclusions were obtained.

・By implementing the devised restraint system, the number of fractured rib was significantly decreased in the elderly HBM.

・In the THOR model, the risks of rib fracture predicted by all of the chest injury criteria calculated in this study decreased with the devised restraint system. However, the extent of the reduction varied widely among the chest injury criteria, especially in OMDB condition.

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Estimation of injury risk of different child restraint systems in realistic frontal impact tests for future mobility applications

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Abstract

Motorized vehicle crashes represent the highest injury risk for children. Furthermore, new devices and new transportation applications potentially bring new challenges and injury risks. Therefore, the main objective of this work is to analyze the safety performance of seat belt alone, booster seat and belt guide only devices in frontal impact tests under regulatory and realistic conditions. We analyzed the kinematics of the dummy, calculated the injury risks and compared it with the meta-analysis of past published crash analysis complemented with the most recent accident data retrieved from the EU CARE database. We calculated the risk attributable to the studied restraint solutions and test conditions.
Test on belt guide only devices show that they are statistically equivalent to seat belt alone solutions. Therefore, replacing an appropriate booster seat with belt guide only devices potentially increase the number of injured children by 33% (95 confidence interval:16%, 50%).
Finally, we performed gap analysis to improve the fitness-for-purpose of regulations for future mobility applications.

Keywords: child restraint system, passive and active safety, motorized vehicle crash, vulnerable users, crash statistics

1. Introduction

The use of child restraint systems (CRS) is mandatory in all Member States of the European Union (Directive 91/671/EEC) for children less than 150 cm tall. The technical criteria of CRSs are regulated by UNECE Regulation 44 which was replaced by UNECE Regulation 129.
In spite of the widespread use of CRS, road fatalities are a leading cause of death of children (defined as 14 years old or younger persons) both in the EU (EU Observatory, 2018a) and in the US (NHTSA, 2019). In the EU 50% (Dovile Adminaite *et al.*, 2018) and in the US 74% (NHTSA, 2019) of all dead children in road crashes were car occupants.

According to the European Road Safety Observatory (EU Observatory, 2017, 2018b) child fatality in motorized vehicle crashes (MVC) decreased from 1,888 to 615 between 2007 and 2016, but leveled off around 500 fatalities in the recent years. In the US the decline of child fatality (NHTSA, 2019) is smaller compared to EU data and it has flattened in the recent years too. Since MVCs are a consistent part of overall child fatalities, the effectiveness of CRS has a major influence on the reduction of injured and dead children.

New devices, such as belt guide only have been provided on the market as a cheaper/lighter alternative to child seats. However; testing procedures and regulations were not developed for such devices and are not always sensitive enough to determine their safety performance. Previous findings showed that Q-series dummies are less sensitive in regulatory tests (Visvikis, Thurn and

Müller, 2020) on the abdominal region when the dummy is placed on the test bench without a CRS and even the adult seat belt can pass the regulatory limits of UN ECE R129. We investigated the effectiveness and estimated the efficacy of belt guide only solutions in real car seat, as it is prescribed in UN ECE R129 comparing its safety performance with a booster seat.

The efficacy of different CRSs can be estimated from accident data by comparing the odds ratio (OR) of injury and fatality between CRS and no restraint use. However, accident databases can be used if an intervention or protection device is widespread enough to have measurable statistical significance. Alternatively, safety performance of new devices can be estimated by establishing causal relationships between the kinetics of a simulated crash and injury severity. However, this latter method is not able to assess the change of injured children attributable to the device. Therefore, in this work we combined accident statistics with injury assessment of simulated crash data applying machine learning techniques to calculate the potential risk of belt guide only devices on the population of 8-12 years old children in frontal impact MVC.

1.1. *Efficacy of child restraint systems*

Elvik et al. (Elvik *et al.*, 2009) applied meta-analysis of 19 accident studies originated from 1977 to 2006 and concluded that any restraint, including the car seat belt alone, reduces injuries; however, CRS had beneficial advantage over the (adult) seat belt alone for kids between 0-9 years old. A proper CRS can reduce the number of injuries by 33% more than the car's seat belt alone.

The correlation between age and CRS types was studied in a NHTSA technical report(Robert Sivinski, 2010) by analyzing crash data between 1998 and 2008. It was found that the injury reduction for 4 to 8-year-old kids in CRS was 14% (95% CI 10-19%) compared to seat belt alone. Furthermore, the analysis suggested that for 3 to 4-year-old kids, the booster seat, which is not designed for this age, may have caused more injuries than the child safety seat. For older kids, Anderson(Anderson, Carlson and Rees, 2017a) analyzed Washington state data of 8 to 12-year-old kids and found 29% reduction in the odds of experiencing any injury in a booster seat than with the seat belt alone (OR=0.709, 95% CI=0.675, 0.745). The adjusted estimation resulted in 19% (OR=0.814, 95% CI=0.749, 0.884) reduction of the odds of injury. Children in side impact crashes benefitted the most from booster seats showing an 82% and 62% reduction in injury risk for far side and near side, respectively, compared to seat belt alone (Arbogast, Jermakian and Ghati, 2009).

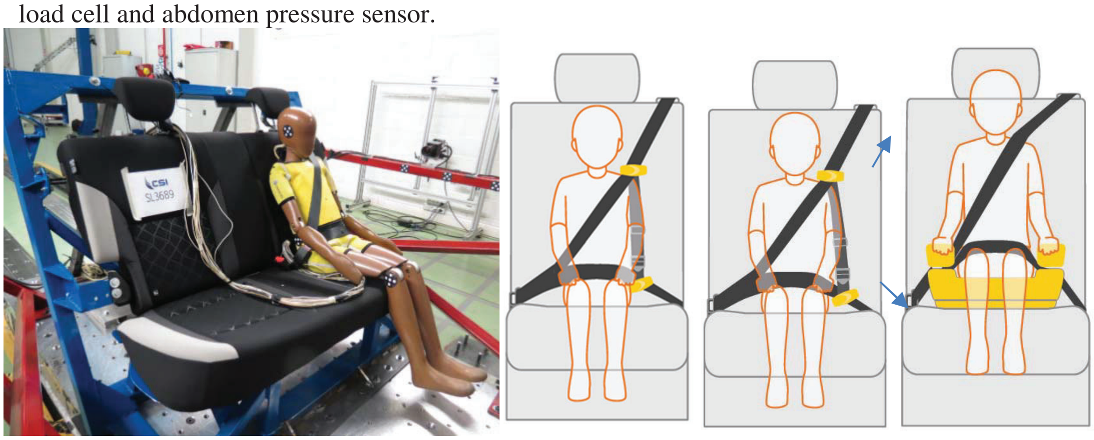
On the contrary, Ma et al. (Ma *et al.*, 2013) reported that 0 to 10-year-old children using booster seats experienced equal risk of injury but higher risk of neck and thorax injury than children restrained by seat belt only. Despite kids up to 10 years were added to the analysis, 0-4 years were also included in the data, hence the average age was 4.7 years. A previous NHTSA study (Robert Sivinski, 2010) found that booster seat for smaller kids (<4 years) is not safe and they should be restrained in child safety seat rather than in a booster seat only, therefore the analysis of Ma et al.(Ma *et al.*, 2013) measured most probably the effect of misused booster seats for smaller kids.

Obviously, any restraint, which prevents child occupants from free flying and from hitting the interior of a vehicle, provides protection from many injuries. However, the restraint itself can cause injuries if it is not properly designed for the occupant. The "seat belt syndrome" described by Garrett and Braunstein (Garrett and Braunstein, 1962) in 1962 identified a distinctive pattern of injuries associated with the lap belt. The immaturity of the pelvic structure of kids to properly anchor the lap belt combined with the tendency to scoot forward so that their knees bend at the edge of the seat create a constellation in which the lap belt directly compresses the abdominal organs against the spinal column. Furthermore, the child's body may "jack-knife" around the belt (Durbin *et al.*, 2011), putting high tension force on the lumbar spine increasing the risk of distraction injuries of the posterior elements of the spine. A lap belt that starts out too high can lead to a kinematic pattern known as submarining, in which the pelvis slides down under the belt and the

body is restrained through abdominal soft tissue, rather than through loads applied to the bony pelvis (Reed *et al.*, 2009).
Arbogast et. al (Arbogast, Jermakian and Ghati, 2009) studied the occurrence of injuries by body regions between seat belt alone and booster seat users. Head injuries represented ~65% of injuries and showed the same prevalence for both groups. For booster seat users, face and lower extremity injuries were the next most common at 9% and 8%, respectively, while children in seat belt alone sustained injuries to the abdomen and face at 12% and 9%, respectively.

2. Assessment methodology

We tested three restraint devices: 1) a universal category booster seat, 2) a seat belt alone, and 3) a belt guide only device in two installation configurations as Figure 1 depicts. All devices were type approved according to the respective UN ECE regulations. We performed frontal impact tests in real a car seat (vehicle body shell) with a Q10 dummy (equivalent of a 12 year-old child) according to the UN ECE Regulation 129. We installed the dummy in its rear seat with its seat belt system buckled according to the installation instructions of each type of device tested as it is seen in Figure 1. Because the instruction was not fully clear for the belt guide device, we tested two different webbing positions (Figure 1b and c). The Q10 dummy was equipped with head, thorax and pelvis accelerometers, lower and upper neck tension load cell, rib deflection sensor, lower lumbar spine load cell and abdomen pressure sensor.



a) b) c) d)

Figure 1 Picture of the equipment used: the reproduced steel frame of Nissan Micra 5th Generation with Q10 manikin a). Schematics of the tested belt guide only configuration #1 b), belt guide configuration#2 c) and booster seat d). Arrows in inset c) show the differences from the configuration in inset b).

3. Results

We measured 48 different parameters during frontal impact tests. We recorded the tests with five high-speed, high-resolution cameras (1000 fps), which measured the displacement of the manikin's head and knee in the vertical and horizontal directions and analyzed potential submarining. Then we used the injury limits of UN ECE R129 or estimated limits from literature data to assess the risk of the different restraint devices.

We compared the kinematics acquired from all tests by using machine learning techniques such as principle component and cluster analysis, to classify the behavior of the dummy under different conditions and in different devices.

Finally, we calculated the risk ratios (RR) from previous studies by using meta-analysis of published motorized vehicle crash studies. Since these data were sometime more than 10 years old, we complemented the analysis with uncorrected accident data involving children and where the use of child restraint system has been recorded in the EU CARE and NHTSA databases in the last 5 years.

3.1. *Frontal impact tests*

Figure 2a shows that the behavior of head acceleration for both installations of the belt guide only (BGO) device and the seat belt alone (SBA) have a very similar pattern. The resultant head acceleration of belt guide only and seat belt alone show ca. two times higher head acceleration than a booster seat (BS) at around 100 ms, i.e. at the time of the maximum horizontal head excursion. The maximum of head acceleration for BGO and seat belt alone is above the head acceleration threshold of 80 g. Another sharp peak appears at ca. 220 ms for BGO and seat belt alone when the dummy bounces back and the head hits the back of the seat. In Table 1 the head performance criterion (HPC as it is defined in R129) is also calculated which indicates a significantly higher values for BGO and SBA than for booster seat, although all values remain below the injury threshold (800) .

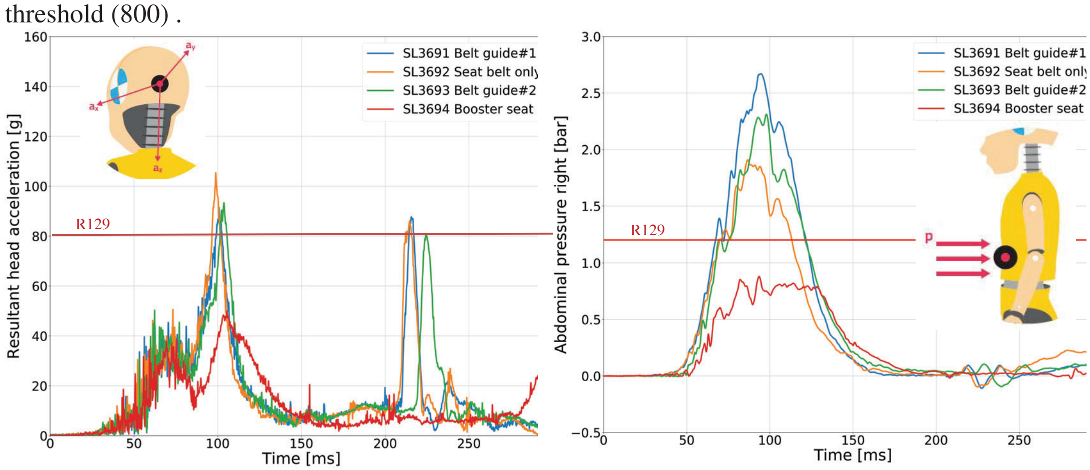


Figure 2. Resultant head acceleration a) and abdominal pressure on the right side b). The inset of the dummy shows positive directions of the acceleration in each direction.

Figure 2b shows that the abdominal pressure is much higher than the threshold of 1.2 bar in the case of belt guide only with both configurations and in the case of seat belt alone. The high abdominal pressure together with the visual observation (not shown here) that the lap belt fully passes the pelvic structure, is a strong indication of excessive stresses on the weak parts of the child's abdomen that could lead to serious injuries (Johannsen and Schindler, 2007; Beillas *et al.*, 2012; Lesire, 2012). For the BS the pressure is never higher than 0.88 bar, consequently below the threshold of R129.

Table 1 Injury thresholds and measured values of each dynamic test. Limit values with * are from R129 paragraph 6.6.4.3. others are estimation from literature.

	Limit AIS≥3	Belt guide #1		Belt guide #2		Seat belt alone		Booster Seat	
		SL3687	SL3691	SL3690	SL3693	SL3689	SL3692	SL3688	SL3694
Head performance	800*	545.65	558.96	669.38	570.73	667.72	668.46	271.57	180.58

criterion									
Head acceleration 3 ms [g]	80*	86.32	85.48	100.67	85.22	96.36	91.37	57.35	47.24
Upper neck tension force F_z [kN] (max)	3.7 (2.8-4.6)	5.85	5.65	6.09	6.00	6.52	6.30	3.89	2.69
Upper neck flexion moment [Nm] (max)	135 (113-156)	13.78	12.44	12.89	10.11	14.9	3.17	5.86	6.19
Chest acceleration [g]	55*	45.30	46.58	46.66	45.26	47.42	44.23	42.16	39.43
Abdominal pressure [bar] Left/Right	1.2*	2.40 2.09	2.92 2.67	2.45 2.06	3.09 2.31	1.82 1.73	2.59 1.91	0.38 0.39	0.28 0.88

Table 1 summarizes the absolute values of the relevant injury limits and measured values. The BS values are lower than the thresholds for all parameters; however, for BGO and the SBA tests, the abdominal pressure and the head acceleration exceed the threshold by 250% and 25%, respectively. The red values in Table 1 indicate that the respective injury threshold is exceeded. Orange values are higher than the reference booster seat case and indicate the possibility of serious injuries despite no threshold has been defined in R129 paragraph 6.6.4.3.1.

Furthermore, we extracted 96 features from the times series of the measured values to compare the overall behavior of the different devices. Then we applied principal components analysis and we performed K-means clustering with 2, 3, 4 centroids using Wide method with covariance (using JMP statistical software, USA). The 2-centroid case yielded the optimal cluster numbers that is shown in Figure 3c. The density plot clearly shows that both configurations of the belt guide only and seat belt alone devices are in the same cluster while the booster seat is in another one. Injury assessment, ANOVA and principal component analysis unequivocally indicate that belt guides (regardless of the installation) behave similarly to seat belt alone, but differently from booster seat.

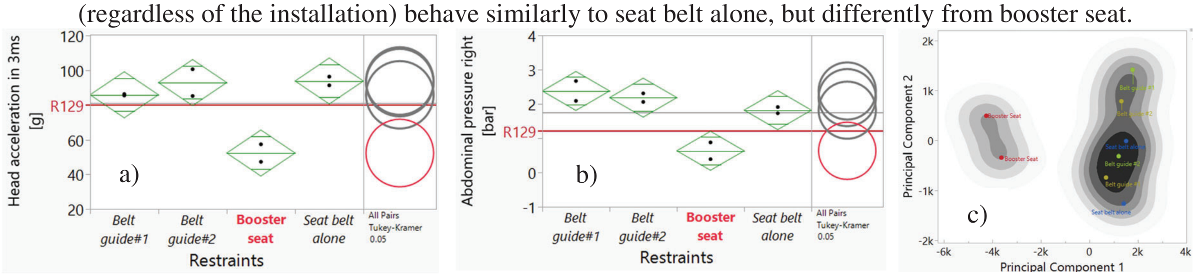


Figure 3 ANOVA analysis of resultant head acceleration a) and abdominal pressure b). Principal components analysis of all features c).

3.2. *Population attributable risk of belt guide only solutions*

Beside the already published relative injury risk ratio (RR) and odds ratio (OR) in literature, we supplement the data calculated from the latest available data sources from 2015 to 2018. We aggregate accident data of EU (CARE) and the USA (NHTSA, 2019) related to children and then we calculate the population attributable risk (PAR) of belt guide alone (PAR_{BGO}) in the following way:

- Unadjusted risks of injured, killed and seriously injured children are estimated from the number of injuries, fatality and serious injury of children, respectively, as a car occupant in different restraining solutions on children travelled km basis
- The exposure to different restraining solutions is estimated from CRS usage in the USA and EU member states from data of NHTSA (NHTSA, 2019) in 2017 and of ESRA (Nakamura *et al.*, 2020), European Transport Safety Council in 2018 (Dovile *et al.*, 2018), respectively. The EU exposure is averaged by weighing the use of restraints in each member states by children population data accessed from the OECD statistical portal, Historical Population Data (HPD) of ages between 5-14 years old and between 2015 and 2018 (Organization for Economic Co-operation and Development, 2021).
- In the EU, the number of injured, died or seriously injured children is aggregated between 2015-2018 for all EU countries and grouped by seat belt alone, CRS and no seat belt categories.
- The PAR_{BGO} is predicted from the RR and the use/penetration of belt guide alone among CRS for the investigated vehicles

Unadjusted injury risk ratio between CRS and seat belt alone is calculated by using the following formula:

$$RR_{CRS} = \frac{\frac{\#_{SBA}}{V_{km}KID_{vehilce}p_{Belt\ alone}}}{\frac{\#_{CRS}}{V_{km}KID_{vehilce}p_{CRS}}} = \frac{\#_{Belt}}{\#_{CRS}}\frac{p_{CRS}}{p_{SBA}} \qquad (1)$$

where $\#_{CRS}$ and $\#_{Belt\ alone}$ are the number of injured, died or seriously injured children when CRS or seat belt alone were used in the reported crash, respectively. V_{km} is the total driven km by all vehicle in a region/country in a year [km], $KID_{vehicle}$ is the average number of kids in a vehicle, and p_{SBA} and p_{CRS} are the EU weighted average of usage of CRS [%] and seat belt alone [%] respectively in the same period.

Despite vehicle km and the average number of kids per vehicle can be calculated from other sources (e.g. IRTAD by OECD), the risk ratio RR_{SBA} does not necessitate the knowledge of these parameters assuming that V_{km} and $KID_{vehicle}$ are independent from the usage of any restraint.

Unadjusted injury risk ratio between CRS and no restraint is calculated in the similar way

$$RR_{No\ restrain} = \frac{\#_{No\ restrain}}{\#_{CRS}}\frac{p_{CRS}}{p_{No\ restrain}} \qquad (2)$$

The different restraint use ratios are calculated from ESRA (Nakamura *et al.*, 2020) as follows

$$p_{CRS} = (1 - ESRA_{no\ restain}) * (1 - ESRA_{CRS})$$
$$p_{SBA} = (1 - ESRA_{no\ restrain}) * (ESRA_{CRS})$$
$$p_{no\ restrain} = ESRA_{no\ \ restrain} \qquad (3)$$

where $ESRA_{no\ restrain}$ is the perceived social normative of transport of children in the car without securing them and $ESRA_{CRS}$ is transport of children (under 150cm) without using child restraint systems.

The US fatality data and restraint use were accessed from NHTSA Traffic Facts (NHTSA, 2019). The numbers were aggregated for all types of CRS i.e. rear-forward facing, booster and high back booster seat data into “CRS used” category. “Seat belt” and “no restrain” were used as they are.

The EU accident data was accessed from CARE database on 15/03/2021, which contains the number of injured (killed and injured), died and seriously injured children between 5-12 years old from 29 EU member states from 2015 to 2018 as a function of different safety solutions. First, the data summarized for all EU member states, then aggregated to categories “CRS used” (backward, forward, not specified), “Belt used” (seat belt worn and air bag released, seat belt worn no airbag released, seat belt worn) and “No restraint” (no use of safety equipment) categories. The category “Belt alone” is calculated as the difference between “CRS used” and “Belt used”, since when CRS is used belt should be used as well. The unspecified cases and incomplete data were omitted from the analysis.

The population attributable risk quantifies the increase of injuries in a population taking into account the exposure to the scenario. We calculate PAR in accordance to the WHO (Chisholm and Naci, 2008) methodology by using the Levin's formula:

$$PAR_{BGO} = \frac{p_{BGO}(RR_{SBA}-1)}{p_{BGO}(RR_{SBA}-1)+1} \qquad (4)$$

where p_{BGO} is the use ratio of the belt guide alone among other CRS, i.e. exposure to belt guide alone in the population. Figure 4 shows the calculated PAR from the different data sources. As it is expected from *RR*>1 relationship, PAR_{BGO} is positive, therefore the use of the device potentially increases the number of injury and death. The current unadjusted estimation is in line with the latest study about booster seats in the age group 8-12 by Anderson et. al (Anderson, Carlson and Rees, 2017b) as Figure 4 shows the that lines of unadjusted data are in close proximity with the EU data. Therefore, these data do not show significant changes in the efficacy between historical and recent data.

Table 2 Calculation of unadjusted relative risks for different age groups and regions in 2018 for US in the period 2015-2018 for EU, with the corresponding 95% CI. RR and CI are calculated by a Python script

Number incidents	*CRS used*	*Belt alone*	*NO restrain*	*All*
USA 8-12 year-old				
Fatality	9	96	89	194
CRS usage (2017) (p)	12%	75%	14%	100%
Relative risk (RR)	Ref	1.70 (0.8-3.8)	8.72 (4.3-19.1)	
USA 4-7 year-old				
Fatality	72	43	55	170
CRS usage (2017)	69%	21%	11%	100%
Relative risk	Ref	1.97 (1.3-2.9)	4.94 (3.3-6.9)	
EU 5-12 year-old				
Accidental injury	7050	1610	695	9355
Weighted CRS usage	83%	13%	3%	100%
Relative risk	Ref	1.40 (1.3-1.5)	2.5 (2.3-2.7)	
EU 5-12 year-old				
Serious injury	379	637	132	1148
Weighted CRS usage	83%	13%	3%	100%
Relative risk	Ref	10.8 (9.5-12.2)	8.5 (7.0-10.4)	
EU 5-12 year-old				
Fatality	33	32	17	82
Weighted CRS usage	83%	13%	3%	100%
Relative risk	Ref	5.8 (3.6-9.1)	16.3 (9.3-27.6)	

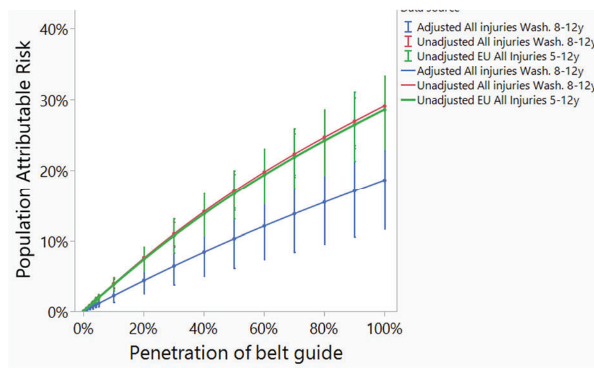


Figure 4 Estimated attributable risk of using belt guide only instead of a CRS (booster seat) for older children. The error bar shows the 95% CI calculated from the 95% CI of the risk or the odds ratios (RR and OR). The respective ORs (Adjusted/Unadjusted All injuries Wash. 8-12y) are taken from Anderson et. al(Anderson, Carlson and Rees, 2017b).

4. Conclusions

Previous findings showed that Q-series dummies are less sensitive in regulatory tests on the abdominal region; however, we showed that this does not hold for real conditions. By performing frontal impact tests in realistic conditions, we showed that booster seats provide the highest level of safety for children in motorized vehicle crashes. The belt guide only device investigated exceeded the abdominal injury and the resultant head acceleration threshold by 250% and 25%, respectively.

Therefore, new types of child restraint systems, which may provide more flexibility, need to be investigated in more detail not just under regulatory criteria but also under real conditions. This lack of sensitivity of regulatory tests potentially increases the risk that unsafe CRSs are able to enter the market. Therefore, new regulatory research is suggested to assess whether alternative child restraint systems provide enough protection in future mobility applications where the seating and hence child restraint devices can have higher variability.

For comprehensive study, tests on the Q3 and Q6 dummy, with other car seats, seating positions (e.g. according to UMTRI), different pulse combinations will be necessary to improve the assessment of submarining effects. Finally, the comparison of the behavior of the dummy in real car crash with regulatory test bench results is desirable to develop fit-for-purpose regulations suitable for new transport systems to guarantee protection under non-fixed testing conditions.

Acknowledgements

The authors gratefully acknowledge the support of the colleagues at the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) of the European Commission. The helpful comments and the contributions of the colleagues of the Sustainable Transport Unit at the Directorate-General, Joint Research Centre (JRC) are also highly appreciated.

The contribution of JRC Knowledge Management for Energy Union Unit to design and creation of infographics are highly appreciated.

We thank to Directorate-General for Mobility and Transport (DG MOVE) for the supply of accident data from CARE database.

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MAPPING THE PATH FORWARD TOWARD EQUITY IN CRASH SAFETY: RECOMMENDATIONS FROM AN EXPERT WORKSHOP

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Paper Number: 23-0285

ABSTRACT

Crash testing historically has focused on the use of midsize male anthropomorphic test devices (ATDs). These tools and, more recently, ATDs representing a small female have been used to drive improvements for a diverse population with many differences that can affect injury risk. However, there are still gaps in protection for some population groups that may require different strategies to optimize their protection. To address this, 23 experts from industry, academia, and government convened in October 2022 for a 2-day workshop to reflect on opportunities and challenges in protecting both male and female occupants of different ages and sizes. Workshop participants included experts in biomechanics, behavioral science, human factors, communications, and policy. The discussion focused on how current tools and resources can be used to better protect a range of occupants and what future tools and data are needed to improve safety evaluations and incentivize robustness across the occupant protection design space. This paper reports on the workshop discussion and recommendations along the following key themes: the need to understand the current state of occupant protection to identify priority populations; the need for fundamental data on the populations of interest to improve ATDs and computational tools; computational modeling and human body models as critical tools for studying injury causation and evaluating countermeasures; currently available tools and strategies that can benefit a diverse population; and the importance of collaboration. The recommendations provide several paths to improve safety today and work toward improved protection in the future for a broader range of occupants with diverse needs.

INTRODUCTION

Crash testing historically has focused on the use of midsize male anthropomorphic test devices (ATDs) based on 50th percentile values for stature and body weight for U.S. men in the 1970s. These tools and, more recently, small female ATDs based on 5th percentile stature and body weight for U.S. women, have been used to drive improvements for a diverse population with many differences that can affect injury risk, such as age, sex, and size.

Improvements in vehicle crashworthiness ratings have been shown to have benefits for occupants in real-world crashes. Drivers in vehicles with a good-rating in the Insurance Institute for Highway Safety (IIHS) moderate overlap frontal crash test have a 46 percent lower fatality rate in frontal crashes than drivers in poor-rated vehicles [1]. A study by Teoh and Lund also found drivers in vehicles with a good side crash test rating were 70% less likely to die in a near-side crash compared with a driver of a vehicle rated poor [2]. Occupants in vehicles with a 5-star rating from the European New Car Assessment Programme have a 34% and 40% lower risk of serious injuries and fatalities, respectively, than occupants in 2-star-rated vehicles [3]. An analysis of head-on collisions of vehicles of similar weight from 1979-91 found fatality risk was 20%–25% lower for belted drivers of vehicles with good U.S. New Car Assessment Program composite scores than those in vehicles with poor scores [4]. Regulatory and consumer information crashworthiness evaluation programs have been important means of driving structural and restraint system improvements that have reduced injuries and saved lives.

Despite this progress, there is wide agreement that further improvements are possible. In recent years, there has been growing attention on equitable protection for all vehicle occupants, with a particular focus on narrowing the gap in protection for females relative to males. Studies garnering much of the attention have focused on the increased fatality risk [5] and injury risk [6] for females relative to males. A follow-up study by Noh et al. showed disparities in fatality risk between female and male front row occupants is lowest in the newest generation of vehicles (2.9%in 2015–2020 models) [7]. In 2021, Brumbelow and Jermakian showed that countermeasures have been effective at reducing risk for both males and females, with slightly greater reductions for females. Despite this, females still have a higher risk of moderate (2 on the Abbreviated Injury Scale [AIS]) lower extremity injuries [8].

Although most of the recent attention on inequity has focused on sex, other segments of the population could benefit from additional consideration during the vehicle design and evaluation process. This includes occupants of different sizes, shapes [9], ages [5], and seating positions [10,11]. In October 2022, a group of experts convened to discuss the current state of occupant protection and the necessary next steps to better protect all occupants. The purpose of this paper is to report on the group's findings.

PROCESS

Twenty-three experts from industry, academia, and government convened in October 2022 in Warrenton, Virginia, for a 2-day workshop to reflect on opportunities and challenges in protecting occupants of different ages, sizes, and sex. Workshop participants represented expertise in biomechanics, behavioral science, communications, and policy with experience in vehicle and restraint design, regulation, consumer information ratings programs, ATD development and evaluation, postmortem human subjects research, computational modeling, and behavioral research.

On the first day of the workshop, participants discussed individual perspectives on the theme *Achieving crash safety for all: how to protect our diverse population*. They shared their views on the current state of occupant protection and challenges and opportunities for improvements.

Based on the themes of Day 1, the following key scientific questions were developed and formed the basis for small group discussions on Day 2:

- Changes to regulation and consumer information programs aim to be rooted in real-world data. If we want to make relevant policy changes, what are the gaps in knowledge about real-world injuries and outcomes that will help us take the next leap forward in occupant protection? What are the most compelling research questions that need to be answered?

- We have made tremendous progress in protecting occupants with the tools we have available but there are still gaps in protection. How can we use the tools available today to optimize protection for a wider range of occupants? What tools hold the most promise for the future and what do we need to do today to make those tools viable?

- There is a need for additional human data on a wider range of subjects to improve our physical and computational tools. What are the priority populations for which we need these data? What types of data and how much more do we need? Are there opportunities to expand the avenues to get these data?

The discussion below reports on five key themes and recommendations of the workshop.

DISCUSSION

Theme No. 1: We need to understand the current state of occupant protection to identify priority populations.

Differences in injury risk to men and women have been the focus of many recent studies [6,8,12] and have captured the attention of policymakers and the media. A broader consideration of the literature suggests that while there have been large improvements in protecting all occupants [13,14], there are some populations that could benefit from more targeted occupant protection strategies [6]. To truly understand the significant sources of injury vulnerability requires looking beyond sex-related differences to also consider occupant age, stature, weight, body shape/weight distribution, body mass index (BMI), health comorbidities, posture, and different seating positions. Previous research has provided significant insight into some risk factors such as age [15,16,17], but less has been published about other risk factors such as posture. We need a more thorough understanding of the factors that make people more vulnerable in vehicles and adversely affect system performance, as well as the interdependence of these factors. This is required not only to design more effective countermeasures today, but also to plan for future needs as the population, vehicle fleet, and crashes change. For example, future designs should account for a population that is both older and has a higher BMI and for occupant compartments that allow different seating postures.

Recommendation: Focus research on injury risk differences due to occupant age, stature, weight, body shape/weight distribution, posture, and seating position in addition to sex.

Many studies aimed at identifying priority populations for improved protection continue to group vehicles across design generations. This can produce results that distract from opportunities with the greatest potential future impact. Analyses that include a wide range of model years do not account for the improved vehicle structures, energy management, and restraint systems that have resulted from the current suite of regulatory and consumer information tests [2,8,13]. Since only future vehicles can be improved, it is more informative to study outcomes in the most recent vehicles subject to current crashworthiness tests than to study outcomes in older vehicles that were produced under older, less rigorous safety norms. There are research questions that require grouping many years of data together to increase sample size or focusing on older models that remain on the road. However, needed improvements to regulatory or consumer information crash test programs will be identified most effectively by focusing on the modern vehicle fleet, thereby separating factors that have already been addressed from those that remain.

Recommendation: When analyzing crash data to identify occupant protection gaps, focus on issues that remain in the newest vehicles with the newest countermeasures.

Studies using real-world crash data are critical to developing relevant priorities but also have many limitations due to the nature of the data sources and study methods. Differences in injury risk among populations may present particular challenges, both for researchers and for those communicating the results of the research. For example, some occupants who are perceived as vulnerable may be more likely to have moderate or severe injuries coded than those who are perceived as less vulnerable. Some portions of the population may be more likely to refuse treatment for themselves or others. These types of data biases can influence the results in multiple ways, some of them more obvious, such as whether an occupant counts as injured in the data set, and others less so, such as how an individual crash is sampled and weighted. As another example, since crash injuries are rare compared with all crashes, small absolute differences between population groups may seem large when compared. Beyond data reliability, all analysis methods require assumptions and have strengths and weaknesses that affect the study outcomes. These challenges make it critical for authors to clearly convey study limitations to aid the reader in putting the study in perspective.

Recommendation: Recognize, consider, and clearly communicate limitations of data sources and methods as well as the potential effect on conclusions drawn by the audience.

Theme No. 2: We need fundamental data on the populations of interest to improve our ATDs and computational tools to effectively evaluate safety for diverse populations.

Data supporting our understanding of how crashes occur, which loading conditions produce different injury types, and human injury tolerance have guided significant progress in occupant protection for decades, but there are still knowledge gaps that need to be filled to enable further progress.

Increasing the number of cases available in real-world crash investigation studies like the Crash Investigation Sampling System (CISS) conducted by the National Highway Traffic Safety Administration will help speed the rate of transmission of valuable data available to the research community. The possibility of adding new data sources from state and local municipalities also should be explored. The CISS sampling procedure emphasizes data collection from crashes involving the newest vehicles. Other data sources should follow this model to determine how the newest safety systems are performing. Information from Event Data Recorders (EDRs) provides the opportunity to obtain more accurate data for important crash variables such as impact velocity, occupant belt status, and precrash conditions that may affect an occupant's position at the beginning of the crash (e.g., accelerator pedal position, braking, steering). Even though almost all (99%) of vehicles on U.S. roads have EDRs, only around one-third (36%) of vehicles in 2017–2020 CISS in which occupants sustained moderate to fatal injuries (AIS2+) also have EDR data available for the crash. Increasing the percentage of cases with EDR data should be a priority for administrators of crash investigation programs. Similarly, better collection of anthropometric data is essential for understanding the unique risks faced by segments of the population. Height and weight measurements do not exist for 34% of drivers in 2017–2020 CISS. Where it does exist, it may have been obtained from unreliable sources like driver's license data.

Crash investigation studies also can be targeted toward crashes with injury types relevant to groups of specific interest. For example, because females have a higher risk of lower extremity injuries in frontal crashes, selection criteria used to determine which crashes are investigated can be refined to increase their representation in the sample. At the same time, inclusion of uninjured occupants provides data on how occupants are being protected and also is important for improving the accuracy of injury risk assessments. This can be hampered when detailed crash and occupant characteristics are not as well documented for cases without injury.

Some precrash variables are difficult to determine retrospectively. Additional naturalistic driving data and volunteer studies are needed to better quantify how seating posture, seat position, belt placement, and head restraint adjustment vary for occupants of different shapes and sizes. Studies of foot posture and footwear may also improve the understanding of lower extremity injury mechanisms. Understanding how occupants are seated or positioned before a crash is necessary to determine the factors that may affect restraint system performance. These efforts could be supported by the increasing number of vehicles with data loggers (not just EDRs) associated with driver assistance systems. Data and video from these systems could provide information on seat position, driver posture, belt fit, and other precrash conditions.

Recommendations: Expand existing crash investigation programs and push to obtain EDR data from a greater number of cases.

Oversample specific injury types where disparities exist for vulnerable groups.

Expand data collection beyond crash studies to better understand variability in occupant shape, size, posture, and seating position and the effects of these factors on restraint conditions such as belt placement and head restraint position.

Where crash investigation data indicate that certain populations are more likely to be injured or to sustain specific injury types, additional study is needed to understand whether these tendencies are due to physiological differences (e.g., vulnerability related to age or size), anatomical differences (e.g., certain body shapes/sizes that are less protected by restraint system designs), or a combination of both. Vulnerability related to sex, age, stature, shape, and BMI has studied to some extent, but there are still many opportunities for further research. In addition, there may be other indicators that factor into vulnerability and should be explored, such as preexisting conditions (comorbidities), socioeconomic status, and crash location, which can determine the availability of quality health care.

Additional funding is needed to expand post-mortem human subject (PMHS) testing. Groups underrepresented in available PMHS testing include females (including those of average size), larger body shapes (high BMI), and statures different from standard ATDs. Selection of PMHS also should take into consideration future population trends. Whole body testing is needed to better understand how subjects respond kinematically to varying test severity and loading conditions. Additional isolated segment testing also is needed to establish biomechanical corridors and improved injury thresholds for body regions of interest, like the female thorax and lower extremity. Edge cases where PMHS testing severity is close to human injury tolerance (cases with and without injury) are important for establishing good biomechanical reference data.

Human subject testing needs to move beyond the norms established over the last 50 years. Boundary conditions for PMHS testing should reflect the load conditions a person would experience in a modern vehicle (belts, airbags, knee bolsters). ATDs and human body models (HBMs) used in computational modeling depend on realistic biofidelity and injury data for validation. HBMs have the potential to improve our understanding of how the range of physiological and anatomical differences in the population influence injury tolerance, but this depends on the availability of relevant PMHS tests to validate the models. For example, PMHS data investigating seat belt submarining for different body types is an important step toward developing models that can be used to design systems that protect a wide range of occupants in real-world crashes.

Recommendations: Increase collection of fundamental biomechanics data that capture the range of variability in the population.

Increase collection of fundamental biomechanics data with boundary conditions representing modern vehicles for improved validation of physical and computational modeling tools.

Theme No. 3: Computational modeling and human body models are critical tools for studying injury causation and evaluating countermeasures for diverse populations.

Physical testing traditionally has been the foundation of occupant protection system evaluation, but computational modeling already is prevalent during vehicle development and is poised to move into regulatory and consumer information evaluations. Crash tests are necessarily limited by available physical tools and resources such as lab time and monetary constraints. Computational modeling is a critical complement to physical testing because of the flexibility to evaluate additional test conditions in a more comprehensive and cost-effective manner. Creation of computational models is resource-intensive, but once created they can be exercised to evaluate a broader range of initial conditions such as crash severity or direction and occupant posture, size, or shape. These additional scenarios, even ones that represent relatively small changes from the physical test, will result in occupant protection systems that are more robust to variations in evaluated parameters. This flexibility to vary parameters makes computational modeling an ideal tool to evaluate protection for occupants not well represented by ATDs in standard crash test protocols.

Computational human body models have historically been developed with reference to the same body sizes as ATDs. However, the development of parametric human body modeling allows these baseline models to be morphed to represent a wide range of body sizes and shapes. These tools provide the best available means of assessing the effects of body size, shape, and posture on crash outcomes. Most importantly, using human models with a wide range of characteristics, rather than only 5^{th} percentile female and 50^{th} percentile male models, enables improved predictions of how changes in physical test procedures or injury criteria will affect the population of vehicle occupants.

While computational models already are used by automakers and suppliers during vehicle and restraint system development [18,19,20] and by researchers investigating the role of occupant factors on outcomes [21,22], they have not yet been fully embraced for regulatory or consumer information testing. This is due, in part, to the challenge of sharing proprietary data between organizations. Overcoming this requires collaboration to develop a data sharing framework that ensures confidence in the validity of the results while maintaining protection of intellectual property.

Perhaps an even greater obstacle to more widespread use of computational modeling is uncertainty that the models and associated simulation results represent what would be obtained from comparable physical tests. To encourage greater confidence, limits should be placed on the difference in the boundary conditions of the models relative to their underlying physical validation tests. It may be necessary to conduct more physical tests in the short term in order to provide more validation points for virtual testing. It also is important to understand the relative strengths and weaknesses of virtual testing with ATDs and HBMs, and to choose the tool most appropriate for a certain context. Simulations that replicate ATD response can be validated against physical tests with ATDs, but their ability to represent human response is more limited. HBMs are designed to better replicate human response but come with the added requirement to validate the models with limited available physical test data. In addition to better validation data (described above), we need better recommended practices and standardized protocols for use and validation of HBMs.

Recommendations: Expand and prioritize computational modeling as a complement to physical testing to ensure protection systems are robust enough to account for variation in occupant factors such as shape, size, and posture.

Accelerate development, validation and use of human body models to identify safety system advancements that would improve protection for diverse occupant populations.

Develop a framework for sharing simulation data among automakers, suppliers, and regulatory and consumer information programs.

Develop recommended practices for use of computational modeling tools, especially human body models.

Theme No. 4: There are tools and strategies available today that can be used to design for a diverse population.

There are a wide range of tools that can be used to further improve safety for all vehicle occupants. Recently, specific attention has been given to the perceived lack of representation of female ATDs in regulatory and consumer information testing. While ATD choice is one part of a crash test assessment, ATD development is a multidecade process, and there are other potential changes that could be made more quickly that may provide similar or greater benefits than would be achieved with an additional ATD. For example, higher female injury risk often is associated with vehicle selection differences between women and men [8], which is an issue better addressed by improving compatibility across vehicle types. In general, relatively quick progress could be made by improving how we interpret the data we get from current ATDs, evaluating additional occupant seat positions, varying test configurations, and incentivizing faster implementation of technologies known to prevent crashes or mitigate crash severity.

Analysis of real-world crashes has helped identify specific injury types for which improved test metrics are needed. These include chest injuries, especially rib fractures, and lower extremity fractures, especially in the foot and ankle. Potential solutions include adjustment of the maximum allowable ATD injury metrics, introduction of external sensors (e.g. seat belt load cells), metrics based on vehicle structure and/or qualitative measures of performance that can drive improvements in vehicle design. Updating injury assessment values requires additional research and should be done in a manner that aims to minimize harm across a wide range of occupants.

In addition to improving injury outcomes in high-severity crashes, more work is needed to reduce injuries in lower-severity frontal crashes where most rib fractures and lower extremity injuries occur. This would especially help improve outcomes for the most vulnerable occupants, such as the elderly. In high-speed frontal crash tests, modern vehicles tend to have minimal deformation of the occupant compartment, so it is reasonable to assume that injuries in low-severity crashes result from occupant interactions with the vehicle interior and/or restraint system components. Because full-vehicle crash tests can be very costly and time-consuming, improvements to restraint system performance in low-severity crashes can be achieved through sled tests focused on belt engagement and limiting belt loads to levels that are appropriate for older occupants. As with optimization of any system, there is potential for unintended consequences that may put occupants at greater risk in more severe crashes. If potential design changes result in safety trade-offs, optimization should target reduction of harm across a range of crash severities.

Using the existing family of ATDs in a wider range of seat positions is another example of a change that could be made today to improve occupant protection. Studies have shown that safety benefits for front-seat occupants have outpaced those of rear-seat occupants in frontal crashes [10,11]. Technologies that are standard equipment for all drivers and front passengers, like seat belt tensioners and force limiters, are commonly unavailable in rear seating positions. Beyond advances in seat belt technologies, novel airbags eventually may be needed to maximize safety benefits for rear-seat occupants, although care must be taken to ensure these are safe for all rear-seat occupants, including children in child restraints. Tests with existing ATDs may be sufficient for identifying appropriate restraint strategies.

The newest generation of frontal ATDs (THOR) is equipped with increased sensing capabilities and has improved biofidelity compared with the Hybrid-III family of ATDs for certain body regions. However, there is not yet established consensus that testing with these ATDs will result in significantly different test outcomes or drive changes that will benefit real-world occupants. If future test programs utilize new ATDs, they will only be effective at encouraging meaningful improvements when the new sensors have relevant injury criteria and limits.

Recommendations: Explore the use of modified injury criteria and supplemental assessment metrics to differentiate varying levels of occupant protection in existing crash modes.

Establish test methods and best practices for promoting restraint designs that mitigate injury risk in lower-severity crashes.

Establish test methods and best practices for promoting restraint designs that mitigate injury risk for occupants in rear seat positions.

Determine whether the newest generation of ATDs will enable improved crashworthiness and restraints for occupants in the broad spectrum of crashes in the field. If they do not, find ways to redesign these tools or modify how they are used.

The strategies described above involve tools aimed at reducing occupant injuries when a crash occurs, and this reflects the background and expertise of most of the workshop participants. However, strategies that avoid crashes altogether, reduce crash severity, or encourage restraint use will play a crucial role in improving safety for everyone. Many crash avoidance technologies available today already have proven benefits. Studies have shown that:

- Lane departure warning systems have lower rates of involvement in targeted crash types of all severities (18%), those with injuries (18%), and those with fatalities (86%) [23].
- Blind spot monitoring systems reduce lane change crashes of all severities (14%) and those with injuries (23%) [24].
- Automatic emergency braking (AEB) systems reduce all rear-end crashes involving passenger vehicles (50%) and those with injuries (56%); they also reduce rear-end crashes involving large trucks (41%) [25,26,27,28,29].
- Seat belts reduce injuries by 50%–65% and fatalities by 45%–60% [30], but unbelted occupants make up almost half of annual crash fatalities in the U.S. Incorporating fleet-wide persistent audible seat belt reminder systems could increase belt use by about a third [31].
- Speed affects crash frequency and injury severity [32]. Technologies that can help limit speeds (intelligent speed assistance systems) have the potential to prevent speed-related crashes or reduce the energy that needs to be absorbed by vehicle structures and restraint systems when they do occur.

While the diversity of the population presents unique challenges for crashworthiness technologies, active technologies can benefit all occupants in equipped vehicles, occupants in other involved vehicles, and vulnerable roadway users.

Recommendations: Increase adoption of technologies that prevent crashes or mitigate their severity, such as crash avoidance technology, intelligent speed assistance, and alcohol detection technology.

Incentivize persistent seat belt reminder systems in all new vehicles.

Theme No. 5: Collaboration will be the key to success.

The remaining areas for improved occupant protection are diverse. Optimizing protection for a small, young adult female may require different solutions than optimizing for a high-BMI, older occupant. As a result, our efforts in protecting a diverse population are likely to require multiple, potentially divergent paths that will divide a pool of limited resources. To maximize the effectiveness of our efforts, we need to rely on collaboration at all levels: across borders, organizations, and disciplines. This will allow our industry to take advantage of the strengths of different entities and expedite data sharing while limiting project overlap. Some specific needs include:

- Joint collection or development of data (see data needs above)
- Increased data sharing, especially for modeling purposes
- Round robin testing to identify issues with physical and/or computational tools more thoroughly and quickly
- Recommended practices or standards for use of computational modeling tools, especially human body models

In addition, our community should actively consider potential end users at all stages of research. This means considering other researchers and disciplines, policymakers, and designers, beginning with the research and design phase through the ultimate communication of research findings and their proper application.

Recommendation: Explore new formal or informal working groups and new mechanisms for funding and/or distributing research.

CONCLUSIONS

Large strides have been made in improving occupant protection for everyone. Although significantly reduced in newer vehicle designs, injury risk disparities remain, due to diversity in the occupant population and crash exposure differences. These factors must be better understood to keep making progress toward the goal of zero injuries and fatalities. Understanding the state of vehicle crashworthiness and the benefits of occupant protection countermeasures is a continual feedback process. To move beyond countermeasures that already are working, targets for improvement should be based on studies of the newest vehicles, which require up-to-date crash investigation databases. Additional human subject and PMHS data also are needed to augment our understanding of human kinematics and injury tolerance across a broader range of occupant sizes and shapes. This will allow us to improve our physical and virtual tools (ATDs and HBMs) as well as the injury metrics required to use those tools to protect a diverse range of occupant types.

Virtual testing holds much promise as an area that could enable future occupant protection improvements. To realize this promise, we need to develop a framework and best practices for model validation and data sharing that will allow simulations to supplement traditional crash test programs. This will allow industry to quickly develop robust structures, interior compartments, and restraint systems.

Many of the findings listed above require additional research and/or development time. The push to improve crash outcomes for specific groups of occupants should not overlook things we can do now to benefit everyone. Increasing belt use and accelerating the adoption of existing crash avoidance technologies will have an immediate effect on rates of crashes and injuries.

Studies consistently have shown that advances in vehicle crashworthiness have benefited the entire population. While future improvements will likely be smaller in magnitude, substantial gains can still be achieved as we collaborate to identify the risks faced by specific groups within the diverse occupant population and the countermeasures that are most effective at reducing those risks.

ACKNOWLEDGEMENTS

Thank you to the workshop participants, who all contributed greatly to the discussion and whose ideas formed the basis for this paper. The concepts described in this paper are an interpretation of the discussions in the workshop and do not necessarily represent the views of all workshop participants or of their organizations. The authors also thank the Insurance Institute for Highway Safety for supporting the workshop.

In addition to the authors, the following people participated in the workshop:

- Amanda Agnew, PhD, Ohio State University
- Julie Brown, PhD, The George Institute
- James Ellway, Euro NCAP
- Jason Forman, PhD, University of Virginia
- Scott Gayzik, PhD, Wake Forest University
- Jason Hallman, PhD, Toyota Collaborative Safety Research Center
- Warren Hardy, PhD, Virginia Tech
- Erin Hutter, PhD, National Highway Traffic Safety Administration
- Annette Irwin, PhD, General Motors
- Lotta Jakobsson, PhD, Volvo Cars
- Shaun Kildare, Advocates for Highway and Auto Safety
- Agnes Kim, Ford Motor Company
- Dan Parent, National Highway Traffic Safety Administration
- Kristin Poland, PhD, National Transportation Safety Board
- Matthew Reed, PhD, University of Michigan
- Jennifer Stockburger, Consumer Reports
- Cecilia Sunnevang, PhD, Autoliv
- Suzanne Tylko, Transport Canada
- Philipp Wernicke, BMW AG
- Joe Young, Insurance Institute for Highway Safety

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AN NCAP RATING FOR FEMALES

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Paper 23-0323

ABSTRACT

This paper defines NCAP rating factors that would be useful to improve the safety of females in frontal crashes. The study is based on an analysis crash tests available on the NHTSA website and analysis of Crash Investigation Sampling System (CISS) and Crash Report Sampling System (CRSS) data.

Analysis of NHTSA databases of crash tests and collision data suggest that a Female NCAP should focus on encouraging crash safety countermeasures in three priority areas – reducing chest injuries, reducing lower limb injuries (especially foot and ankle injuries) and reducing the crash severity in lower speed crashes.

Based on the available literature and the additional data analysis, proposals are offered for a Female NCAP to address the three principal issues. These include better controls of the safety belt and foot positioning, measuring chest and foot/ankle injury risk more accurately, limiting brake pedal motion and limiting the initial frontal stiffness of vehicles.

INTRODUCTION

In their 2019 paper in Traffic Injury Prevention, researchers from the University of Virginia analyzed National Automotive Sampling System – Crashworthiness Data System NASS-CDS 1998-2015 and found that, in frontal crashes, belted females were at a higher risk than belted males of being injured at the AIS 2+ and AIS 3+ level (Foreman, 2019). They also found that risk reduction of thorax injuries has lagged the safety improvements for other body regions, resulting in an increasing prevalence of skeletal thorax injuries in newer model year vehicles.

Several studies have shown that the frontal stiffness as measured in frontal NCAP tests has increased with vehicle model year (Samaha, 2010, Sahraei 2009, 2013). Based on regression analysis, Sahraei found that passenger car stiffness had increased by 119% and large platform vehicle stiffness had increased by 128% over a 28 year period. The study also found that increases in vehicle stiffness also increased chest injury measurements on rear seat dummies. Samaha (2010) found that overall, the advances in restraint technologies, specifically seat belt load limiters, seemed to compensate for the higher vehicle acceleration resulting from increased stiffness. The increased stiffness has allowed the bumper-to firewall distance to be shortened. Brumbelow (2020b) concluded that vehicle bumper-to-firewall distance was a better predictor of thoracic injury outcomes than measurements by the Hybrid III dummy.

A further issue with the NCAP test conditions is that the chest deflection measurement in the test does not represent the actual deformation of the chest., as documented in several papers (Haight, 2013, Digges, 2017). Failure to control the shoulder belt position relative to the single point chest deflection gage on Hybrid III dummies, has permitted lower chest injury measurements than would be obtained with a properly positioned belt. Brumblow

(2020a) estimated that properly positioned shoulder belts in NCAP tests would increase the medium sternum deflection measured on Hybrid III by 49%. Rib-eye chest gages incorporated into the chest of the 5% Female Hybrid III dummy have been shown to improve the chest deflection measurements (Digges 2019). This failure in test protocol, along with the increase in vehicle frontal stiffness may have contributed to lag in skeletal thoracic injury reduction found in on-the-road injury data by Foreman.

A separate ESV paper by Dalmotas controlled Fatality Analysis Reporting System (FARS) and CRSS data for additional crash factors and showed that, in crashes, females are more likely than males to be driving smaller cars (Dalmotas, 2023). Males are more likely to be driving heavier vehicles, especially pickup trucks and larger vans. Consequently, a gender difference in crash exposure could account for some of the apparently increased injury risk experienced by females, as reported by Foreman.

The disparity of crash severity in cars vs pickups and vans has been documented by numerous studies (Joksch 1998, Gabler 1998, ESV and SAE). Joksch examined front-to-front collisions in FARS and found there were 5 driver fatalities in cars for each driver fatality in vans or SUV's. For pickups the ratio was 3 to 1. Gabler (1998) found that the car to van fatality ratio for full size vans was 6 to 1 and for full size pickups was 5.3 to 1. The female preference for lighter vehicles increases their fatality risk in frontal collisions with heavier vehicle that are more likely to be driven by a male.

Morgan (1991) conducted an in-depth study of 480 occupants with AIS 2+ foot/ankle injuries. For 57% of the driver ankle injuries, the foot was on a pedal. Contact with the foot controls accounted for 43% of foot/ankle injuries; the floor contact accounted for 24% and pocketing between the floor and instrument panel accounted for 12%. The authors concluded that foot/ankle injuries were most frequent in lighter weight vehicles.

Others have reported differences in male and female injury risks by body region. Rudd (2009) found that females, especially those less than 164 cm in height were more likely to sustain foot/ankle injuries than males and the foot/ankle injury risk had increased in vehicles later than MY 2001. Brumbelow (2021) and Jermakian (2022) found that the overall injury risk for males and females was not statistically different in NASS-CDS 1998-2015, if extremity injuries were excluded from the comparison. They also attributed some of the female increased injury risk to a gender difference in crash exposure. Foreman (2022) found that the higher frequency of AIS 2+ ankle injuries to females in frontal crashes accounted for much of the overall male-female injury risk difference. Female AIS 2+ injuries tended to occur at lower delta-V than for males with the median at 25 kph.

METHODOLOGY

The gender preference for vehicle type was analyzed using data from the Collision Reporting Sampling System (CRSS). Both Single Vehicle and Two-Vehicle collisions were examined. For Well Defined Single Vehicle Crashes, the following constraints were applied: CRSS Calendar Years: 2016 – 2020; Selected Light Duty Vehicles (Cars & LTVs) / 1994-on MY Vehicles; VIN (B10) Available and Decoded; Vehicle Class (VIN) : CAR, CUV, PUT, SUV, VAN; Gender & Age of All LDV Occupants Known; Seating Position of All LDV Occupants Known; All Involved Occupants 15 Years of Age or Older. For Well Defined Two-Vehicle Crashes, the same constraints were applied plus the VIN (B10) Available and Decoded for Both Vehicles.

The Single Vehicle Sample was comprised of 34,780 (4,864,877 Weighted) Occupants, Drivers, Vehicles and Collisions. The Two-Vehicle Sample contained 183,810 (25,208,458 Weighted) Occupants, Drivers, Vehicles and 91,905 (12,604,229 Weighted) Collisions.

To explore injury mechanisms of injured females, cases from (CISS) 2017-2020 were examined statistically. The CISS cases were restricted to belt restrained outboard front seat occupants of light duty vehicles (LDV) in Well-defined Frontal Planar Crashes with known injuries MAIS 0-6 and known VIN. The cases were limited to adults at least 16 years of age with known gender and age and protected by safety belts and airbags. The injury data set was examined for body region, gender, age, and classes of vehicles involved. To study crash severity, an added restriction was that DeltaV had to be known. To study braking, the EDR data had to be known.

For the Well-defined Frontal Planar Crashes, the resulting occupant sample for the injured body regions study was 3,797 (3,834,943 Weighted). Of this population there were 1,938 (2,700,766 Weighted) uninjured occupants and 1,859 (1,134,177 Weighted) injured occupants (MAIS:1 – 6). These injured occupants had 8,656 (3,481,470) individual AIS 1-9 injuries. The analysis to follow will include 1,168 (405,613) AIS 2-9 injuries. The number of AIS 2-9 body region injuries was 291 (121,252) for the chest and 332 (73,987) for the lower extremities. This data set was labeled Well-defined Frontal Planar Crashes. Females accounted for 61% of the AIS 1+ injuries and 54% of the AIS 2+ injuries. For the crash severity study, the unweighted sample of AIS 2+ injuries was 1168 (258,394 Weighted).

In examining the environment that may influence ankle injuries, we analyzed the influence of braking on driver ankle and foot injuries. Braking was determined from the EDR based on the last entry of the brake status captured in the pre-crash data. The braking analysis involved Lower Extremity AIS 2+ injured drivers in 2017-2020 CISS Single Event Frontal Crashes (SEF) with Pre-Crash EDR Data available. The data controls were as follows: Driver Belted (Lap/Shoulder Belt); Gender and Age of Driver Known; Vehicle Brake Engagement Information Provided. The Driver Sample was 1,114 Drivers. Of these Drivers 525 were uninjured at AIS 1+ and 589 were injured. The Number of Female Driver AIS 2+ Lower Extremity AIS 2+ injuries was 48.

Using data from NCAP like crash tests reported by Summers (2021), injury measures from the 50% male THOR dummy in the driver position and the 5% Female HII as the right front passenger were analyzed with special examination of the videos showing the toepan area and the lower limb motion.

Further analysis involved a series of tests to evaluate THOR under the offset/oblique test conditions that NHTSA has been evaluating. In these tests, a stationary target vehicle was impacted by a 2519 Kg moving deformable barrier traveling at 90 kph. The impact angle was 15 degrees and the overlap 35% (Saunders, 2012, 2015, 2018).

The study also examined data from the load cells on barriers in NCAP tests. Plots of barrier force distribution at peak loading were downloaded from the NHTSA website. Plots and tables of vehicle Average Height of Force/Moment and Test Mass were based on the vehicle test data from the NHTSA website. Average Height of Force and stiffness metrics have been defined in earlier papers (Digges, 1999, 2000, 2001, 2003).

A 2023 ESV paper by Dalmotas shows that a major factor in male/female injury risk difference results from differences in their crash exposure. The female representation in well-defined two-vehicle collisions as a function of vehicle type/size classification is displayed in Figure 1 (Dalmotas, 2023). Because females are overrepresented in the smaller vehicles and underrepresented in the larger vehicles, their crash exposure differs from males. Males are more likely than females to be exposed to crashes while in heavier vans and pickup trucks. Females are more likely to be in smaller cars, and subjected to higher crash forces when a collision occurs with a heavier vehicle.

Figure 2 shows the distribution of AIS 2+ HARM by body region. The distributions in Figure 2 are for 2017-2020 CISS cases of belt restrained outboard occupants of passenger cars or LTV's in Well-Defined Frontal planar crashes with injuries AIS 1 to 9. The HARM factors are based on US costs of injuries as determined by Miller and shown in Table A1 (Miller, 1990), The female injury data is in Table A2. The HARM calculation uses the procedure developed by Mallaris (1982) and applied in a 1998 SAE Paper (Digges, 1998). The cost of an AIS 9 injury was assumed to equal an AIS 2 Injury.

It may be noted from Figure 2 that Lower Extremities are the greatest sources of AIS 2+ HARM to females and the largest male to female difference is the lower extremities. A further analysis of lower limb injuries is in the discussion section of this paper. In addition, chest injuries merit further analysis because they are a large source of HARM that is not being adequately addressed in current NCAP, as discussed in the introduction to this paper.

Figures 3a and 3b provide AIS 2-6 injury distributions of chest injuries in Well-Defined Frontal Planar Crashes by gender, occupant age and crash severity. Figure 3c provides female AIS 2-6 injury distribution for two occupant age ranges and two crash severity ranges. Figures 4a, 4b and 4c provide similar plots for lower limb injury data. The distribution of female AIS 2+ injuries by body region is shown in Tables A3. Table A4 shows AIS 2+ Thorax and Lower Extremity injuries by age and gender for two DeltaV groups.

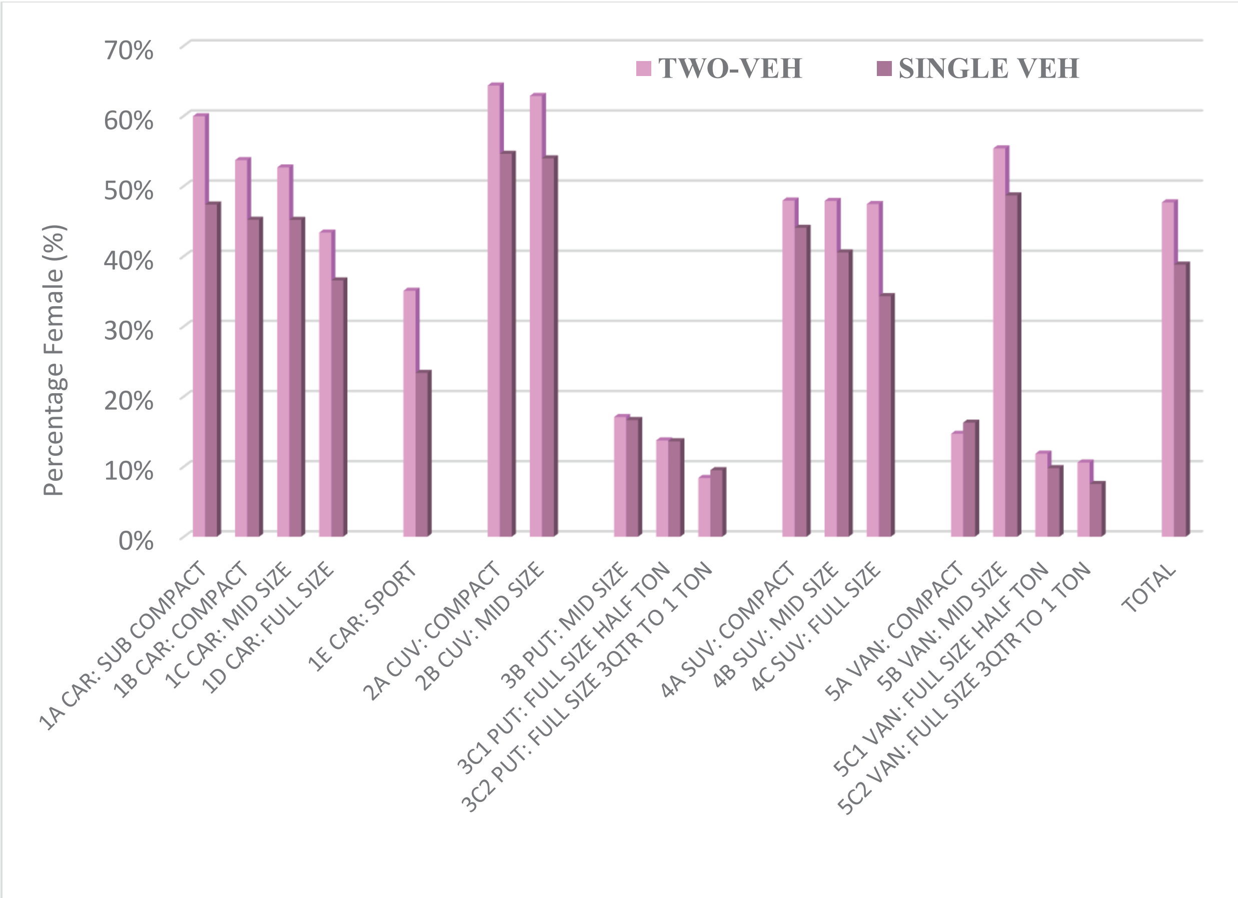


Figure 1. Female Representation in Well-Defined Collisions as a Function of Vehicle Type/Size Classification

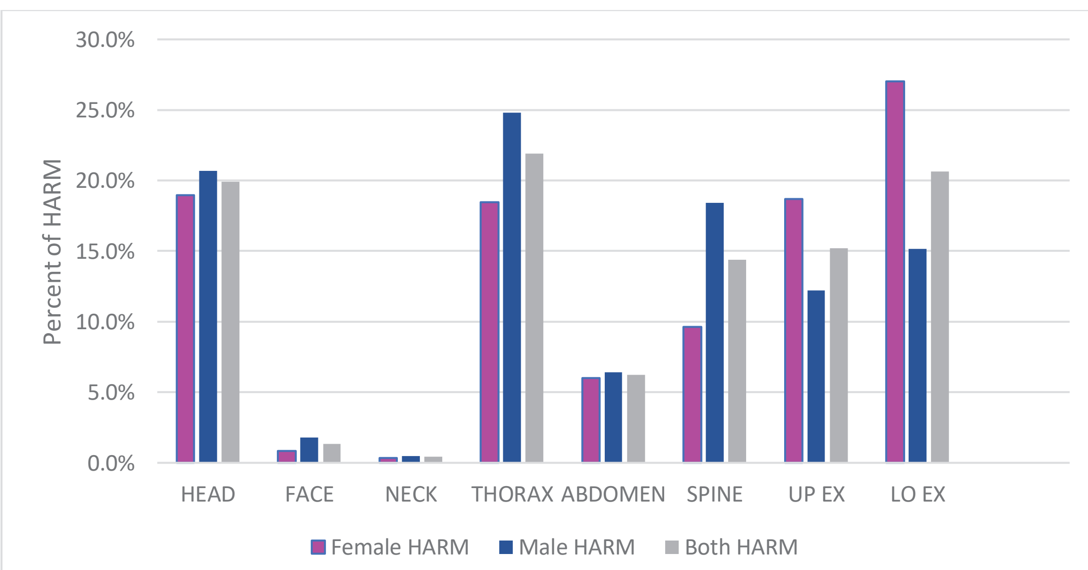


Figure 2. Occupant Injury Inventory, Distribution of AIS 2+ HARM by Body Region and Gender

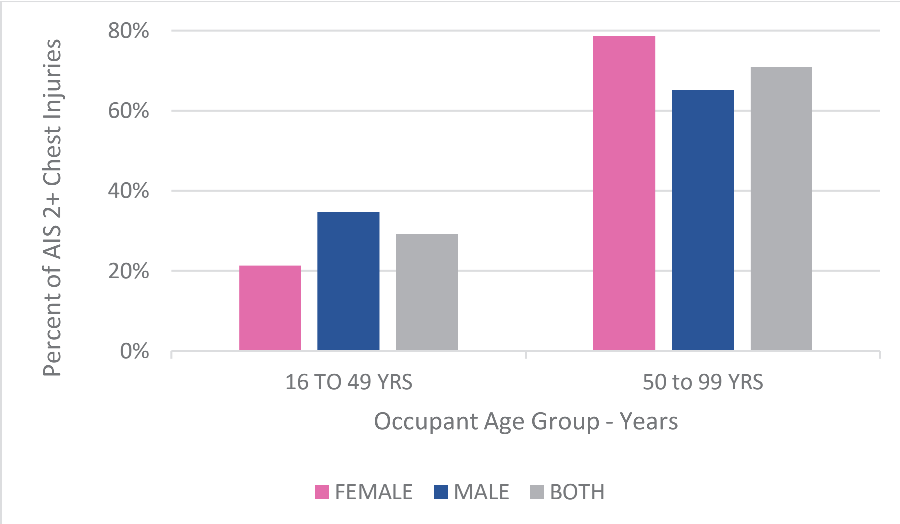


Figure 3a. AIS 2-6 Chest injuries in Well-defined Frontal Crashes by Gender and Age

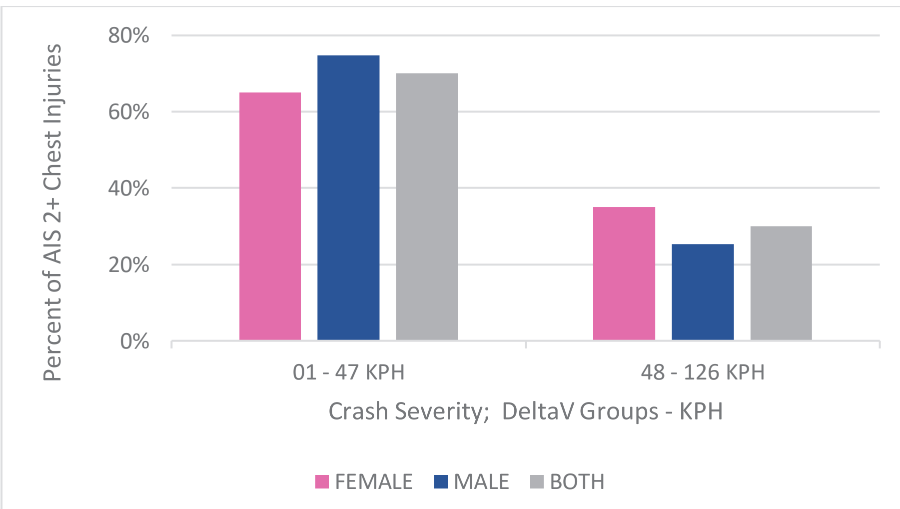


Figure 3b. AIS 2-6 Chest injuries in Well-defined Frontal Crashes by Gender and Crash Severity

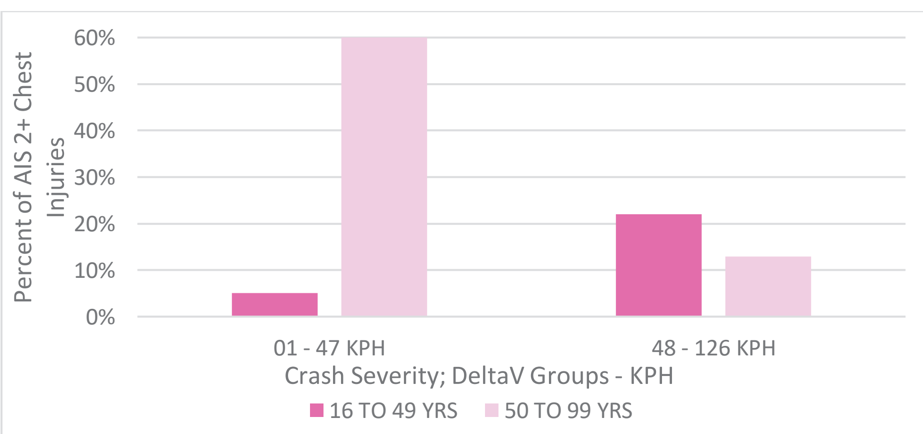


Figure 3c. AIS 2-6 FEMALE Chest injuries in Frontal Crashes by Age, Gender and Crash Severity

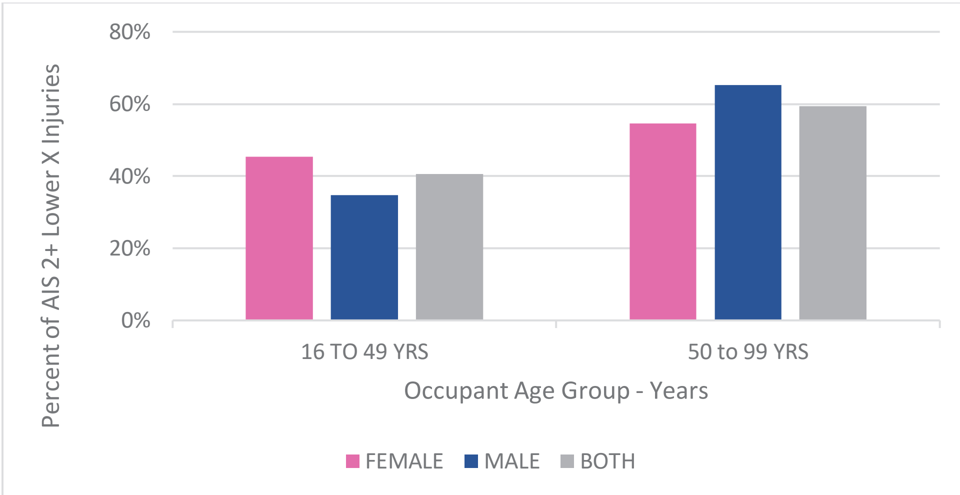


Figure 4a. AIS 2-6 Lower X Injuries in Well-defined Frontal Crashes by Gender and Age

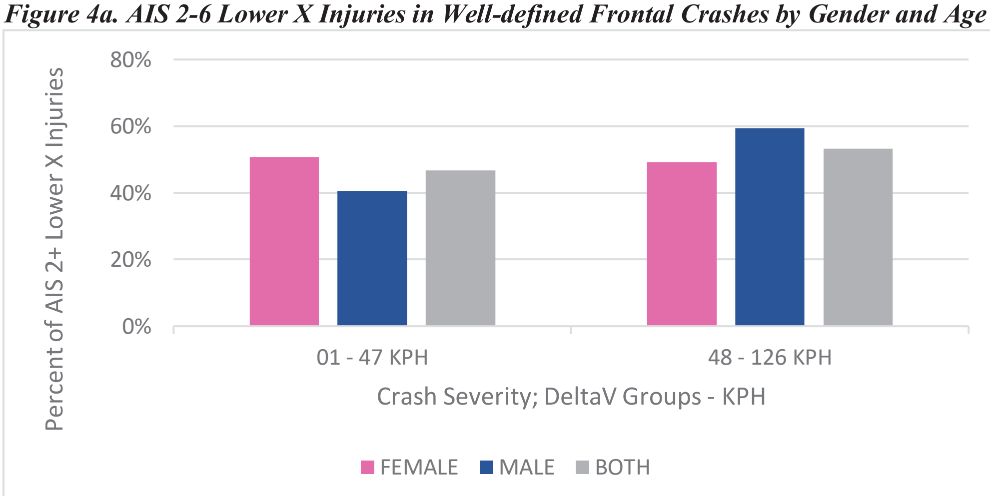


Figure 4b. AIS 2-6 Lower X Injuries in Well-defined Frontal Crashes by Gender and Crash Severity

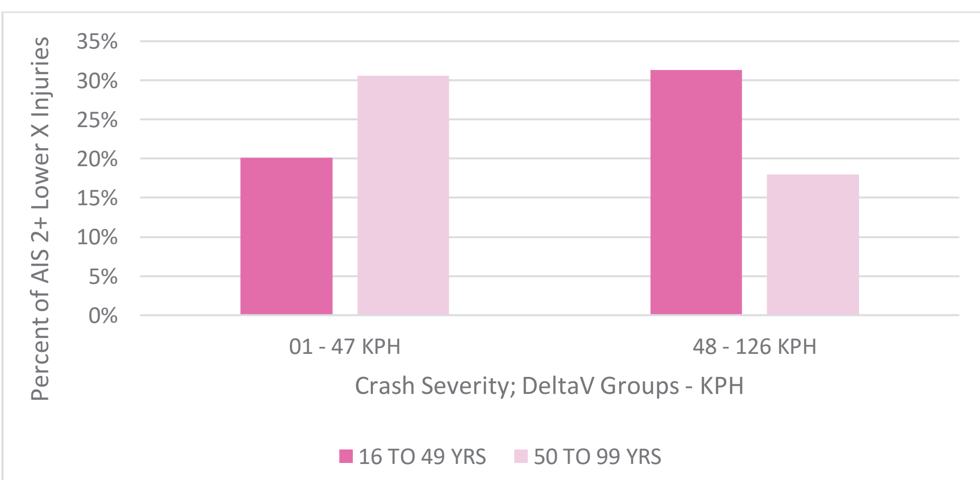


Figure 4c. AIS 2-6 FEMALE Lower X Injuries in Frontal Crashes by Age, Gender and Crash Severity

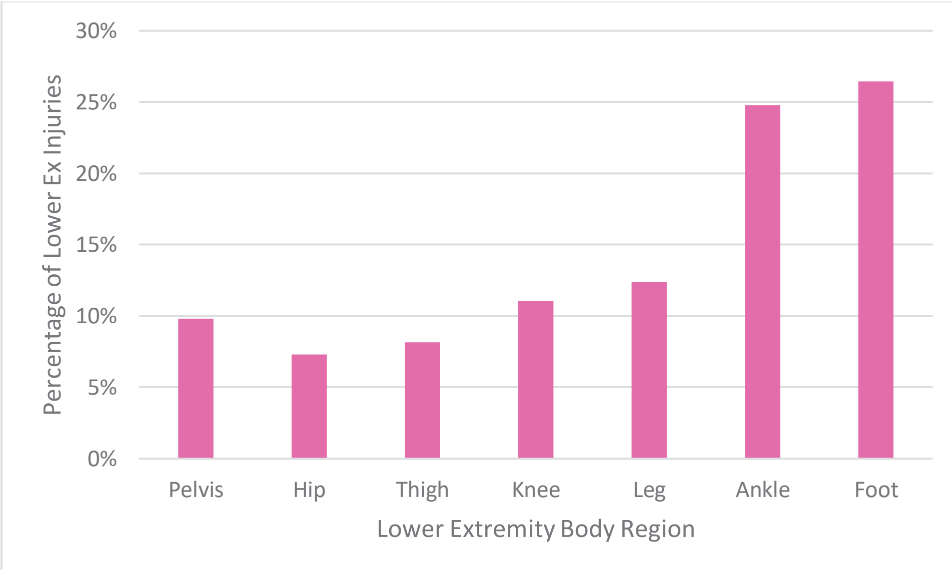


Figure 5. Distribution of Pelvic and Lower Extremity AIS 2-4 Injuries to Females in CISS 2017-2020 Well-defined Frontal Crashes

The distribution of CISS Lower Extremity AIS 2+ injuries sustained by females in Well-Defined Frontal crashes is shown in Figure 5. A further disaggregation of foot and ankle injury data by left and right lower extremity is contained in Table 1. Table 1 shows the unweighted and weighted injury counts and percentage distributions for the foot and ankle injuries.

Table 1
Number and Distribution of Unweighted and Weighted AIS 2-3 Foot and Ankle Injuries to Front Seat Females in CISS 2017-2020 Well-defined Frontal Crashes

Body Region	Unweighted Number	Weighted Number	Unweighted Distribution	Weighted Distribution
Ankle Left	36	6,789	24%	33%
Ankle Right	38	3,291	25%	16%
Foot Left	19	2,990	13%	14%
Foot Right	59	7,749	39%	37%
Total	152	20,819	100%	100%

An examination of the Event Data Recorder data for the Single Vehicle Well-Defined Frontal cases found that braking was present when 79% of the 48 AIS 2+ injuries to the lower limbs. The body regions included in this Lower Limb category were foot, ankle, leg and knee. Table 2 shows the number of female driver foot and ankle AIS2+ injuries that occurred when the driver was braking. The table shows that the right foot injuries were predominately to the foot (66.6%) rather than the ankle. Braking was indicated by the EDR data for 79% of the female lower limb injuries and 88% of the foot/ankle injuries. The percentage of female all AIS 2+ foot/ankle injuries that occurred to the right foot/ankle was 64% unweighted and 53% weighted. During braking, the percentage was 70% (unweighted), as shown in Table 2.

Table 2.
CISS Documented Injuries to the Foot and Ankle During Braking

FEMALE BRAKING	Foot/Ankle	Foot/Ankle	Percent
Lower Limb Region	AIS 2-6	Percent	On Brake
Foot Left	5	17%	
Ankle Left	4	13%	
Foot Right	14	47%	
Ankle Right	7	23%	70%
All	30	100%	

.0 Sec .06 Sec .15 Sec

Figure 6a. Brake Pedal Motion in Test 9335; 5 mm Recorded Brake Pedal Intrusion

.0 Sec .06 Sec .15 Sec

Figure 6b. Brake Pedal Motion in Test 9336 – 110 mm Recorded Brake Pedal Intrusion

In their vehicle database, NHTSA has a series of NCAP like frontal crash tests with the 50% Male THOR Dummy in the Driver position. These tests also positioned a camera to record the motion of the brake pedal. Figures 6a and 6b show comparative motion from two different tests. The ankle inversion/eversion angles for the Figures 6a and 6b images are plotted in Figure 7.

Analysis of NHTSA crash test database provides insights into injury mechanisms and possible countermeasures for lower limb injuries. Figure 8 shows a comparison of Driver and Right Front Passenger Foot Accelerations that is typical of the NCAP like frontal tests conducted by NHTSA to evaluate the 50% male THOR Dummy in the driver position. The right front passenger was a 5% Female HIII dummy. Since the foot position 5% Female HIII is further away from the toepan than the 50% Male THOR, a more severe impact occurs and a higher acceleration results.

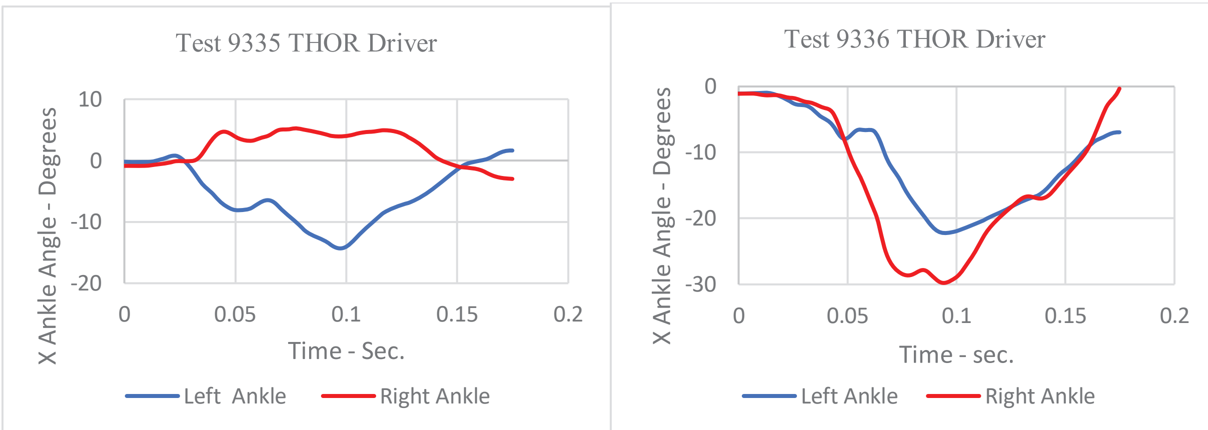


Figure 7. Ankle Inversion/Eversion Angle of 50% Male THOR Driver in NCAP Like Frontal Tests 9335 and 9336

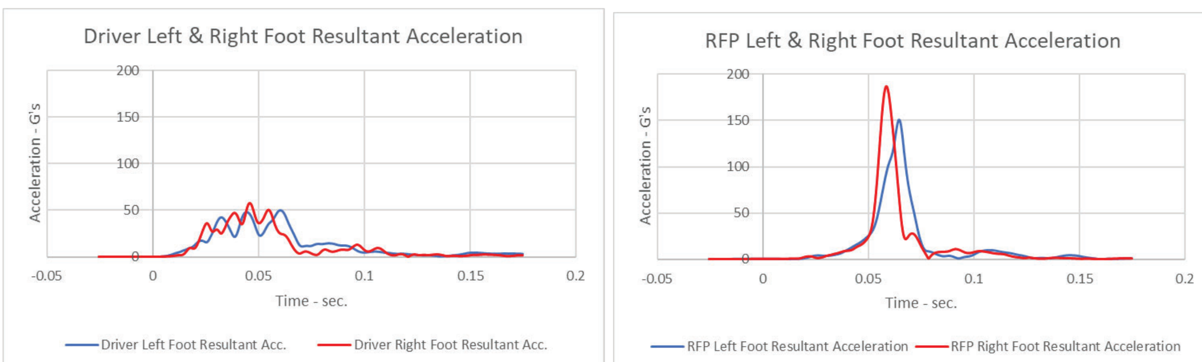


Figure 8. Foot Accelerations of 50% Male THOR Driver and 5% Female HIII in NCAP Like Frontal Test 9336

NHTSA's research testing of the Moving Deformable Barrier Evaluation of Small Overlap/Oblique Crashes clearly demonstrate a crash environment conducive to ankle eversion/inversion injuries (Saunders, 2012, 2015, 2021; Hu, 2019). The test condition was an impact by a moving deformable barrier traveling at 90 kph at an angle of 15 degrees and 35% offset. Ankle motion typical of this test mode is shown in Figure 9. Figure 9 shows the actual ankle position at three time periods. Figure 10 shows the plot of the THOR ankle eversion/inversion angles. The left ankle undergoes eversion and the right inversion. Note that the sign convention for eversion/inversion reverses from left to right foot. The longitudinal and lateral accelerations for the tested vehicle are shown in Figure 11.

.0 Sec .05 Sec .07 Sec

Figure 9. Foot and Ankle Motion Test 9500

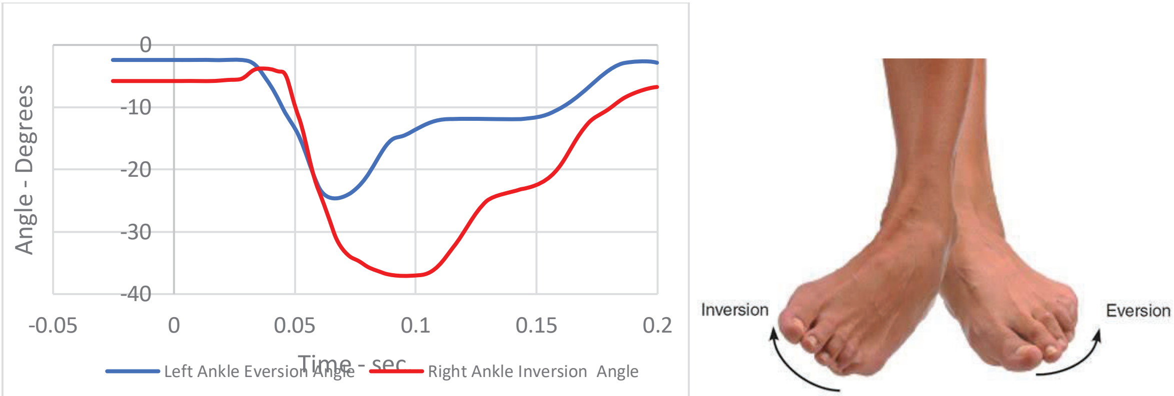


Figure 10. Foot and Ankle Eversion/Inversion Angle Test 9500

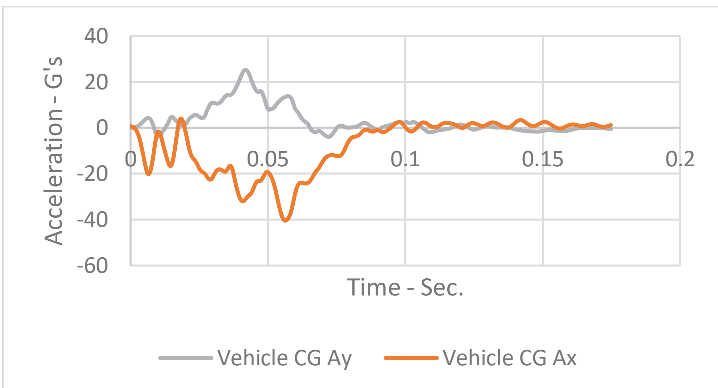


Figure 11. Vehicle Longitudinal and Lateral Accelerations in NHTSA Oblique/Offset Test 9500 (2015 Mazda CX5)

NHTSA's frontal NCAP tests include the force measurements from 176 load cells mounted in a 1375 mm by 2000 mm array on the test barrier. Analysis of the barrier load cells permits the measurement of stiffness and force distribution for each vehicle tested. This test data allows an assessment of the stiffness and geometric compatibility of various vehicles.

Figure 12 shows a comparison of the force vs. displacement for the Ford Focus subcompact car and the Ford F 150 pickup. Based on the barrier results, a frontal deformation of 120 mm on the F 150 would produce 350 mm of deformation on the Focus in a head-on collision. These results are typical of stiffness differences that currently exist in the NCAP test database.

Additional compatibility tests of the 2002 Ford Focus crashed head-on into more aggressive vehicles can be found on-line in the NHTSA vehicle test database. The following test numbers in the NHTSA database are of the 2002 Ford Focus vs other more aggressive vehicles: Test 5448 – 2003 Chevrolet Silverado pickup; Test 5686 – 2006 Honda Ridgeline pickup; Test 5685 2005 Honda Odyssey MPV; Test 5642 – 2005 Chrysler Town and Country MPV. These tests illustrate the vulnerability of small car occupants in frontal collisions with more aggressive vehicles (Patel, 2009).

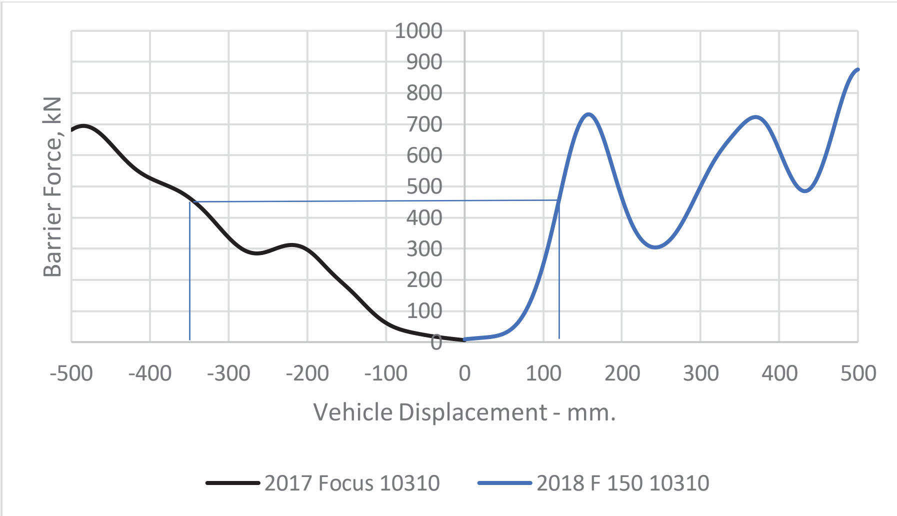


Figure 12. Stiffness comparison of the Focus vs F 150

In view of the expected increase in the population of electric vehicles in the fleet, it is essential to anticipate their influence on gender inequality. Like pickup trucks, electric vehicles have a weight advantage over most cars. Figure 13 and 14 show comparisons of the stiffness and weight of the F 150, the Tesla X, Polestar 2 and the Focus.

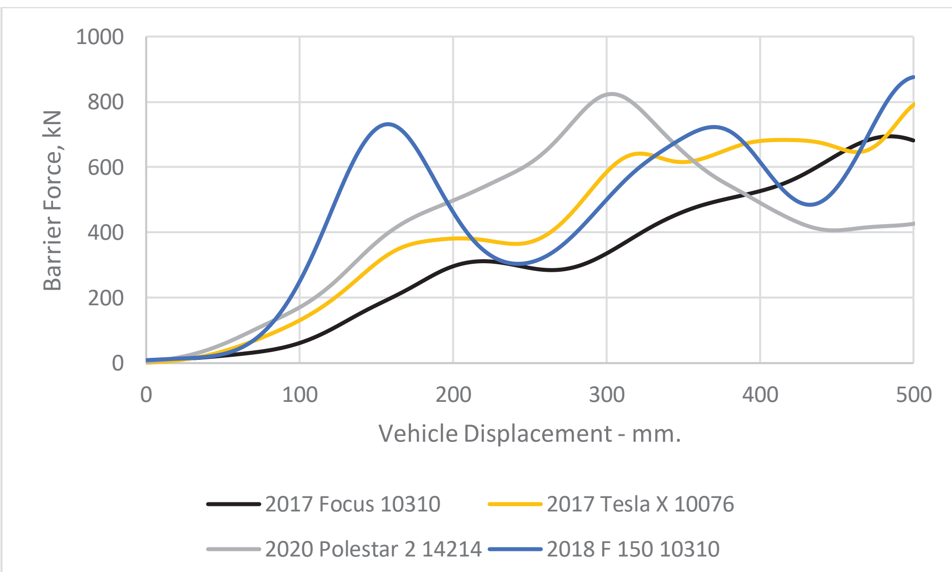


Figure 13. Frontal Stiffness of the F 150, Tesla X, Polestar 2, and Focus

The combination of weight and stiffness incompatibility makes it essential to encourage compatibility countermeasures to reduce the crash severity experienced by occupants of lighter vehicles that are more likely to have female occupants.

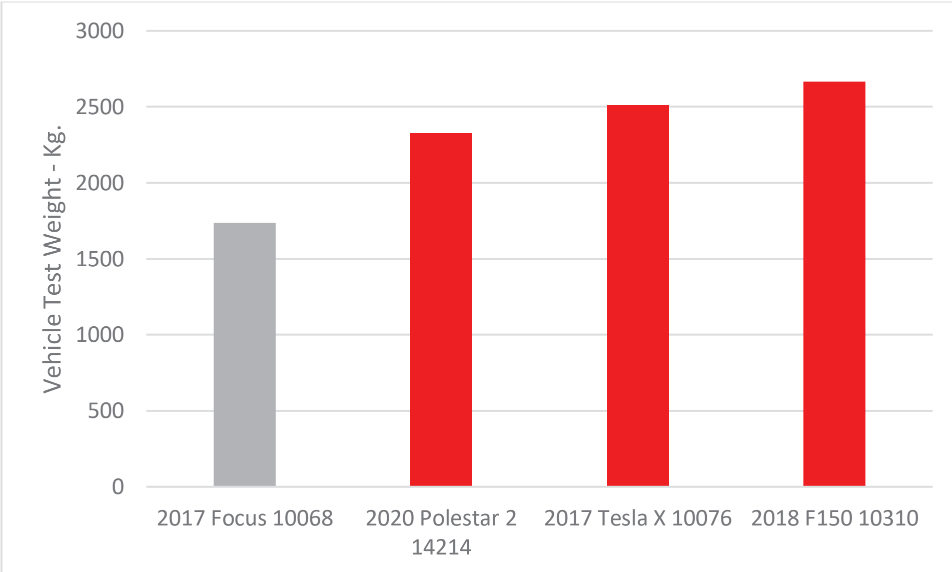


Figure 14. Vehicle NCAP Test Weight of 2017 Focus and Three Heavier Vehicles

Analysis of barrier force distribution has been reported in several papers (Digges, 1999, 2000, 2001, 2002). In a study for NHTSA, Digges, Eigen and Harrison analyzed barrier data to asses vehicle compatibility issues (Digges, 1999). They produced comparative barrier force distribution patterns for different classes of vehicles and proposed a geometric compatibility metric based on the Height of the Center of Force required to produce a restoring moment to the barrier forces. This metric, subsequently named the Average Height of Force (AHOF), was further applied in a paper that examined the aggressiveness of light trucks (Digges 2001). Figure 15 shows the AHOF for four vehicles.

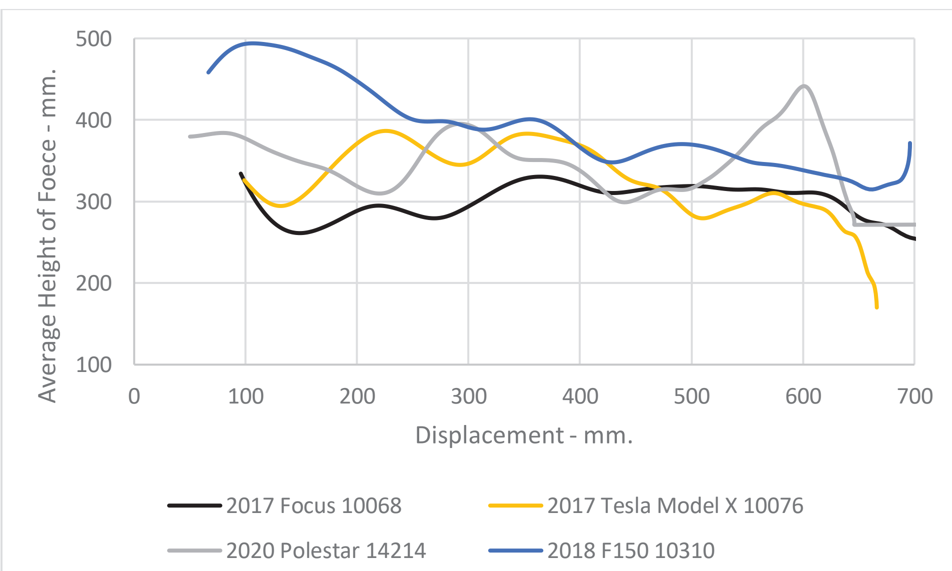


Figure 15. Average Height of Force Vs. Displacement for Focus, Polestar 2, Tesla X and F 150

Figure 16 shows the barrier force distribution for the Ford Focus, Tesla X and the Ford F 150 taken from NCAP test data on NHTSA website.

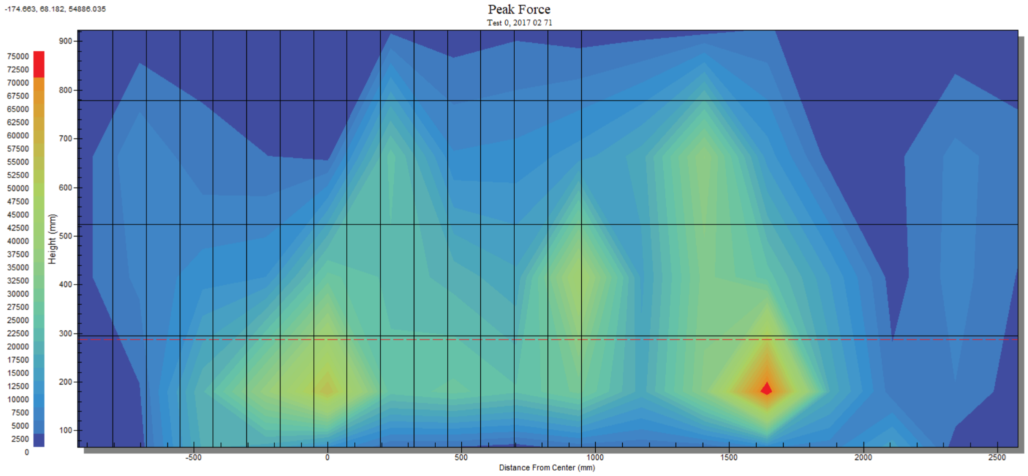


Figure 16a. 2017 Focus 10068 Barrier Force Distribution

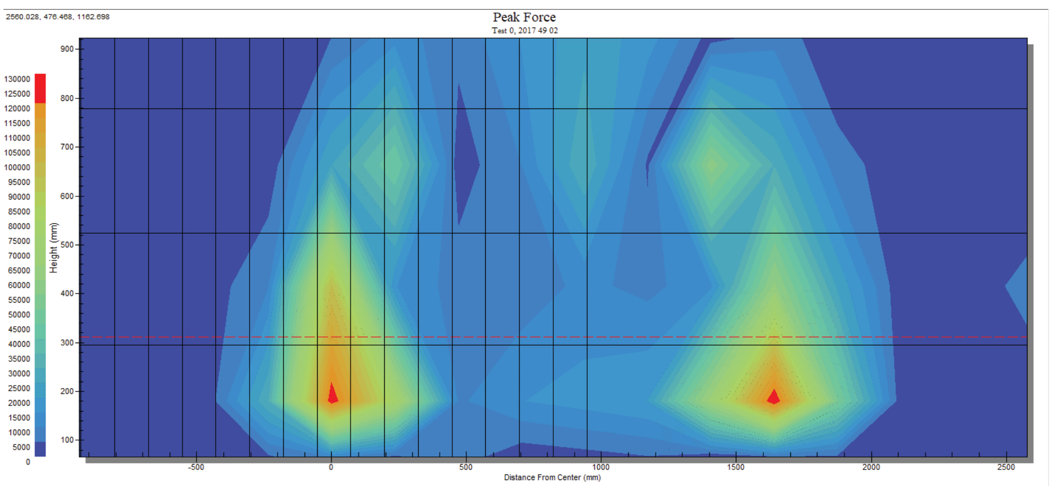


Figure 16b. 2017 Tesla X 10076 Barrier Force Distribution

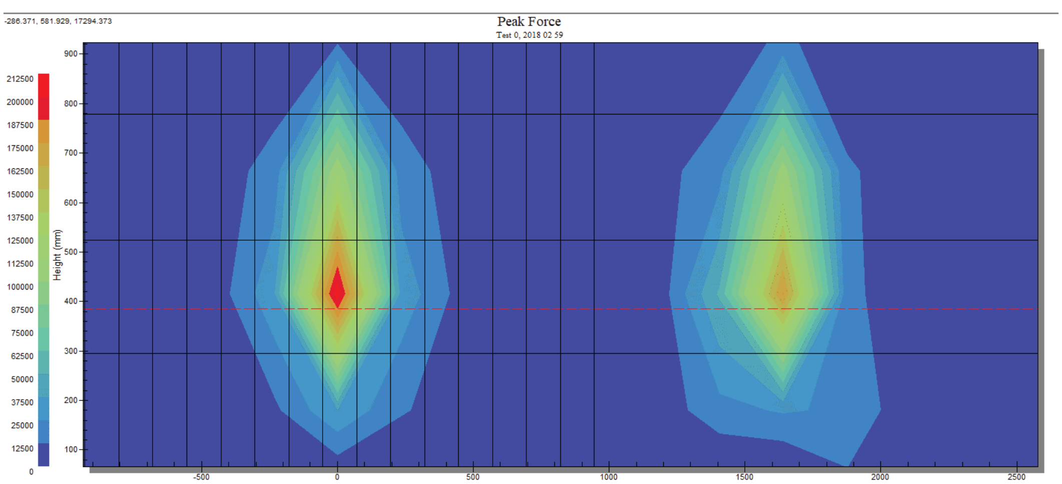


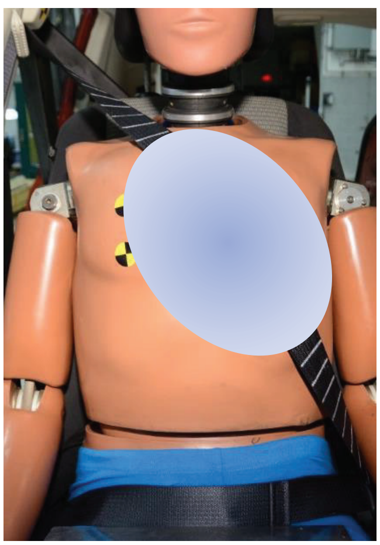
Figure 16c. 2018 Ford F 150 10310 Barrier Force Distribution

DISCUSSION: CHEST INJURIES

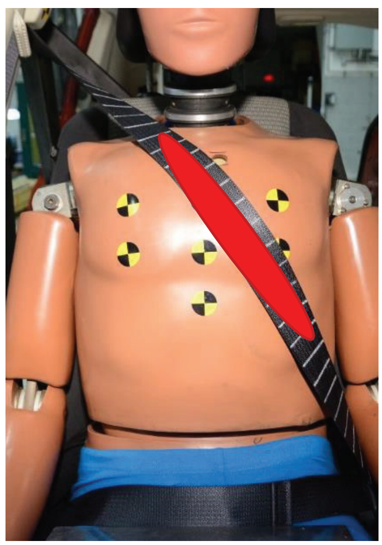
The 2019 research by the University of Virginia showed that the post 2009 cars very little change in the percentage of occupants with thorax injuries at the AIS 2+ severity (Foreman, 2019) The thorax injury reduction at the AIS 3+ level was small in comparison with the reductions in other body regions.

To enhance thorax protection, improved chest measurements that better distinguish the injury risks of different restraint systems should be introduced in NCAP. Past research has shown that the lack of control of belt routing as permitted in current testing practices, results in chest deflections and associated injury risks being understated. This , in turn, severely limits NCAP in its ability to encourage advances in chest protection (Digges, 2019, 2017). In view of the preponderance of older females with chest injuries in lower severity crashes (Figures 3a and 3c), it is essential that older female chest injury risk curves be applied to NCAP injury measurements (Figure A1). To further address female chest injuries, audit crash tests should be performed on selected NCAP vehicles to ensure that the injury risks measured at 56 kph are lower at 40 kph, where most female injuries occur.

Improvements in safety belt technology such as inflatable belts which seek to broaden belt loading area should be encouraged to reduce chest injury risks. Extensive research that documents the benefits of inflatable belts has been reported in the literature. An earlier paper by Digges and Morris summarizes extensive inflatable belt testing conducted by NHTSA (Digges, 1991) This research included human volunteers, cadavers and ATD tests that involved both sled tests and vehicle crash tests (Digges, 1991). One of the findings of the research was that ATD's of that period did not adequately measure the chest injury reduction benefits provided to the human subjects by the inflatable belt. More recent tests of inflatable belts have been reported by Foreman (2010) and Edwards (2017). Figure 17 illustrates the difference in pressure distribution across the chest of an inflatable belt vs a conventional belt (Gato, 2020). Improved chest injury measurements is a requirement to encourage improved countermeasures to reduce safety belt induced chest injuries.



Inflatable Belt Pressure Distribution



Conventional Belt Pressure Distribution

Figure 17. Typical Difference in Pressure Distribution Inflatable Belt vs Conventional Belt (After Goto, 2020)

A recent study indicates that the THOR may not adequately distinguish injury risk differences between concentrated pressure from the shoulder belt and distributed pressure from an inflatable belt (Goto,2020). Further improvements in chest injury measurement accuracy, including the use of contact pressure measurements, as being used in current IIHS Moderate Frontal Overlap Tests (IIHS 2022), should be researched and incorporated in order to further reduce shoulder belt loading of the chest.

It may be observed from Figure 3b that the female chest injury frequency is highest (66%) in the crash severity range of 0 to 47 kph. Figure 3a shows that the 50 to 99 age range of females have the highest frequency (79%) of chest injuries. As shown in Figure 3c, the largest opportunity for chest injury reduction is in the older population at the lower speed range. These observations suggest a Female NCAP should encourage a reduction of chest injuries for older occupants at lower crash severities. It may be noted from Figure 4 that this addition to NCAP could benefit men more than women. Ensuring chest ratings are based on more accurate chest measurement would greatly enhance the utility of NCAP in terms of improving chest protection. Both genders could benefit from this improvement.

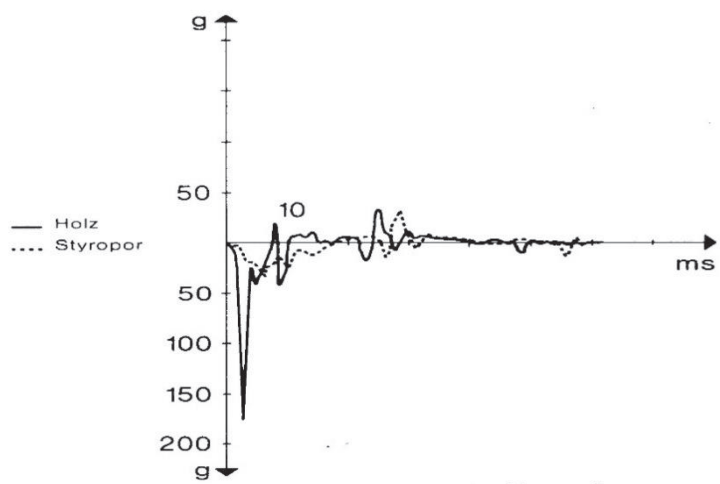
In recent model year vehicles, inflatable belts have been offered by Ford and Mercedes to improve the crash protection for rear seat occupants. It is time for NCAP to encourage the use of this countermeasure to reduce the chest injuries sustained by all occupants. This can be done simply by improving the belt routing and penalizing the high contact pressure that is characteristic of existing shoulder belts.

DISCUSSION: LOWER LIMB INJURIES

An examination of the CISS data for lower limb injuries shows that younger women are slightly more frequently injured (52%) than older women (Figure 4a) and that lower extremity injuries are about equally distributed in the two speed ranges (Figure 4b). Figure 4c indicates that more older women are injured at the lower speeds and more younger women are injured at the higher speeds. Figure 5 shows that the foot and ankle exhibit the largest fraction of AIS 2+ Lower Extremity injuries – exceeding 50%.

Crash test data shows that foot acceleration can vary greatly as a function of dummy size and seating position. Figure 8 shows that foot impact with the toepan in NCAP like crashes can cause foot acceleration spikes of 187 G's. for the 5% female dummy right front passenger. This compares with 52 G's for the 50% male dummy driver. The higher acceleration was caused by the gap between the foot and the toeboard that resulted in a foot impact. Shorter occupants seated in the right front position would be especially vulnerable to this kind of loading. Control of foot acceleration to encourage energy absorbing toepans would be useful to reduce talus and calcaneus injuries. The placement of the foot relative to the toepan for the RFP should also be controlled so that toepan impacts typical of female seating positions can be simulated in the Female NCAP Test. The test procedure should require a minimum distance between the foot and the toeboard for the right front passenger 5% Female Dummy.

Mercedes Benz has published research findings that show energy absorbing materials in the footwell can reduce the foot acceleration (Kallina, 1995). The foot accelerations before and after a countermeasure was applied are shown in Figure 18. Kallina reported that the accident data had shown a reduction of foot injuries after the introduction of the countermeasure in the Mercedes fleet.



After Kallina, 1995

Figure 18. Mercedes Crash Test Foot Acceleration With (Styropor) and Without (Holz) Countermeasure

Figures 9 and 10 illustrate how the lateral acceleration in a crash (Figure 11) can induce extensive ankle inversion/eversion under small overlap/oblique test conditions being researched by NHTSA. Earlier studies indicate that even non-oblique crashes can induce lateral accelerations in vehicles. Ishikawa (1996) analyzed crash pulses of car-to-car aligned frontal crashes with 40% and 60% offset. The authors found that the peak lateral acceleration (+y) was often as high as the peak longitudinal acceleration (-x). Bedewi (1998) and Digges (1997) reported on finite element computer modeling of the lower limb that showed a relationship between vehicle lateral acceleration and ankle inversion/eversion angles. The authors found that the lateral acceleration pulse in car-to-car offset crashes could be a source of ankle inversion/eversion injuries, especially when no intrusion occurs. The authors found that the offset barrier tests did not produce similar lateral accelerations. Consequently, a different type of crash test may be required to simulate the crash environment that produces most ankle eversion/inversion injuries. Countermeasures to mitigate for ankle eversion/inversion injuries may need additional research. However, the inclusion of energy absorbing material in the toepan as demonstrated by Mercedes could be beneficial to the ankle as well as the foot, and should be encouraged by incentivizing lower foot acceleration in the Female NCAP test. The test should require a minimum distance between the toepan and the feet of the 5% Female right front passenger.

Yoganandan (1996) published a compilation of dynamic impact tests to the feet of human specimens that produced foot and ankle injuries. Based on the test results, he produced injury risk curves and an injury risk formula that included age of the injured subject. A dynamic axial force of 3.7 kN produced a 10% injury risk. A 20% injury risk occurred at 4.7 kN. However, for a 65 year old specimen, the 4.7 kN force resulted in a 30% injury risk.

Foot/ankle injury assessment could be made by attaching force measurement instrumentation to the shoes of the dummy or by translating the force measurements to foot acceleration and setting limits on the latter. This translation may require testing the dummy lower limbs in a similar mode to the human specimen tests that produced the injury risk curves. This improvement should be incorporated in existing NCAP for during the near term. For a longer-term objective, tests and countermeasures for ankle inversion/eversion injuries should be developed.

The testing summarized by Yoganandan involved only axial loading. As noted by Ishikawa (1996) and as observed in NHTSA research tests (Figures 9, 10 and 11) lateral acceleration is present in vehicle-to-vehicle offset crashes. A comparison of the NCAP frontal tests (Figures 6a, 6b and 7) NHTSA oblique/overlap tests (Figures 9 and 10) clearly show that the lateral acceleration increases the extent of ankle inversion/eversion. Consequently, the final Female NCAP should include a test condition that induced lateral acceleration that is typical of on-the-road offset crashes. Ishikawa found that the offset deformable barrier test in common use did not satisfy that condition.

Begeman has conducted several studies that involve human specimen tests to determine ankle injury tolerance (Begeman 1993,1994 and 1996). In his study of inversion/eversion, he found that 50 degrees produced a 10% risk of ankle injury (Begeman, 1993). The ankle of the dummy would need to be correlated with the ankle of tested specimens in order to base a Female NCAP rating on this injury risk metric

Based on the CISS field injury data (Figure 5), a reduction of foot/ankle injuries should be a goal of Female NCAP. Some reduction should occur from controlling the dynamic force transmitted to the foot by the toeboard. That capability should be immediately incorporated in NCAP by measuring the foot dynamic force or the acceleration. Limiting the dynamic force to less than 10% injury risk should be a goal. Possible countermeasures include energy absorbing toepans (Figure 21) and seat cushion air bags, as are present in some Toyota vehicles.

Figure 6a shows a brake pedal that was relatively stable during the crash. The position is almost the same at each of three time periods, and the measured static intrusion was + 5 mm. Figure 6b shows a brake pedal that intrudes rapidly during the initial .06 seconds of the crash. The measured static intrusion was -110 mm. However, the position of the brake pedal when the static intrusion was measured post-crash does not capture the extent of brake pedal motion or its velocity.

In view of the high percentage (62%) of female driver foot and ankle injuries in CISS that occur during braking, it is evident that some safety features of the brake pedal should be included in a Female NCAP. The variability of brake pedal motion as displayed in the series of frontal crash tests with the 50% male THOR positioned as the driver clearly demonstrate that differences exist in brake pedal performance across vehicle models (Figure 6). As a minimum, a Female NCAP should limit brake pedal displacement and velocity during the NCAP test. EuroNCAP 2023 has discouraged pedal intrusion by penalizing a pedal blocked with a 200N force when its intrusion exceeds 50 mm. (EuroNCAP, 2022). Adoption of the EuroNCAP criteria in a Female NCAP could offer incentives for an immediate improvement in brake pedal stability and an associated reduction in dynamic loading of the right foot.

DISCUSSION: COMPATIBILITY

Figure 1 shows that females are more likely to be in lighter cars and males in heavier vans and pickups. This observation suggests the need to better control the aggressivity of pickups and other heavy vehicles in order to reduce their crash severity, especially at lower speeds where most injuries occur (See Figures 3c, 4c and Table A3). While females in lighter vehicles are expected to be the largest benefactors, even heavier vehicle occupants could benefit during collisions with fixed objects and other heavier vehicles. In addition, the occupants of vehicles involved in side impacts would benefit from bullet vehicles with more compatible front structures.

Figure 13 compares the stiffness of a compact car with a pickup and two electric vehicles. The initial stiffness of the electric Tesla X is a closer match to the small car than the electric Polestar 2. However, after the initial 350 mm the Tesla X is stiffer than Polestar 2. The higher stiffness of the heavier vehicles suggests that making electric vehicles stiffness compatible is not a design priority. Requiring stiffness compatibility in a Female NCAP would incentivize this compatibility improvement.

It may be noted in Figure 16 that the location of the maximum force for the Tesla X electric vehicle is close to the height of the max force of the Focus. The pickup tends to exert the max force at a higher level on the barrier. Figure 15 shows how the Average Height of Force varies with displacement for the three vehicles. The difference in Average Height of Force suggest that the pickup would tend to override the smaller vehicle more than the electric vehicles. The better alignment of electric vehicle crash forces should result in added structural engagement and increase the benefit to be expected from control of the stiffness of the heavier electric vehicles.

In order to improve stiffness compatibility, it would be desirable to design all vehicles so that their initial frontal stiffness is limited. Figure 19 shows the stiffness plot for a fixed barrier crash of a concept vehicle designed for stiffness compatibility. Either vehicle acceleration or barrier force are candidates for use in controlling initial vehicle stiffness. For an initial 400 mm of vehicle crush, there is a structural force or acceleration plateau that provides for structural stiffness compatibility. This structural force plateau will limit the force transmitted to both vehicles in lower severity vehicle-to-vehicle collisions. Consequently, occupants of both vehicles would benefit from the lower vehicle accelerations. Lower accelerations would also benefit compatible vehicle occupants in low severity single vehicle collisions with fixed objects.

Two different acceleration plateaus are shown in Figure 19 – the lower one for compatibility and the higher one for self-protection. The optimum vehicle crush and acceleration levels for these plateaus will require added research and analysis to determine.

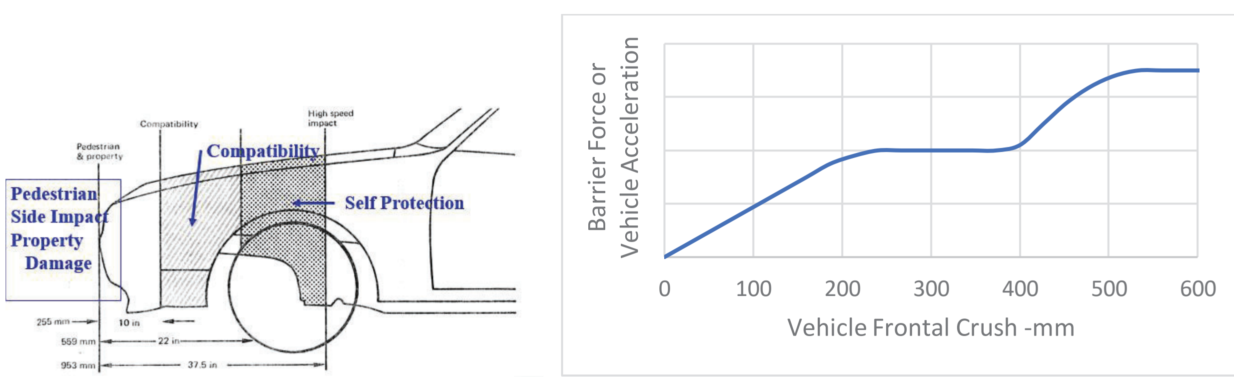


Figure 19. Vehicle Frontal Stiffness Compatibility Concept

CONCLUSIONS

The research presented here supports a Female NCAP that encourages safety improvements in three areas: (1) Chest injury reduction, (2) Lower Limb injury reduction and (3) Improved Vehicle Stiffness Compatibility. Improved Compatibility should focus on reducing the crash severity in lower speed two-vehicle collisions where females are most frequently injured.

An earlier study found that risk reduction of thorax injuries has lagged the safety improvements for other body regions, resulting in an increasing prevalence among skeletal thorax injuries in newer model year vehicles (Foreman 2019). Samaha, 2010, Sahraei 2009, 2013 found that increasing frontal stiffness had increased chest injury measurements for rear seat occupants and that improvements in safety belt technology had permitted front seat dummies to accommodate increased vehicle stiffness in NCAP crash tests. As shown in Figure 2, chest injuries are a large source of HARM for both male and female belted front seat occupants. The female AIS 2+ chest injuries occur mostly (70% Figure 3b) at the lower 0 to 47 kph speed range. Since the existing NCAP has not adequately encouraged chest injury reductions in the vehicle fleet, changes should be incorporated by way of a Female NCAP.

An immediate change should be an improvement of chest injury measurement via a better control of the shoulder belt position so that it engages the chest deflection gauge on the dummy chest. (See Digges 2017 for a detailed evaluation.) In the near term, the accuracy of chest injury measurements on the right front passenger should be improved by incorporating rib-rye gauges in the 5% Female Hybrid III dummy chest (See Digges 2019 for detailed analysis and discussion.). In addition, older female injury risk criteria should be applied to the 50% Male HIII (Figure A1) and the risk curves should be scaled by a factor of .817 when applied to the 5% female (Mertz 1997). Finally, audit testing at lower speeds should be conducted to ensure that injury risks are reduced at the deltaV's where most injuries occur.

Because females have increased presence in lighter vehicles (Figure1) they are more frequently exposed to crashes with heavier vehicles and could benefit most from improved front structure compatibility. Figure 14 shows the mass difference between a small car, a pickup and two electric vehicles. The higher mass of the electric vehicles and the increasing presence of these vehicles in the fleet suggest an urgent need to limit the stiffness aggressiveness of these vehicles. Research by Sahraei (2013) and Samaha (2010) indicates that much of the benefits of force-limited and pretensioned belts has been offset by the increased stiffness of vehicle front structures. This increase in stiffness increases the vehicle acceleration for each added increment of vehicle deformation during collisions, thereby increasing the crash severity. Figure 12 illustrates the structure deformation difference between two current on-the-road vehicles. Small deformation increments of the heavier vehicle structure cause much larger deformation increments in the lighter vehicle. This relationship contributes to the high fatality rates when car drivers collide with heavier vehicles as has been reported by Gabler (1998) and Joksch (1998).

Figure 13 shows that stiffness incompatibility exists not only in pickups, but also in some electric vehicles such as Tesla X and Polestar 2. It may be observed in Figures 15 and 16 that the geometric compatibility of the Tesla electric vehicle is a closer match with the small car than the pickup. This geometric match of the structures will tend to increase the vehicle acceleration for a given deltaV. In view of the large number of heavier electric vehicles expected to enter the fleet, it is imperative that Female NCAP address the resulting stiffness incompatibility issue that could result.

In order to encourage the added technology of inflatable belts, further improvements in chest injury measurement may be required. The research by Goto (2020) indicates that the THOR dummy gages may not adequately measure the beneficial pressure distribution of inflatable belts as compared to the conventional belts. This is because the conventional belt may not engage the existing chest deflection gages. The application of a pressure sensing vest may be required to encourage inflatable belts for a mid-term Female NCAP. It may be noted that a pressure sensing garment is being used on the dummies in the new IIHS protocol for the Frontal Offset Test (IIHS 2022).

Figure 4 shows the Female Lower Extremity injuries are about equally divided between the two speed ranges and age groups. However, more older females are injured in the lower speed range. Figure 5 shows that over half the

Female Lower Extremity injuries are foot/ankle injuries. This suggests the need to immediately address foot/ankle injuries in the existing frontal NCAP test. This could be done by penalizing vehicles with foot accelerations that produce greater than 10% injury risk. According to Yoganandan (1996) a dynamic force of 3.7 kN would cause a 10% injury risk to the foot/ankle body region. The test should require a minimum distance between the toeboard and the feet of the 5% female right front passenger. This near-term addition to NCAP is expected to encourage known improvements such as energy absorbing toe-pans (Figure 18) and innovative new technology such as seat cushion air bags.

The issue of ankle inversion/eversion injuries in crashes with lateral acceleration should be the subject of continuing research to determine appropriate countermeasures and associated test conditions and injury criteria. However, based on Yoganandan (1996) criteria, limiting the force transmitted to the foot in an NCAP frontal crash could be initiated in the near term and should provide benefits.

As shown in Figure 6, there is a large vehicle to vehicle difference in the brake pedal motion during an NCAP like frontal test. For CISS Well Defined Frontal Single Vehicle Crashes with EDR data, 79% of the Female Lower Limb injuries occurred with braking was indicated as present. For female foot/ankle injuries with braking, 70% were to the right foot. This data suggests an opportunity to reduce foot/ankle exposure to injuries induced by brake pedal motion by controlling the pedal intrusion. EuroNCAP (2022) proposes a method of brake pedal penalties that should be immediately incorporated in a Female NCAP.

These studies confirm earlier research that shows the chest and lower limbs as priority body regions for improved female protection. Females are generally exposed to crashes at lower severity than males. For Female AIS 2+ injuries, the percentage that occur in the 0 to 47 kph range are: Head/neck – 90%; Thorax – 65%; Spine – 71% and Upper Extremity – 83%. This suggests the need to ensure that the improved protection at crash speeds below the NCAP frontal test. A lower speed NCAP crash test may be necessary to address the majority of female injuries.

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APPENDIX A

Table A1

Average Cost of Injury in US$ 000s (1988 prices) from Miller, et al (1990).

	INJURY SEVERITY					
BODY	Minor	Moderate	Serious	Severe	Critical	Maximum
REGION	(AIS = 1)	(AIS = 2)	(AIS =3)	(AIS = 4)	(AIS = 5)	(AIS = 6)
EXTERNAL	*3*	*16*	*45*	*73*	*106*	*644*
HEAD	4	19	78	180	636	644
FACE	4	19	78	103	211	644
NECK	4	19	78	103	211	644
CHEST	3	16	45	73	106	644
ABDOM/PELVIC	3	16	45	73	106	644
SPINE	3	16	105	905	1082	644
UPPER X	4	28	66			
LOWER X	3	28	84	124	*211*	

Table A2

AIS 2-6 Injuries to FEMALES in Well-defined Frontal Crashes by Body Region and Age Groups

BODY REGION	16 TO 49 YRS	50 TO 99 YRS	ALL	16 TO 49 YRS	50 TO 99 YRS	% of Body Regions
HEAD/NECK	26,354	14,055	40,410	65%	35%	18%
FACE	2,943	269	3,212	92%	8%	1%
THORAX	10,923	40,283	51,206	21%	79%	23%
ABDOMEN	8,614	7,513	16,127	53%	47%	7%
SPINE	6,490	16,317	22,808	28%	72%	10%
UPPER X	29,004	16,355	45,359	64%	36%	21%
LOWER X	18,417	22,210	40,627	45%	55%	18%
ALL	102,745	117,003	219,748	47%	53%	100%

Table A3
AIS 2-6 Injuries to FEMALES in Well-defined Frontal Crashes by Body Region and DeltaV Groups

BODY REGION	01 - 47 KPH	48 - 126 KPH
HEAD/NECK	90%	10%
FACE	43%	57%
THORAX	65%	35%
ABDOMEN	32%	68%
SPINE	71%	29%
UPPER X	83%	17%
LOWER X	51%	49%
ALL	69%	31%

Table A4
AIS 2-5 Weighted Thorax and Lower Extremity Injuries in CISS 2017-2020 Well-defined Frontal Crashes by Age, Gender and Crash Severity

	AGE / GENDER			
01 - 47 KPH	16 TO 49 YRS		50 TO 99 YRS	
REGION_DESC	FEMALE	MALE	FEMALE	MALE
THORAX	1,989	14,902	23,588	16,894
LOWER EXTREMITY	5,741	4,612	8,704	2,797
	AGE / GENDER			
48 - 126 KPH	16 TO 49 YRS		50 TO 99 YRS	
REGION_DESC	FEMALE	MALE	FEMALE	MALE
THORAX	8,655	4,249	5,103	6,519
LOWER EXTREMITY	8,926	3,807	5,119	7,012

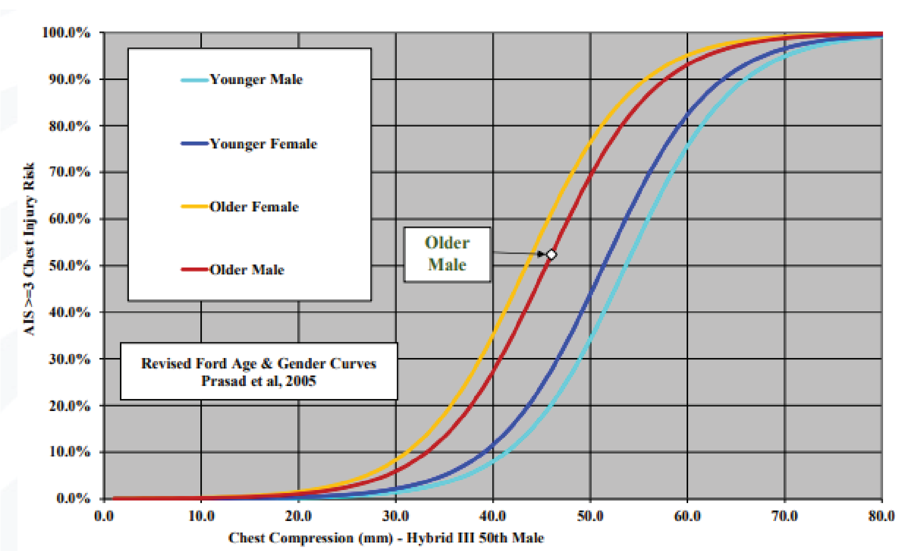

Figure A1. Risk of AIS 3+ Chest Injury Based on HIII 50% Male Dummy Measurements (Prasad 2004)

HOW GENDER PREFERENCES FOR VEHICLE SIZE/CLASS INFLUENCE FATALITY OUTCOMES

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Paper Number 23-0337

ABSTRACT

In recent years, the issue of gender equity in real-world crash protection has been the focus of a great deal of research [1, 2, 3, 4]. Concerns that females may be subject to elevated risks of injury relative to their male counterparts under similar circumstances have prompted a debate over the need for a 50th percentile female dummy.

Early automotive testing concentrated on crash test dummies with 50th percentile male characteristics. By the mid 1990s there was general recognition of a need to expand the family of dummies to address a wider range of the population. Initially, the use of a smaller female dummy was prompted by the introduction of frontal airbags and the need to put design controls in place to address proximity issues to the airbags. However, this was quickly followed by an appreciation of the benefits and the need for the "family of dummies" approach in side impact testing as well as in frontal testing.

More recently, the possibility has been raised that some of the risk disparity between males and females may not be physiological, but may be related to vehicle preferences between males and females [5].

The present study is one in a series of investigations which seek to determine the extent to which injury outcome differences by gender are driven by different male and female preferences for vehicle size and class.

METHODS AND DATA COLLECTION

The current work is based on an analysis of Fatality Analysis Reporting System (FARS) data for calendar years 1993 to 2020. The dataset was restricted to well-defined fatal two-vehicle crashes between 1994 model year and later light duty vehicles (cars, light trucks, and vans).

To be included in the sample, the gender, the age, and the seating position of all occupants involved in the collision had to be reported. This was done to facilitate the definition of injury outcome metrics for the collision as a whole, the vehicle occupied, as well as for the partner vehicle in the collision. A further requirement was that vehicle identification numbers (VINs) for both vehicles had to be reported so that the size and class of each vehicle could be categorized. This, in turn, allowed the analysis to examine driver survival rates as a function of gender and age, in fatal two-vehicle crashes of both similar and different classes of vehicles.

Parallel well-defined single vehicle and two-vehicle datasets with the same restrictions were constructed using the Collision Reporting Sampling System (CRSS). The CRSS single vehicle subset consisted of 34,780 drivers (4,864,877 weighted). The CRSS two-vehicle subset consisted of 183,810 drivers (25,208,458 weighted). The FARS two-vehicle subset consisted of 136,612 drivers.

RESULTS

The representation of females among drivers involved in well-defined single vehicle and two-vehicle collisions in the CRSS dataset as a function of vehicle type/size is depicted in Figure 1. In the case of the larger dataset for two-vehicle collisions, a complimentary analysis was performed to explore vehicle preferences considering driver gender and age. For this expanded analysis, two age groups were considered, drivers under 50 years of age and drivers 50 years of age or older. The results from the expanded analysis are summarized in Table 1.

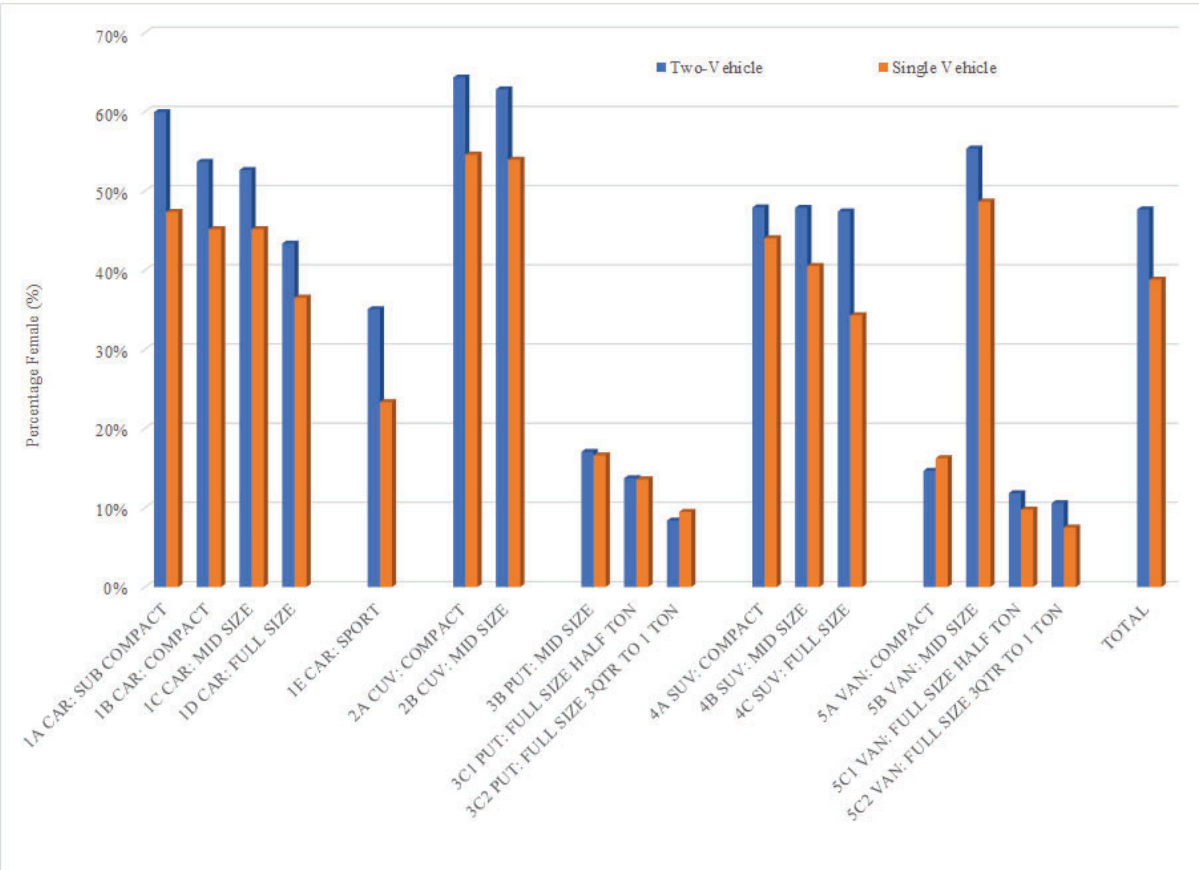

Figure 1. Female Representation Among Drivers as a Function of Vehicle Type/Size Class and Collision Configuration (CRSS).

The female driver representations reflected in Figure 1 highlight the strong preference of females to favor smaller/lighter vehicles. The findings also highlight the extremely low representation of females in the case of pickups (< 15%) and larger vans (<14%). In the case of vans, we can see that the representation of females as drivers is high, but it is highly concentrated in mid-sized vans. When we further consider driver age, we can observe in Table 1 a bias towards sub-compact cars in the case of younger females. On the other hand, older males reflect a bias towards full-size cars. Consequently, any gender-risk analysis must consider these vehicle choice preferences. This necessity can be easily appreciated if we examine the driver survival (rates by gender in pickup-to-car collisions (Figure 2).

From the results presented in Figure 2, we can see the survival rates in these collisions are strongly influenced by vehicle occupied and the age of the occupant. When we control for these factors, there are minimal "gender" influences on the driver survival rates.

Table 1.
Representation of Drivers Collision Exposures by Gender and Age Grouping as a Function of Vehicle Type and Class/Size (CRSS 2017-2020, Two-Vehicle Collisions, All Collision Severities)

WEIGHTED DATA		GENDER/ AGE GROUP				
VEHICLE TYPE	**VEHICLE CLASS/SIZE**	**F, 15 TO 49 YRS**	**F, 50 TO 120 YRS**	**M, 15 TO 49 YRS**	**M, 50 TO 120 YRS**	Grand Total
CAR	CAR: SUB COMPACT	44.5%	15.4%	29.6%	10.5%	100.0%
	CAR: COMPACT	41.3%	12.4%	36.2%	10.1%	100.0%
	CAR: MID SIZE	38.3%	14.3%	35.0%	12.3%	100.0%
	CAR: FULL SIZE	28.3%	15.0%	39.1%	17.6%	100.0%
	CAR: SPORT	26.5%	8.4%	51.7%	13.3%	100.0%
CAR TOTAL		**37.9%**	**13.5%**	**36.6%**	**12.1%**	**100.0%**
CUV	CUV: COMPACT	40.7%	23.6%	21.8%	13.8%	100.0%
	CUV: MID SIZE	40.6%	22.2%	21.8%	15.4%	100.0%
CUV TOTAL		**40.7%**	**23.1%**	**21.8%**	**14.4%**	**100.0%**
3 PUT	3A PUT: COMPACT	9.0%	5.8%	56.0%	29.1%	100.0%
PUT	PUT: MID SIZE	10.4%	6.6%	49.5%	33.6%	100.0%
	PUT: FULL SIZE HALF TON	9.4%	4.4%	53.8%	32.5%	100.0%
	PUT: FULL SIZE ¾ TO 1 TON	5.8%	2.5%	59.6%	32.1%	100.0%
PUT TOTAL		**9.1%**	**4.6%**	**53.6%**	**32.7%**	**100.0%**
SUV	SUV: COMPACT	36.6%	11.2%	36.0%	16.3%	100.0%
	SUV: MID SIZE	35.0%	12.8%	36.0%	16.2%	100.0%
	SUV: FULL SIZE	36.8%	10.6%	36.2%	16.4%	100.0%
SUV TOTAL		**35.8%**	**11.9%**	**36.0%**	**16.3%**	**100.0%**
VAN	VAN: COMPACT	8.5%	6.2%	56.1%	29.2%	100.0%
	VAN: MID SIZE	38.4%	17.0%	24.8%	19.8%	100.0%
	VAN: FULL SIZE HALF TON	6.8%	4.8%	56.3%	32.2%	100.0%
	VAN: FULL SIZE ¾ TO 1 TON	7.4%	3.2%	59.3%	30.1%	100.0%
VAN TOTAL		**28.6%**	**12.9%**	**35.3%**	**23.2%**	**100.0%**
ALL TOTAL		**33.8%**	**13.9%**	**36.0%**	**16.4%**	**100.0%**

Further appreciation of the need to carefully consider the specific vehicle pairings in two-vehicle collisions when calculating gender-risk metrics can be gained from the three vehicle pairing scenarios depicted in Table 2. First, let us consider the baseline car-to-pickup scenario (C1). Here we can see the overall driver survival rate is 56.9% and is made up by unadjusted (no control for vehicle occupied) survival rates of 39.8% and 63.4% for female drivers and male drivers, respectively. When we control for vehicle class, the survival rates differ greatly as a function of vehicle occupied, 29.4 % for car drivers and 84.5% for pickup truck drivers. However, we see little difference in the adjusted survival rates as a function of gender.

Next, let us consider how survival rates change when we reduce the size/mass of the car and increase the size/mass of the pickup. This scenario (C2) can be assumed to be approximated by pairing compact cars with full-size pickups. With this pairing, the car driver survival rate decreases to 23.4% while the pickup driver survival rate increases to 90.5%. However, we again see little difference in the adjusted survival rates as a function of gender.

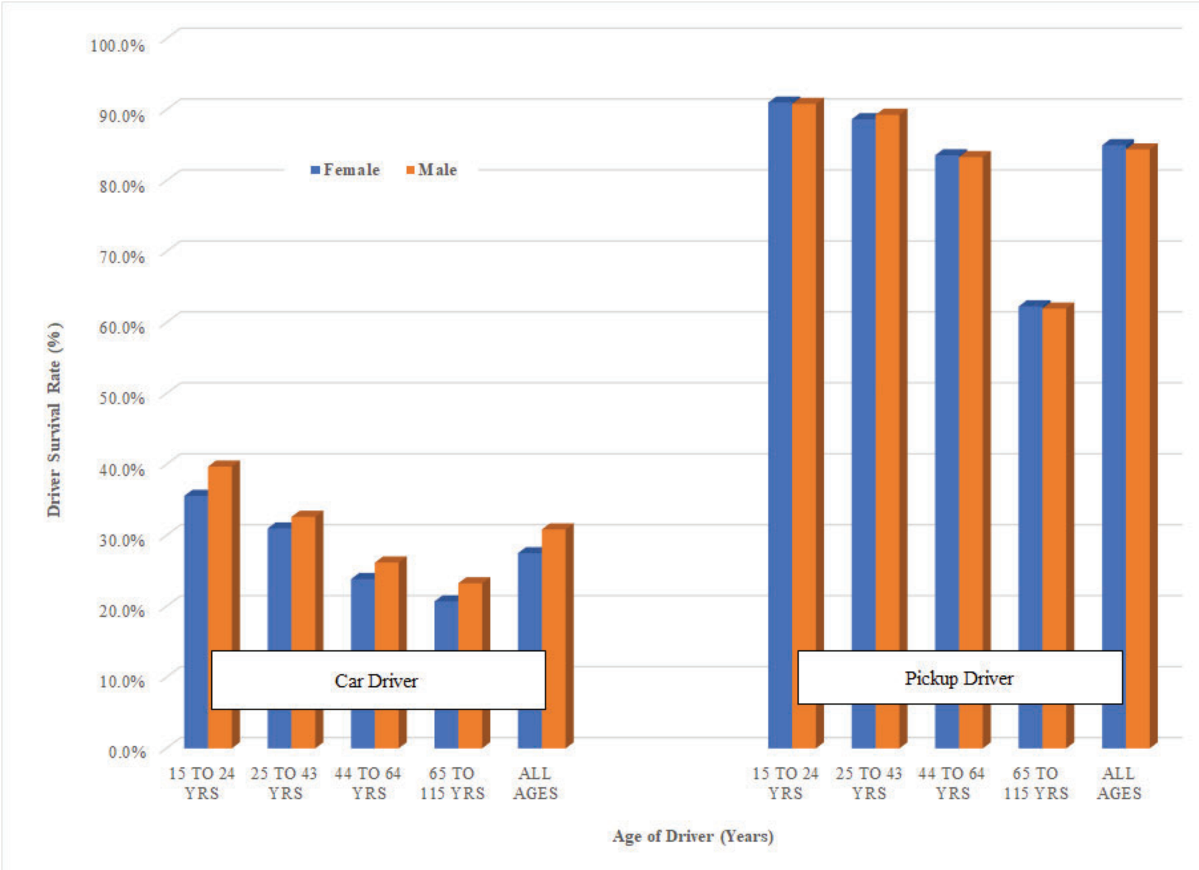

Figure 2. Driver Survival Rates in Car collisions-to-Pickup by Gender as a Function of Vehicle Occupied and Occupant Age Grouping (FARS).

In the final car-to-pickup scenario (C3), we increase the class/size of the car to mid-size while maintaining class/size of the pickup (full-size pickup). With this pairing, the car driver survival rate increases to 25.9% while the pickup driver survival rate decreases to 88.4%. As in the previous two scenarios, we see little difference in the adjusted survival rates as a function of gender.

In all three of the above scenarios, we see a negligible change in the overall driver survival rate for the collision (~ 57%). The changes in survival rates at the vehicle level appear to reflect the traditional trade-off between self-protection and partner protection when mass changes are introduced. In the case of two of the above scenarios (C1 and C3), the female pickup survival rate exceeded the male rate. In all three scenarios, the female car survival rate was marginally lower than that of their male counterparts. The magnitude of the differences could easily be explained due to the trend for females to select lighter/smaller vehicles.

Driver survival rates as a function of gender were also investigated for additional collision scenarios. The first of these (C4) focused on car-to-car collisions between compact and mid-sized cars. The second (C5) focused on collisions between vehicles of the same size class. These results are depicted in Tables 3 and 4, respectively. As expected, in Scenario C4 , the vehicle pairing resulted in the mid-sized car showing a higher driver survival rate than the compact car for both genders. In the two car-to-car vehicle pairings depicted in Scenario C5, the female and male survival rates were identical, while in the pickup-to-pickup vehicle pairing the female survival rate was only slightly lower than the male rate.

Table 2.
Driver Survival Rates for Selected Car-to-Pickup Collisions by Gender of Driver

	VEHICLE PAIRING	VEHICLE OCCUPIED	GENDER OF DRIVER	SURVIVAL RATE (%)	EXPOSURES
C1	1 CAR; 3 PUT		Female	39.8%	9,204
			Male	63.4%	24,454
	1 CAR; 3 PUT Total		ALL	56.9%	33,658
	1 CAR; 3 PUT	1 CAR	Female	27.5%	7,230
			Male	30.9%	9,599
		1 CAR Total		29.4%	16,829
		3 PUT	Female	85.0%	1,974
			Male	84.4%	14,855
		3 PUT Total		84.5%	16,829
	1 CAR; 3 PUT Total		ALL	56.9%	33,658
C2	VEHICLE PAIRING	VEHICLE OCCUPIED	GENDER OF DRIVER	SURVIVAL RATE (%)	EXPOSURES
	1B CAR: COMPACT; 3C PUT: FULL SIZE		Female	34.6%	2,550
			Male	66.1%	6,270
	1B CAR: COMPACT; 3C PUT: FULL SIZE Total			57.0%	8,820
	1B CAR: COMPACT; 3C PUT: FULL SIZE	1B CAR: COMPACT	Female	21.7%	2,072
			Male	24.9%	2,338
		1B CAR: COMPACT Total		23.4%	4,410
		3C PUT: FULL SIZE	Female	90.4%	478
			Male	90.6%	3,932
		3C PUT: FULL SIZE Total		90.5%	4,410
	1B CAR: COMPACT; 3C PUT: FULL SIZE Total			57.0%	8,820
C3	VEHICLE PAIRING	VEHICLE OCCUPIED	GENDER OF DRIVER	SURVIVAL RATE (%)	EXPOSURES
	1C CAR: MID SIZE; 3C PUT: FULL SIZE		Female	36.8%	2,055
			Male	64.8%	5,629
	1C CAR: MID SIZE; 3C PUT: FULL SIZE Total			57.3%	7,684
	1C CAR: MID SIZE; 3C PUT: FULL SIZE	1C CAR: MID SIZE	Female	24.4%	1,676
			Male	27.1%	2,166
		1C CAR: MID SIZE Total		25.9%	3,842
		3C PUT: FULL SIZE	Female	91.8%	379
			Male	88.4%	3,463
		3C PUT: FULL SIZE Total		88.8%	3,842
	1C CAR: MID SIZE; 3C PUT: FULL SIZE Total			57.3%	7,684

Table 3.
Driver Survival Rates Observed in Compact Car-to-Mid-Sized Car Collisions by Gender of Driver

	VEHICLE PAIRING	VEHICLE OCCUPIED	GENDER OF DRIVER	SURVIVAL RATE (%)	EXPOSURES
C4	1B CAR: COMPACT; 1C CAR: MID SIZE		Female	57.0%	3,064
			Male	57.4%	4,244
	1B CAR: COMPACT; 1C CAR: MID SIZE Total			57.2%	7,308
	1B CAR: COMPACT; 1C CAR: MID SIZE	1B CAR: COMPACT	Female	45.4%	1,570
			Male	47.2%	2,084
		1B CAR: COMPACT Total		46.4%	3,654
		1C CAR: MID SIZE	Female	69.3%	1,494
			Male	67.2%	2,160
		1C CAR: MID SIZE Total		68.0%	3,654
	1B CAR: COMPACT; 1C CAR: MID SIZE Total			57.2%	7,308

Table 4.
Driver Survival Rates by Gender Observed in Collisions between Vehicles of Identical Size Class

	VEHICLE PAIRING	VEHICLE OCCUPIED	GENDER OF DRIVER	SURVIVAL RATE (%)	EXPOSURES
C5	3C PUT: FULL SIZE; 3C PUT: FULL SIZE	3C PUT: FULL SIZE	Female	49.45%	362
			Male	52.69%	3,122
		3C PUT: FULL SIZE Total		52.35%	3,484
	1B CAR: COMPACT; 1B CAR: COMPACT	1B CAR: COMPACT	Female	56.33%	1,573
			Male	56.93%	2,185
		1B CAR: COMPACT Total		56.68%	3,758
	1C CAR: MID SIZE; 1C CAR: MID SIZE	1C CAR: MID SIZE	Female	56.2%	1,442
			Male	55.4%	1,940
		1C CAR: MID SIZE Total		55.7%	3,382

DISCUSSION

The present study highlights the need, in any investigation of gender-risk, to consider and control for not only what vehicle is being occupied, but also the characteristics the other involved vehicle in the case of two-vehicle collisions.

The FARS database is confined to very severe crashes which produced at least one fatality. Consequently, what is not clear is the extent to which the present findings can be generalized to less severe crashes. This issue is being addressed through additional analyses of Canadian and US databases.

Historically, establishing the belt use status of individuals, and quantifying crash severity accurately, has proven problematic. With the increasing availability of data from Event Data Recorders (EDR), these problems have been reduced. As EDR databases grow in numbers, the ability to utilize these data to address gender-related risk issues is increasing yearly.

ACKNOWLEDGEMENTS

Initial funding of this investigation into how gender risk may be influenced by differing vehicle preferences was provided by the Alliance of Auto Manufacturers (2019). More recently, substantial parts of the investigation were funded by the Automotive Safety Reseach Institute (ASRI).

The authors would like to thank Glenn Robbins for generating the SAS code to partition the FARS and CRSS datasets into well-defined single vehicle and two vehicle collisions. As well, the authors wish to acknowledge Alan German for his efforts in editing the paper.

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