Evaluation of Adaptive Belt Restraint Systems for the Protection of Elderly Occupants in Frontal Impacts

Krystoffer Mroz, Bengt Pipkorn, Cecilia Sunnevång, Andre Eggers, Dan Bråse

Abstract The effect of belt configuration, load limiting and pretensioning on the protection of elderly occupants was evaluated using the THOR ATD and the human body model THUMS TUC in frontal impacts at 35 km/h and 56 km/h. In total, 18 sled tests were carried out in a generic buck, which comprised of a seat-belt, a rigid seat and a generic driver airbag. The multipoint injury criteria Rmax and PCA score were derived from THOR IR-TRACC deflections and used to assess the thoracic injury risk for elderly occupants.

For a 65-year-old occupant in 35 km/h, a reduction in Rmax-based AIS3+ chest injury risk from 62% to 2% was obtained for the criss-cross belt compared to a 4 kN load limited belt, and a reduction to 14% for a two-retractor belt and to 17% for a split-buckle belt. In 56 km/h, reduction in AIS3+ chest injury risk from 96% to 23%, 76% and 43% was obtained for the corresponding belt systems. Similar reductions in chest injury risk were obtained for the PCA measure. For the THUMS model, risk of fractured ribs reduced from 74% to 0% for the criss-cross system compared to a 4 kN load limited belt in 35 km/h.

Keywords Belt, Chest injury, Frontal impact, THOR, Elderly THUMS.

I. INTRODUCTION

Accident data analysis has shown that the thorax is the most frequently injured body region for car occupants, followed by the head [1]. It was also found that the risk of AIS2+ and AIS3+ thorax injuries is higher for elderly occupants (65yo+) than for mid-aged occupants (25–64yo). The thorax injury risk for elderly occupants is also high in low and moderate frontal impact severities [2]. As the population of elderly occupants is increasing [3], there is a need to introduce restraint systems with enhanced protection for the more frail and fragile occupants. To support such development and implementations, legal and consumer tests can be expanded to include a less severe impact condition [4].

Previous studies have shown that the THOR dummy is more biofidelic than the currently used Hybrid III [5,6] and also more sensitive to restraint variations, as well as able to differentiate injury risk in lower severities [7,8]. The introduction of THOR provides opportunities to evaluate the potential injury reductions accomplished by new restraint systems as well as the protection level in lower impact severity.

Currently on the market, and installed in some modern vehicles, is the adaptive load limiter. The benefit of such a system was also more pronounced using THOR compared to Hybrid III [7]. More novel restraints, such as the multipoint belt or a split between shoulder and lap belt, have also been shown to be effective in reducing chest deflection. The potential of 4-point criss-cross type belt systems to reduce the risk of chest injuries has been shown in frontal impact sled tests using the THOR ATD [9,10]. Reduced chest deflections and number of rib fractures was obtained in PMHS sled tests by using a 4-point harness-type V4 belt [9], in which the two shoulder belts form a V to a central connection point on the lower chest were also the two lap belts are connected to. It was found that the V4 belt performed well because the load to the human body was transferred mainly through the clavicles and pelvis.

The potential benefit of a 3+2 criss-cross system to reduce AIS2+ chest injuries in real-world crashes was estimated using THOR and THUMS human body simulations in combination with NASS and GIDAS accident data [11]. It was shown that 22% and 25% of all AIS2+ injuries in the USA and Germany, respectively, can be

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prevented. The assessment of a belt system with separate shoulder and lap belts, a split buckle concept, was carried out in sled tests using THOR and PMHS [12]. Reduced chest deflection was obtained for the THOR dummy and reduced number of fractures in the PMHS using the split buckle belt compared to a reference 3-point belt system.

With the purpose of evaluating the protection capability of the criss-cross belt for potential chest loading outside the THOR IR-TRACC measurement points, a modified version of the finite element (FE) human body model (HBM) THUMS (Total Human Model for Safety) adult male 50th model [13] was used. The original THUMS model was further developed by the project THUMS User Community (TUC) by validating the model by means of biomechanical data [14]. In the SENIORS project, the THUMS TUC thorax was adapted to represent an elderly (65+ year old) geometry and age-related material changes were implemented to the rib cortical bone and costal cartilage [15]. The elderly THUMS TUC was then validated to the table top PMHS tests reported in [16,17]. The risk to sustain rib fractures for the THUMS model was assessed using a probabilistic fracture prediction approach [18].

The objective of this study was to evaluate the effect of belt configuration, load limiting level and belt pretensioning on the protection level for elderly occupants in frontal impacts. The investigation was carried out for the chest using thoracic deformations from the THOR-M 50th ATD and rib strains from the human body model THUMS TUC.

II. METHODS

The investigation was carried out by means of mechanical sled tests with the THOR ATD in a generic buck [19], which was developed in the SENIORS project with the objective of being more representative of modern vehicles in comparison to other, simplified generic sled test set-ups such as the gold standard set-up [20]. The generic buck comprised of a passenger side seat belt system, a rigid seat and a generic driver airbag. In total, 18 repeated sled tests were carried out in impact severities representing a rigid wall full frontal impact at 35 km/h and 56 km/h using the THOR-M 50th (build level SBL-A) anthropometric test device (ATD) (Table I and Table II).

Three seat-belt configurations were compared to a state-of-the-art double-pretensioned 4 kN load limited 3-point belt:

1. 3-point double-pretensioned two-retractor belt system (Fig. 1): a belt system with locked webbing transport through the buckle. In addition to the shoulder-belt retractor pretensioner, a lap-belt retractor pretensioner was used at the outer anchor. Two retractors were used to facilitate the routing of the belt on the occupant in which belt webbing from both retractors is pulled out.
2. Triple-pretensioned 3+2 criss-cross belt (Fig. 2): an additional pretensioned and load limited diagonal belt was added to the ”3-point two-retractor belt”, creating a criss-cross belt geometry.
3. Triple-pretensioned split buckle belt system (Fig. 3): a belt system with separate lap and diagonal belts. The diagonal belt was retractor pretensioned and load limited. The lap belt was equipped with double pretensioning using a retractor pretensioner and a lap pretensioner.

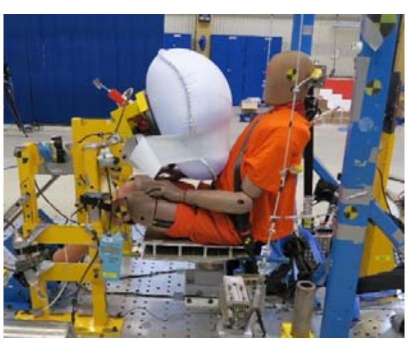

Fig. 1. The 3-point two-retractor belt with double pretensioning.

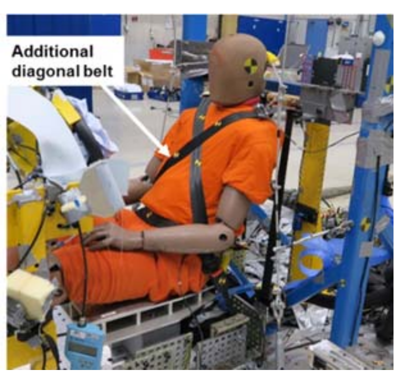

Fig. 2. The 3+2 two-retractor criss-cross belt with triple pretensioning.

Fig. 3. Split buckle belt with triple pretensioning.

Adaptive two-level load limiting was used for the 3-point two-retractor belt and the criss-cross belt (Table I and Table II). The shoulder load limiting level was adapted to the impact severity using a pre-defined switch time for the reduction of belt force from a high to a low level. For the 3-point two-retractor belt, the switch time of 20 ms was defined in the 35 km/h impact, leaving an effective load limiting force of 2 kN. In the 56 km/h impact, the high level 5 kN was used during a part of the crash by defining the switch time to 55 ms. For the criss-cross belt, 20 ms was used in 35 km/h and no switch between levels in 56 km/h. A full test matrix is given in Appendix 1.

TABLE I
THOR TESTS 35 KM/H (LL1=RETRACTOR LOAD LIMITING FORCE HIGH LEVEL, LL2=RETRACTOR LOAD LIMITING FORCE LOW LEVEL).

No	Test Id	Belt Configuration	Belt LL1 (kN)	Belt LL2 (kN)	LL1-LL2 Switch Time (ms)	Shoulder Belt Pret. Right	Shoulder Belt Pret. Left	Lap Belt Pret. Outboard	Lap Belt Pret. Inboard
1	403	3-pt	4,0	-	-	Yes	-	Yes	-
2	404	3-pt	4,0	-	-	Yes	-	Yes	-
3	405	3-pt	4,0	-	-	Yes	-	Yes	-
4	442	3-pt 2-ret	5,0	2,0	20	Yes	-	Yes	-
5	443	3-pt 2-ret	5,0	2,0	20	Yes	-	Yes	-
6	420	3+2 2-ret Criss-Cross	2,0+2,0	0,9+0,9	20	Yes	Yes	Yes	-
7	423	3+2 2-ret Criss-Cross	2,0+2,0	0,9+0,9	20	Yes	Yes	Yes	-
8	435	Split Buckle	6,0	-	-	Yes	-	Yes	Yes
9	436	Split Buckle	6,0	-	-	Yes	-	Yes	Yes

TABLE II
THOR TESTS 56 KM/H (LL1=RETRACTOR LOAD LIMITING FORCE HIGH LEVEL, LL2=RETRACTOR LOAD LIMITING FORCE LOW LEVEL).

No	Test Id	Belt Configuration	Belt LL1 (kN)	Belt LL2 (kN)	LL1-LL2 Switch Time (ms)	Shoulder Belt Pret. Right	Shoulder Belt Pret. Left	Lap Belt Pret. Outboard	Lap Belt Pret. Inboard
1	407	3-pt	4,0	-	-	Yes	-	Yes	-
2	408	3-pt	4,0	-	-	Yes	-	Yes	-
3	409	3-pt	4,0	-	-	Yes	-	Yes	-
4	438	3-pt 2-ret	5,0	2,0	55	Yes	-	Yes	-
5	439	3-pt 2-ret	5,0	2,0	55	Yes	-	Yes	-
6	427	3+2 2-ret Criss-Cross	2,0+2,0	0,9+0,9	1000	Yes	Yes	Yes	-
7	441	3+2 2-ret Criss-Cross	2,0+2,0	0,9+0,9	1000	Yes	Yes	Yes	-
8	437	Split Buckle	6,0	-	-	Yes	-	Yes	Yes
9	440	Split Buckle	6,0	-	-	Yes	-	Yes	Yes

The generic airbag was developed to allow for an adjustable distributed restraining of the occupant, using a design that can be recreated for future testing. The cushion is airtight and without vent holes. The airbag is pre-inflated using compressed air and the venting is controlled with an active venting device (Fig. 4). The force response of the airbag can be varied using initial pressure, venting size and venting activation time. The airbag size and shape can be changed by varying the length and the vertical position and width of the external strap.

In this study, a non-symmetrically shaped frontal airbag with reduced volume in the lower part was used with the low strap positioned as in Fig. 1 and Fig. 4. The airbag was pre-inflated to a target value of 19 kPa and the response was adapted to the impact severity by ventilation start at 50 ms to fully open at 60 ms into the impact. A typical airbag pressure for the 56 km/h impact is shown in Fig. 5.

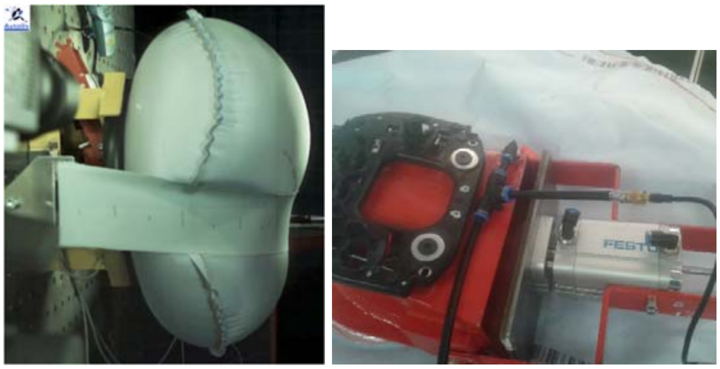

Fig. 4. Generic airbag with external strap (left) and venting device (right).

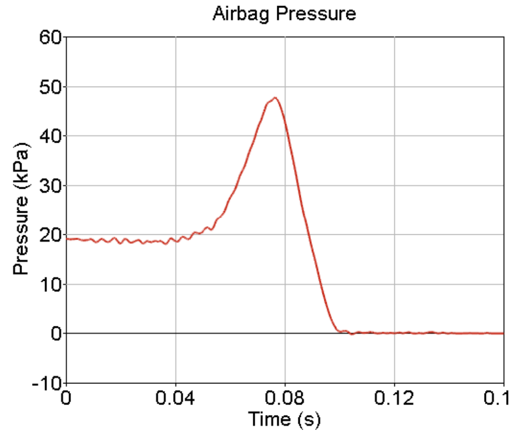

Fig. 5. Airbag pressure for the 3-point belt system in 56 km/h.

Acceleration of the SENIORS sled was carried out using a bending bars mechanical setup. The 35 km/h target pulse was chosen based on accident data analyses of frontal crashes involving elderly (65yo+) occupant casualties with thorax injuries, where a median delta-v of 30–35 km/h was found [21] (Fig. 6). The pulse was also used in other sled test studies with THOR and PMHS within SENIORS [22]. The 56 km/h target pulse corresponds to a full frontal rigid barrier impact for a mid-sized sedan vehicle. Compared to the 35 km/h target pulse, the peak acceleration was well matched, but with a softer initial build-up of acceleration. Compared to the 56 km/h target pulse, higher peak acceleration was obtained in the tests.

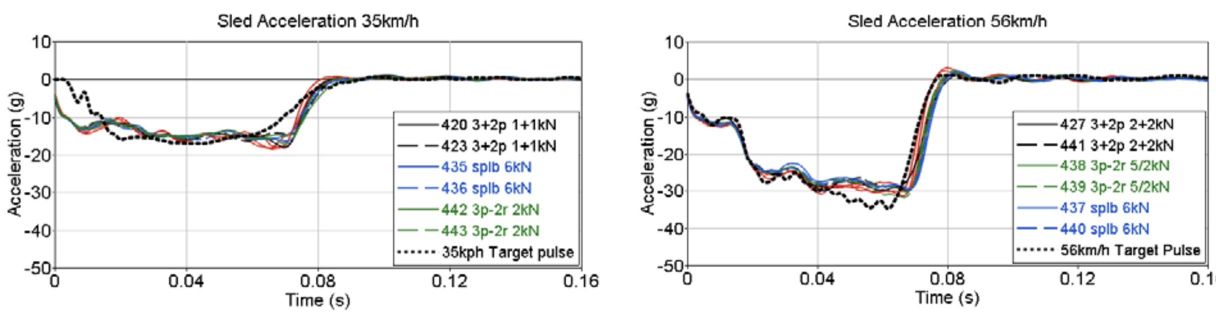

Fig. 6. Crash pulses 35 km/h (left) and 56 km/h (right).

Multipoint injury criterions peak resultant deflections, Rmax (Equation 1) and the PCA score (Equation 2) were derived from the THOR IR-TRACC deflection measurements and used to assess the thoracic injury risk for an elderly occupant based on age-dependent risk curves from the literature (Fig. 7) [23].

$$R_{max} = \max(UL_{max}, UR_{max}, LL_{max}, LR_{max}) \text{ and} \tag{1}$$

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

where R_{max} is the overall peak resultant deflection in mm, $[U/L|R/L]_{max}$ is the peak resultant deflection of the [upper/lower|left/right] quadrant in mm and $[L/R][X/Y/Z]^2_{[U/L]S}$ is the time-history of the [left/right] chest deflection along the [X/Y/Z] axis relative to the [upper/lower] spine segment in mm.

$$PCA\ Score = 0.485\left(\frac{up_{tot}}{17.509}\right) + 0.499\left(\frac{low_{tot}}{15.526}\right) + 0.493\left(\frac{up_{dif}}{10.479}\right) + 0.522\left(\frac{low_{dif}}{11.996}\right) \quad (2)$$

and $up_{tot} = |UL|_{max} + |UR|_{max}$

$low_{tot} = |LL|_{max} + |LR|_{max}$

$up_{dif} = |UL - UR|_{max}$

$low_{dif} = |LL - LR|_{max}$

where up_{tot} is the total upper chest resultant deflection (independent of time), low_{tot} is the total lower chest resultant deflection (independent of time), up_{dif} is the maximum difference in upper chest left and right resultant deflection time-histories and low_{dif} is the maximum difference in lower chest left and right resultant deflection time-histories.

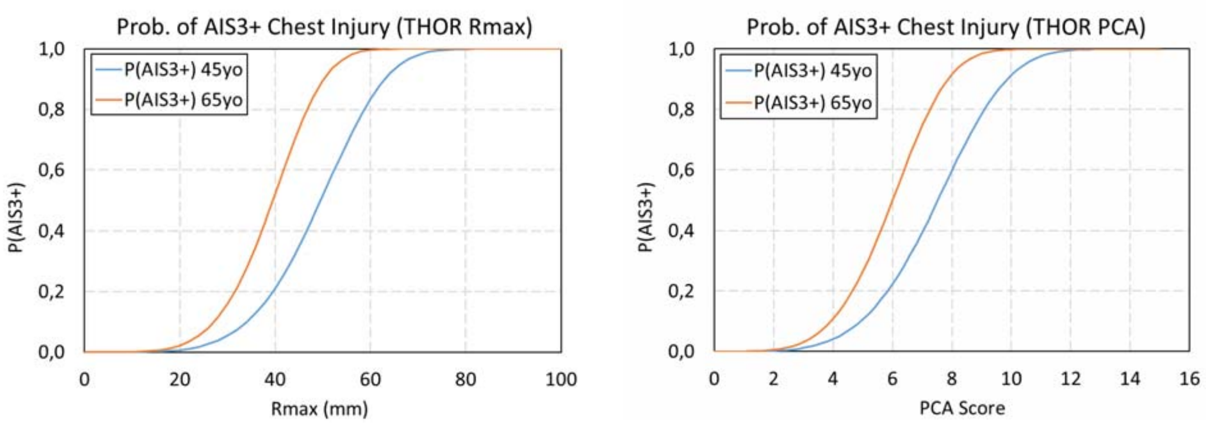

Fig. 7. Age-dependent chest risk curves based on THOR Rmax (left) and PCA (right) [23].

A model of the generic SENIORS buck was created (Fig. 8). The elderly THUMS TUC was positioned in the buck so that the mid-sternum matched that of the THOR ATD in the longitudinal direction. The model was then used to evaluate the performance of the 3+2 criss-cross belt by comparison to that of the 3-point belt in the 35 km/h and 56 km/h impacts. Rib strains were extracted from the rib cortical bones of the THUMS model. The risk to sustain rib fractures was assessed using the peak rib strain in each rib as input to the probabilistic rib fracture prediction method in [18].

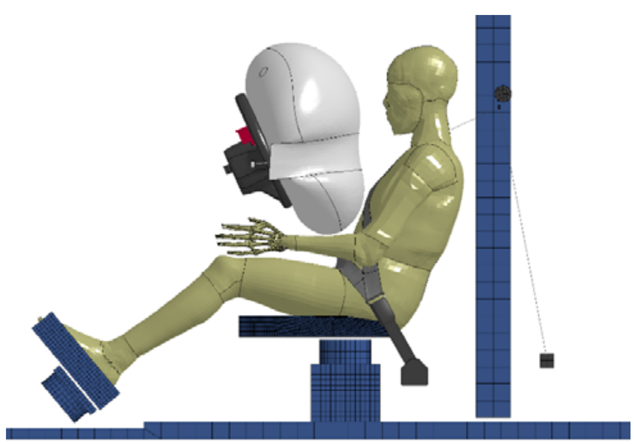

Fig. 8. Finite element model of the generic SENIORS sled with the elderly THUMS TUC.

III. RESULTS

In the 35 km/h impact, average Rmax from three tests of 42 mm was obtained for the 3-point belt system. For the criss-cross, the two-retractor and the split-buckle belt systems, the average Rmax from two tests were reduced to 19 mm, 29 mm and 30 mm, respectively (Fig. 9). Peak chest resultant deflections were evenly distributed at the upper measurement for the criss-cross belt in comparison to the 3-point belt (Fig. 10). For all other systems, the Rmax was obtained in the upper left IR-TRACC measurement point.

In the 56 km/h impact, average Rmax from three tests of 54 mm was obtained for the 3-point belt system. For the criss-cross, the two-retractor and the split-buckle belt systems, the average Rmax from two tests were reduced to 33 mm, 46 mm and 38 mm, respectively (Fig. 9). The Rmax was obtained in the upper left IR-TRACC measurement point for all belt systems. The Rmax was obtained in the lower left IR-TRACC measurement point for the 3-point belt systems, and in the upper left for the criss-cross, two-retractor and split buckle belts. Time-history curves of resultant chest deflections, belt forces and airbag pressures are given in Appendix 1.

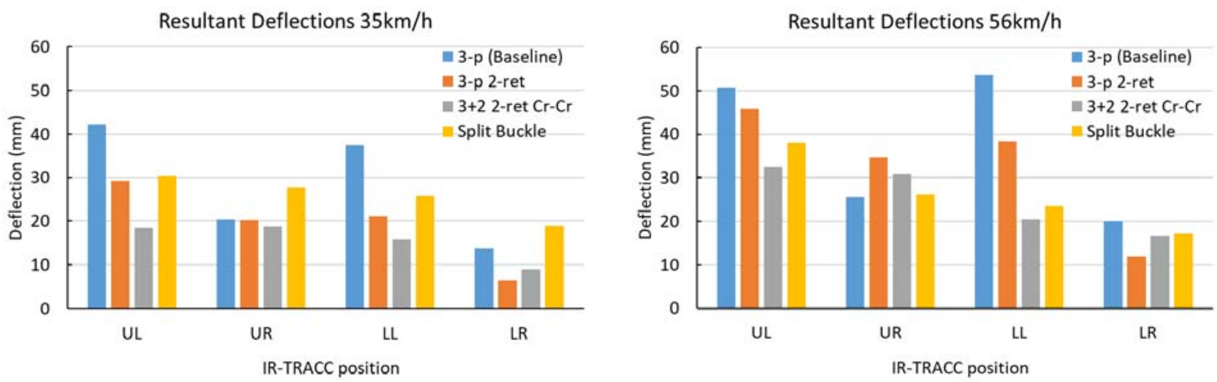

Fig. 9. Average peak values from THOR IR-TRACC chest resultant deflections, 35 km/h and 56 km/h (UL=upper left, UR=upper right, LL=lower left, LR=lower right).

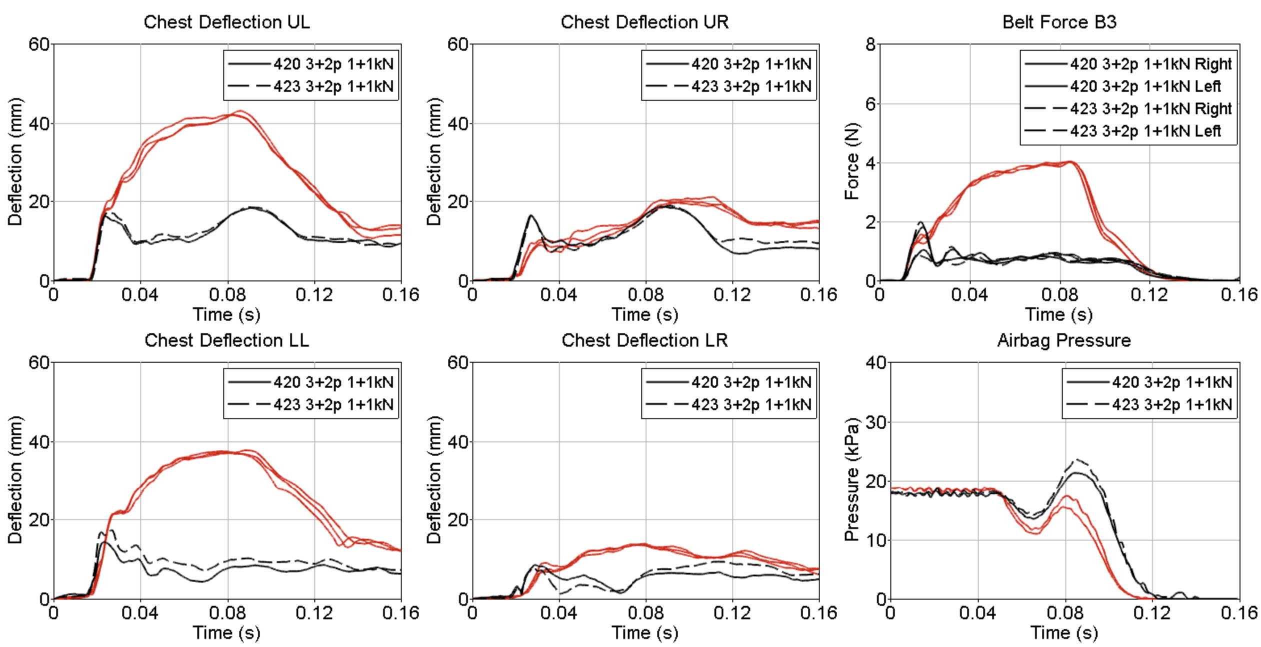

Fig. 10. Chest resultant deflections, shoulder-belt forces and airbag pressures for the criss-cross belt compared to the 3-point belt tests 403 to 405 (in red), 35 km/h.

For a 65yo occupant in 35 km/h, average Rmax-based AIS3+ chest injury risk of 62% was obtained for the 3-point belt system (Fig. 11). The chest injury risk was reduced to 2% for the criss-cross belt, to 14% for the two-retractor belt and to 17% for the split-buckle belt. For a 65yo occupant in 56 km/h, average Rmax-based AIS3+ chest injury risk of 96% was obtained for the 3-point belt system. The chest injury risk was reduced to 23% for the criss-cross belt, to 76% for the two-retractor belt and to 43% for the split-buckle belt. Similar reductions in chest injury risk were obtained using the PCA injury measure.

For a 45yo occupant in 56 km/h, a reduction in average AIS3+ chest injury risk from 64% to 8% was obtained for the criss-cross belt using Rmax and a reduction from 65% to 4% using PCA (Fig. 12). Double pretensioning in the lap belt reduced the pelvis excursions and increased the chest excursions slightly (Appendix 1).

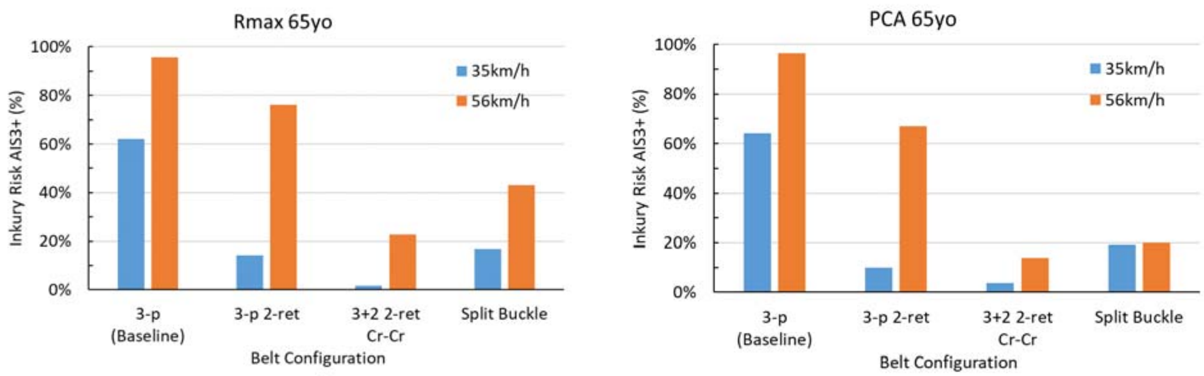

Fig. 11. Average injury risks from repeated tests for a 65yo based on Rmax (left) and PCA (right).

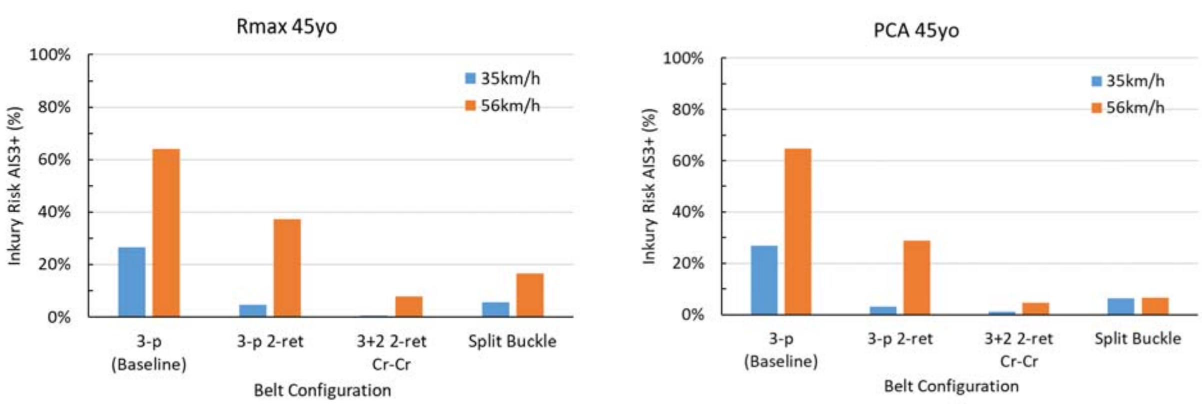

Fig. 12. Average injury risks from repeated tests for a 45yo based on Rmax (left) and PCA (right).

For the THUMS TUC model, the rib cage cortical bone peak strain was reduced from 3.6% to 1.4% in 35 km/h and from 3.9% to 2.6% in 56 km/h using the criss-cross belt compared to the 3-point belt (Fig. 13). The improved load distribution measured in the THOR chest deflection points were confirmed by the symmetric strain distribution in the ribs of the THUMS model. For the criss-cross belt, compared to the 3-point belt, the risk to sustain 3+ fractured ribs (NFR3+) for a 65yo was reduced from 74% to 0% in 35 km/h and from 100% to 19% in 56 km/h.

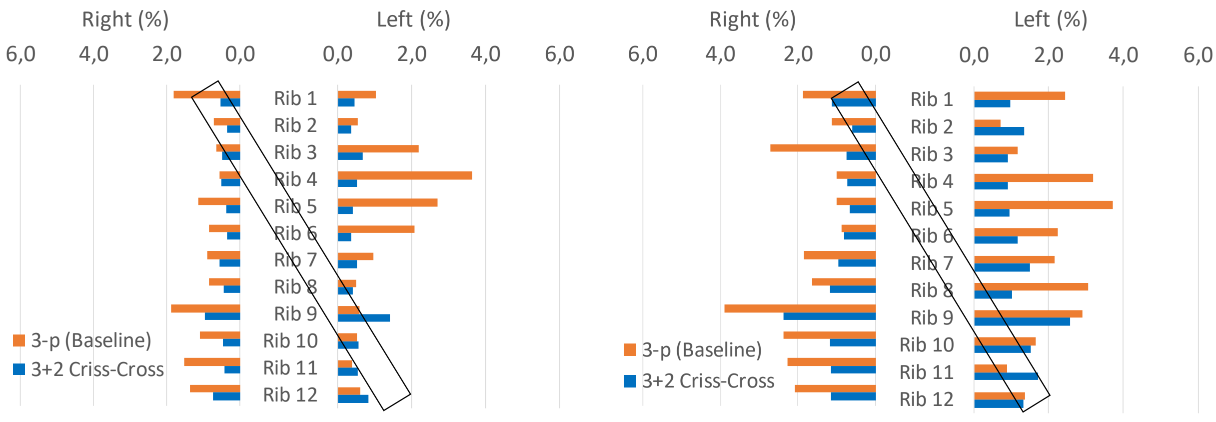

Fig. 13. Peak rib strains for THUMS TUC with the criss-cross belt compared to the 3-point belt in 35 km/h (left) and 56 km/h (right).

IV. Discussion

The effect of belt configuration, load limiting force level and pretensioners on the thoracic response of the THOR-M 50th ATD was carried out with the aim of improving the protection of elderly occupants in frontal impacts. Three seat-belt systems were compared to a double-pretensioned 4 kN load limited 3-point belt: a 3-point double-pretensioned two-retractor belt system; a triple-pretensioned 3+2 criss-cross belt; and a triple-pretensioned split buckle belt system.

The 3-point belt system was chosen to correspond to a state-of-the-art system in current vehicles. The load limiting level of 4 kN and pretensioning in both the lap and shoulder belts is such a system for the protection of front-seated occupants. The load limiting level of 4 kN is defined for non-elderly occupants and high crash severities using the Hybrid III ATD. In this study, the Rmax-based AIS3+ injury risk of 27–64% was obtained for a 45yo occupant in 35–56 km/h impacts. With the same belts, considerably higher AIS3+ injury risk of 62–96% was obtained for the 65yo occupant in the corresponding impact severities, indicating that the load limiting force level is too high for elderly occupants. The results show the increased sensitivity of the THOR, as was observed in previous studies [7,8].

With the 3-point two-retractor belt, reduced loading on the lower chest was obtained from the increased pelvis restraining and reduced loading on the upper chest from the adaptive load limiting. With this belt, the Rmax-based AIS3+ injury risk was reduced from 62% to 14% in the lower velocity for elderly occupants. In high velocity, the risk reduction was limited for the two-retractor belt due to increased upper chest loading late in the impact. A possible cause for this can be the airbag which response was defined to avoid strike-through of the head. With additional retuning of the airbag stiffness together with the implementation of a compressible steering column, higher benefit from this belt configuration is likely possible to obtain.

With an additional diagonal belt added to the 3-point two-retractor belt, creating a criss-cross belt geometry, the load limiting force on each diagonal belt can be reduced from 2 kN to 1 kN in 35 km/h. With this criss-cross geometry, symmetrically distributed deflections with lower peak values were measured at the upper left and right IR-TRACC points. With the improved load distribution on the chest, the Rmax-based AIS3+ chest injury risk was further reduced from 14% to 2% for the elderly occupant. The results are in line with findings from numerical modelling using human body models [11,24] and from tests using PMHS [9].

The 3-point two-retractor belt system and the criss-cross belt system provide an increased restraining of the pelvis due to the locked slippage of the belt webbing through the buckle. For the split buckle belt, similar increased restraining effect was achieved using double pretensioning in the lap belt. As a result, the loading of the lower chest was reduced compared to the 3-point belt, leading to the peak chest deflections being measured at the upper IR-TRACC points. With the lower chest being restrained, the potential benefit of redistributing the loading from the mid chest to the upper chest and shoulder was demonstrated with the split buckle belt. Although high load limiting force levels were used in both velocities for the split buckle belt, the AIS3+ chest injury risk was reduced from 62% to 19% in 35 km/h and from 96% to 43% in 56 km/h for a 65yo occupant. The benefit from the split buckle belt can potentially be further optimized with the use of adaptive shoulder load limiting.

The load limiting levels for the two-retractor, criss-cross and split buckle belts were defined in a pre-study considering a 50^{th} male occupant involved in frontal crashes with a mid-sized sedan. Adaption of the degree of belt restraining was carried out with the switch time from the high to low force level. In the 56 km/h impact using the two-retractor belt, the high load limiting level was used in the first phase of the crash and then switched to the low level at the time when the airbag starts to restrain the occupant head and chest. In the 35km/h impacts, a load limiting switch time of 20ms was defined to avoid deformations of the lower force level torsion bar during the pretensioning phase. This setting assured that full performance from the pretensioners was utilized for cases when the load limiting force in the crash was smaller than the pretensioning force. In a vehicle installation, the trig logic of the belt load limiting can be defined from sensor data measurements of parameters such as occupant size, occupant position and crash severity.

It is likely that the increased lap pretensioning in all three belt configurations favors a belt pull-in of the lap belt to a position below the ASIS points and thus has the potential to reduce the risk of submarining in a vehicle seat. While no submarining occurred in any of the tests, the use of the generic rigid seat limits the use of the test results for the analyses of submarining risk.

Unchanged injury risks were obtained when considering injury criteria other than the chest deflection based. For all three belt configurations, equal or reduced HIC15, Nij, chest and pelvis accelerations were obtained compared to the 3-point belt system in both impact velocities (Fig. A1, Fig. A4, Table A4-A5 in the appendix). In the 56 km/h impact, thoracic spine compression force of 5.2 kN was measured for the criss-cross belt which was slightly higher than that of the 3-point belt. Increased thoracic spine tension forces by a factor of 1.9-2.7 was obtained for the two-retractor and criss-cross belts due to smaller pelvis excursions and larger upper body rotations compared to the 3-point belt. Since no injury limit values currently exist for the THOR thoracic spine forces, the injury limit guidelines for the lumbar spine of the Hybrid III ATD in [25,26] were used. The measured thoracic forces for all belt systems were below the Hybrid III injury limits (Table A4-A5 Appendix).

While adaptive advanced belt systems show a benefit for the protection of elderly occupants in, most importantly, low impact severities (35 km/h), the systems additionally provide improved protection in both low and high impact severities (56 km/h) for both younger and older occupants. The potential of reaching AIS3+ injury risks of 4% (PCA) to 8% (Rmax) for a 45yo in a 56km/h impact with improved distributed chest loading was demonstrated in this study using the criss-cross belt configuration.

Based on the current definitions in [23], similar reductions in chest injury risks for the belt systems were obtained using the PCA criteria as for the Rmax criteria (Fig. 11 and Fig. 12). However, within the SENIORS project, improved versions of the PCA score and new injury risk functions based on an extended data set are being developed [27,28]. With the improved versions of the PCA, injury risks which are different from the Rmax-based can be expected. Compared to the current PCA, the improved versions have the potential to show even more pronounced benefit from the use of advanced load distributing restraints such as 4-point belts.

Systems with adaptive load limiters are already available in vehicles today. Promoting such systems to a higher level of implementation is a straightforward way of addressing thorax injuries in the elderly population without degrading the protection afforded to the younger population. This could be achieved by adjusting the legal or consumer rating test procedure to include a test at lower severity, as proposed by [4]. In the future, further development of adaptive belts for elderly can include the considerations of overweight for both males and females, as occupants also tend to increase in body weight with age. With further development of HBM models and their injury criteria assessment, the models can potentially be used for designing age-specific belt configurations and load limiting force levels for a larger population than is currently considered.

With the THOR, the measurement of thoracic loading is limited to four discrete IR-TRACC points. Restraint systems can potentially apply loading on thoracic parts outside these points in which case the true loading is not fully measured. With the THUMS model, thoracic loading can be measured using the rib cortical bone strains of the whole chest for predicting the risk of rib fractures. The THUMS injury risk predictions were close to the corresponding THOR injury risks, indicating that with the THOR ATD and multipoint criteria, the potential of advanced restraint systems to reduce chest injury risk for elderly occupants can be assessed. Further work is however needed to investigate the biofidelity of the THOR ATD with respect to elderly occupant properties such as upper body stiffness and body composition.

With the generic design of the SENIORS buck, certain simplifications compared to a real vehicle, were necessary. The rigid seat might have restrained the THOR pelvis in the vertical direction more than a conventional vehicle seat, which could possibly have increased the restraining effect from the lap belt. Also, the effect of the rigid seat on the thoracic loading of the THOR need further investigations. The airbag was pre-inflated to a target pressure value which was defined from the working pressure of a vehicle installed airbag in a mid-sized sedan. The response of the airbag was adapted to the impact severities by activation of the venting at the time when the airbag starts to restrain the occupant head and chest. Compared to a production airbag, a more effective retraining of the head and chest was likely obtained in the early phase from the high initial pressure. A stiffer response from the generic airbag in the crash was also obtained from the use of a non-compressible steering wheel, which explains the in general high HIC values which were obtained with the belt systems in the 56 km/h impact. The load limiting level for the additional belt of the criss-cross configuration was defined for a non-flexible seat-back installation. In a vehicle installation, higher load limiting level might be necessary depending on the degree of seat back deformations. Further efforts are also needed with respect to sensor strategy and consumer acceptance before the implementation of the criss-cross and split buckle belt in a real vehicle.

V. CONCLUSIONS

Three different belt configurations with adaptive two-level load limiting were successful in reducing the risk of chest injuries in two velocities, 35 km/h and 56 km/h. All belt systems reduced the risk of chest injuries for elderly occupants in, most importantly, low impact severities, in addition to providing improved protection for both younger and elderly occupants in high impact severities. Compared to the 3-point belt system, the largest reduction in AIS3+ chest injury risk in both velocities was obtained for the distributed loading condition using the criss-cross belt.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

[1] Wisch, M., Lerner, M., et al. Injury Patterns of Older Car Occupants, Older Pedestrians or Cyclists in Road Traffic Crashes with Passenger Cars in Europe – Results from SENIORS. *Proceedings of IRCOBI Conference*, 2017. Antwerp, Belgium

[2] Carroll, J., Adolph, T., et al. Overview of Serious Thorax Injuries in European Frontal Car Crash Accidents and Implications for Crash Test Dummy Development. *Proceedings of IRCOBI Conference*, 2010. Hannover, Germany

[3] European Commission. The 2015 Ageing Report. Economic and budgetary projections for the 28 EU Member States (2013-2060). 2015: ISSN 0379-0991.

[4] Hynd, D., Tress, M., Seidl, M., and Edwards, M. Assessment of Intended and Unintended Consequences of Vehicle Adaptations to meet Advanced Frontal Crash Test - Final Report. June, 2016: European Commission, Brussels, Belgium.

[5] Lemmen, P., et al. Development of an advanced frontal dummy thorax demonstrator. *Proceedings of IRCOBI Conference*, 2012. Dublin, Ireland

[6] Parent, D.P., Ridella, S.A., and Mcfadden, J.D. Thoracic biofidelity assessment of the THOR mod kit ATD. *Proceedings of 23rd International Technical Conference on the Enhanced Safety of Vehicles*, 2013. Seoul, Republic of Korea

[7] Eggers, A., Eickhoff, B., Dobberstein, J., Zellmer, H., and Adolph, T. Effects of Variations in Belt Geometry, Double Pretensioning and Adaptive Load Limiting on Advanced Chest Measurements of THOR and Hybrid III. *Proceedings of IRCOBI Conference*, 2014. Berlin, Germany

[8] Sunnevång, C., Hynd, D., Carroll, J., and Dahlgren, M. Comparison of the THORAX Demonstrator and HIII sensitivity to crash severity and occupant restraint variation. *Proceedings of IRCOBI Conference*, 2014. Berlin,

Germany

[9] Rouhana, S.W., Bedewi, P.G., et al. Biomechanics of 4-Point Seat Belt Systems in Frontal Impacts. *Stapp Car Crash Journal*, 2003. 47: p. 367-399

[10] Bostrom, O. and Haland, Y. Benefits of a 3+2-point belt system and an inboard torso side support in frontal, far-side and rollover crashes. *Int. J. Vehicle Safety*, 2005. 1(Nos. 1/2/3): p. 181-199

[11] Östling, M., Saito, H., et al. Potential Benefit of a 3+2 Criss Cross Seat Belt System in Frontal and Oblique Crashes. *Proceedings of IRCOBI Conference*, 2017. Antwerp, Belgium

[12] Pipkorn, B., Lopez-Valdes, F.J., et al. Assessment of an Innovative Seatbelt with Independent Control of the Shoulder and Lap Portions Using THOR Tests, the THUMS Model and PMHS Tests. *Proceedings of Association of the Advancement of Automotive Medicine (AAAM)* 2016. Hawaii, USA

[13] Iwamoto, M., Kisanuki, Y., et al. Development of a Finite Element Model of the Total Human Model for Safety (THUMS) and Application to Injury Reconstruction. *Proceedings of IRCOBI Conference*, 2002. Munich, Germany

[14] TUC - THUMS User Community. www.tuc-project.org, 2018

[15] Eggers, A., Wisch, M., et al. SENIORS D2.4 Updated Human Body Models representing elderly occupants and pedestrians (incl. overweight/obese). 2018, Eight Framework Programme Horizon 2020 GA No. 636136: European Commission.

[16] Kent, R., Lessley, D., and Sherwood, C. Thoracic Response to Dynamic Non-Impact Loading from a Hub Distributed Belt Diagonal Belt and Double Diagonal Belts. *Stapp Car Crash Journal*, 2004. 48 (2004-22-0022)

[17] Kent, R., Murakami, D., and Kobayashi, S. Frontal Thoracic Response to Dynamic Loading The Role of Superficial Tissues Viscera and Rib Cage. *Proceedings of IRCOBI Conference*, 2005. Prague, Czech Republic

[18] Forman, J.L., Kent, R.W., et al. Predicting Rib Fracture Risk With Whole-Body Finite Element Models: Development and Preliminary Evaluation of a Probabilistic Analytical Framework. *Proceedings of Association for the Advancement of Automotive Medicine*, October 2012. Seattle, USA

[19] Eggers, A., Ott, J., et al. A new generic frontal occupant sled test set-up developed within the EU-project SENIORS. *Proceedings of Conference on the Enhancement of Safety Vehicles (ESV)*, 2017. Detroit, USA

[20] Shaw, G., Parent, D., et al. Impact Response of Restrained PMHS in Frontal Sled Tests Skeletal Deformation Patterns Under Seat Belt Loading. *Stapp Car Crash Journal*, 2009. 53: p. 1-48

[21] Wisch, M., Ott, J., et al. SENIORS D4.2a Evaluated Test and Assessment Procedures for current and advanced passive Elderly Occupants Safety Systems. 2018, Eight Framework Programme Horizon 2020 GA No. 636136: European Commission (In preparation).

[22] Lopez-Valdés, F.J. Chest injuries of elderly Post Mortem Human Surrogates (PMHS) under seat belt and airbag loading in frontal sled impacts. Comparison to matching THOR tests. *Proceedings of Association of the Advancement of Automotive Medicine (AAAM)* 2018. Nashville, USA. Submitted for publication.

[23] NHTSA. New Car Assessment Program (NCAP), RFC#1, in *Docket No. NHTSA-2015-0119*. 16th Dec, 2015, NHTSA, Department of Transportation: Washington DC, USA.

[24] Mroz, K., Bostrom, O., Pipkorn, B., Wismans, J., and Brolin, K. Comparison of Hybrid III and Human Body Models in Evaluating Thoracic Response for Various Seat Belt and Airbag Loading Conditions. *Proceedings of IRCOBI*, 2010. Hanover, Germany

[25] Pellettiere, J.A., Moorcroft, D., and Olivares, G. Anthropometric Test Dummy Lumbar Load Variation. *Proceedings of Conference for the Enhancement of Safety Vehicles (ESV)* 2011. Paper Number 11-0157. Washington DC, USA

[26] General Motors (GM). Occupant Performance Evaluation Consideration Book (Blue book). 1998, Version 3 Revision 0, May 1 1998. Document #SRC-1000G: USA.

[27] Eggers, A., Wisch, M., et al. SENIORS D2.5a Updated injury criteria for the THOR. 2018, Eight Framework Programme Horizon 2020 GA No. 636136: European Commission.

[28] Eggers, A., Wisch, M., Hynd, D., Pipkorn, B., and Mroz, K. A Simulation-based Approach for Improved Thorax Injury Risk Function for the THOR ATD. *Proceedings of IRCOBI Conference*, 2018. Athens, Greece

VIII. APPENDIX

TABLE A1
THOR TEST MATRIX 35 KM/H AND 56 KM/H (TTF=TIME TO FIRE, LL=RETRACTOR LOAD LIMITING FORCE, R200=PRETENSIONER, R230=RETRACTOR, PLP=PYROTECHNIC LAP PRETENSIONER).

Test Id	Vel (km/h)	Belt Type	Retractor Right					Lap Belt Pret. Outboard		Lap Belt Pret. Inboard		Belt +2 Criss-Cross					Generic DAB			
			Type	LL1 (kN)	LL2 (kN)	Pret TTF (ms)	LL1-LL2 TTF (ms)	Type	TTF (ms)	Type	TTF (ms)	Type	LL1 (kN)	LL2 (kN)	Pret TTF (ms)	LL1-LL2 TTF (ms)	Init Target Pressure (kPa)	Vent TTF (ms)	Vent fully open (ms)	Vent Area (mm2)
403	35	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
404	35	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
405	35	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
442	35	3-pt 2-ret	R230	5,0	2,0	8	20	R200	8	-	-	R230	-	-	-	-	19	50	60	8700
443	35	3-pt 2-ret	R230	5,0	2,0	8	20	R200	8	-	-	R230	-	-	-	-	19	50	60	8700
420	35	3+2 2-ret Criss-Cross	R230	2,0	0,9	8	20	R200	8	-	-	R230	2,0	0,9	8	20	19	50	60	8700
423	35	3+2 2-ret Criss-Cross	R230	2,0	0,9	8	20	R200	8	-	-	R230	2,0	0,9	8	20	19	50	60	8700
435	35	Split Buckle	R230	6,0	-	8	-	R200	8	PLP3.1	15	R230	-	-	-	-	19	50	60	8700
436	35	Split Buckle	R230	6,0	-	8	-	R200	8	PLP3.1	15	R230	-	-	-	-	19	50	60	8700
407	56	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
408	56	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
409	56	3-pt	R230	4,0	-	8	-	PLP3.1	15	-	-	R230	-	-	-	-	19	50	60	8320
438	56	3-pt 2-ret	R230	5,0	2,0	8	55	R200	8	-	-	R230	-	-	-	-	19	40	50	8700
439	56	3-pt 2-ret	R230	5,0	2,0	8	55	R200	8	-	-	R230	-	-	-	-	19	40	50	8700
427	56	3+2 2-ret Criss-Cross	R230	2,0	0,9	8	1000	R200	8	-	-	R230	2,0	0,9	8	1000	19	50	60	8700
441	56	3+2 2-ret Criss-Cross	R230	2,0	0,9	8	1000	R200	8	-	-	R230	2,0	0,9	8	1000	19	50	60	8700
437	56	Split Buckle	R230	6,0	-	8	-	R200	8	PLP3.1	15	R230	-	-	-	-	19	50	60	8700
440	56	Split Buckle	R230	6,0	-	8	-	R200	8	PLP3.1	15	R230	-	-	-	-	19	50	60	8700

TABLE A2
THOR IR-TRACC RESULTANT DEFLECTIONS AND THORACIC INJURY RISK, 35 KM/H.

Test Id	Belt Type	UL Res. (mm)	UR Res. (mm)	LL Res. (mm)	LR Res. (mm)	Rmax (mm)	AIS3+ 45yo	AIS3+ 65yo	PCA	AIS3+ 45yo	AIS3+ 65yo	Rmax (mm) Avg	AIS3+ 45yo Avg	AIS3+ 65yo Avg	PCA Avg	AIS3+ 45yo Avg	AIS3+ 65yo Avg
403	3-pt	43,0	21,1	37,7	13,9	43,0	29%	65%	5,72	26%	63%						
404	3-pt	41,9	19,8	37,3	13,6	41,9	26%	60%	5,67	25%	62%	42,3	27%	62%	5,8	27%	64%
405	3-pt	42,0	20,0	37,5	13,7	42,0	26%	61%	5,86	29%	67%						
442	3-pt 2-ret	28,7	21,0	22,9	6,2	28,7	4%	13%	3,47	3%	10%	29,3	5%	14%	3,5	3%	10%
443	3-pt 2-ret	29,8	19,4	19,2	6,8	29,8	5%	15%	3,44	3%	10%						
420	3+2 2-ret Criss-Cross	18,3	18,6	14,4	8,5	18,6	0%	2%	2,59	1%	3%	18,8	1%	2%	2,7	1%	4%
423	3+2 2-ret Criss-Cross	18,5	18,9	17,3	9,4	18,9	1%	2%	2,88	1%	5%						
435	Split Buckle	30,3	28,0	27,6	19,6	30,3	6%	17%	4,15	7%	21%	30,4	6%	17%	4,0	6%	19%
436	Split Buckle	30,5	27,3	24,1	18,0	30,5	6%	17%	3,92	6%	17%						

TABLE A3
THOR IR-TRACC RESULTANT DEFLECTIONS AND THORACIC INJURY RISK, 56 KM/H.

Test Id	Belt Type	UL Res. (mm)	UR Res. (mm)	LL Res. (mm)	LR Res. (mm)	Rmax (mm)	AIS3+ 45yo	AIS3+ 65yo	PCA	AIS3+ 45yo	AIS3+ 65yo	Rmax (mm) Avg	AIS3+ 45yo Avg	AIS3+ 65yo Avg	PCA Avg	AIS3+ 45yo Avg	AIS3+ 65yo Avg
407	3-pt	49,1	23,7	51,8	21,2	51,8	57,8%	93%	7,32	60%	95%						
408	3-pt	51,1	26,0	54,7	22,2	54,7	67,8%	97%	7,72	69%	98%	53,6	64%	96%	7,5	65%	97%
409	3-pt	51,9	27,1	54,3	16,6	54,3	66,5%	97%	7,59	66%	97%						
438	3-pt 2-ret	47,4	35,0	38,5	11,0	47,4	42,4%	82%	5,96	31%	70%	45,8	37%	76%	5,9	29%	67%
439	3-pt 2-ret	44,2	34,5	38,1	13,0	44,2	32,1%	70%	5,76	27%	64%						
427	3+2 2-ret Criss-Cross	31,2	31,3	20,5	17,0	31,3	6,6%	19%	3,68	4%	13%	32,5	8%	23%	3,7	4%	14%
441	3+2 2-ret Criss-Cross	33,6	30,3	20,5	16,2	33,6	9,3%	26%	3,78	5%	15%						
437	Split Buckle	37,8	24,8	23,8	17,1	37,8	16,2%	42%	4,05	6%	19%	38,0	17%	43%	4,1	7%	20%
440	Split Buckle	38,2	27,4	23,2	17,4	38,2	17,0%	44%	4,10	7%	20%						

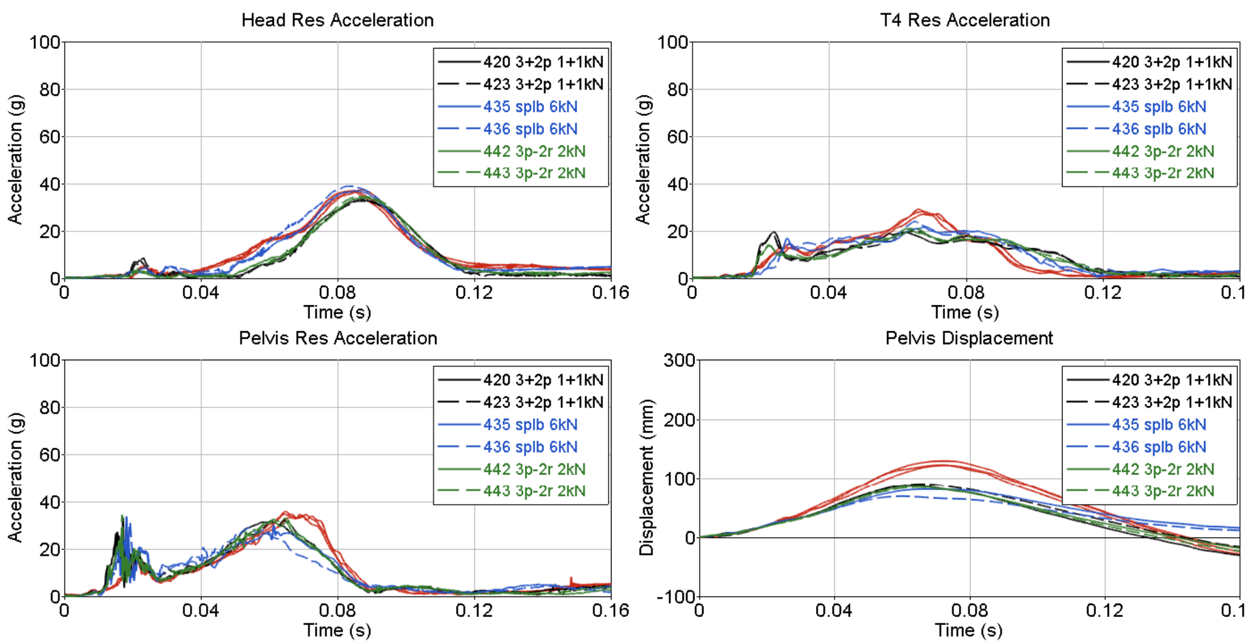

Fig. A1. Head, chest and pelvis resultant accelerations, and pelvis displacements (3-point belt tests 403–405 in red), 35 km/h.

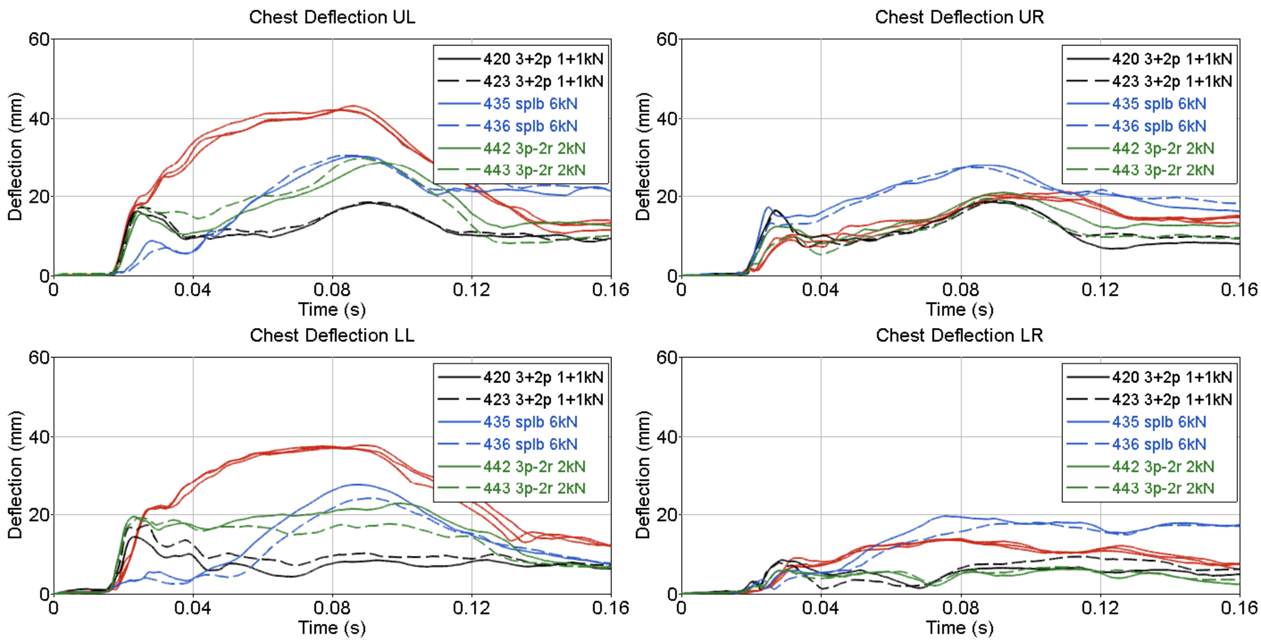

Fig. A2. Chest resultant deflections (3-point belt tests 403–405 in red), 35 km/h.

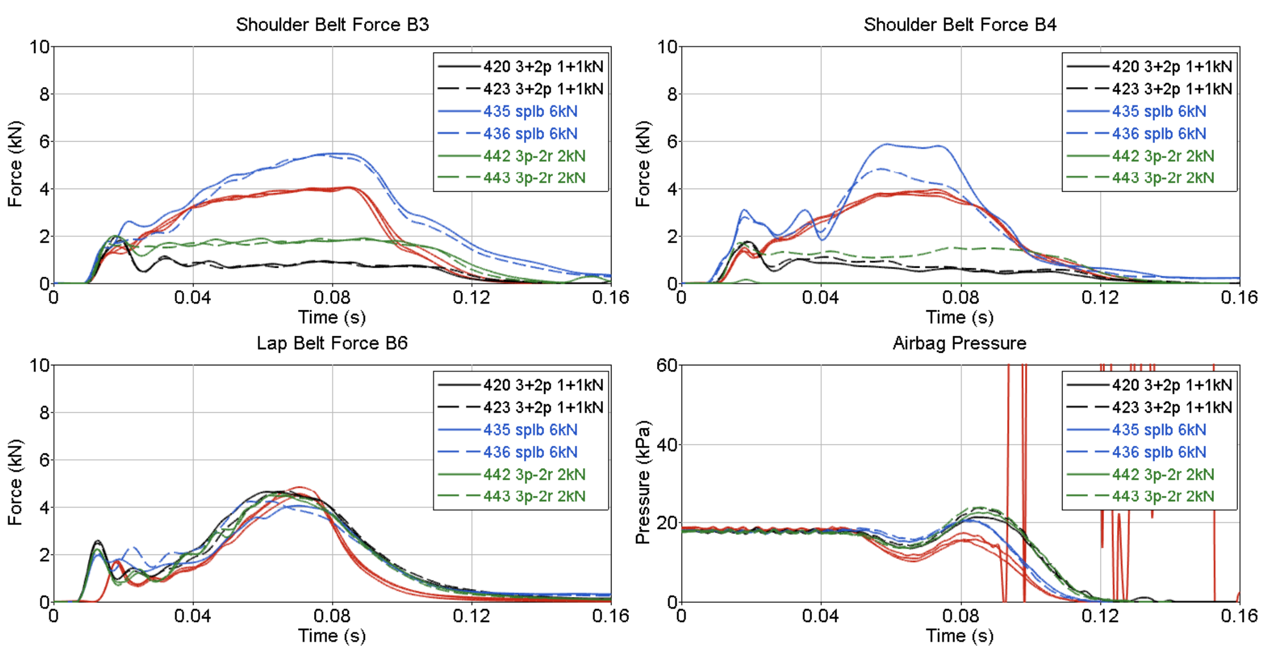

Fig. A3. Belt forces and airbag pressure (3-point belt tests 403–405 in red), 35 km/h.

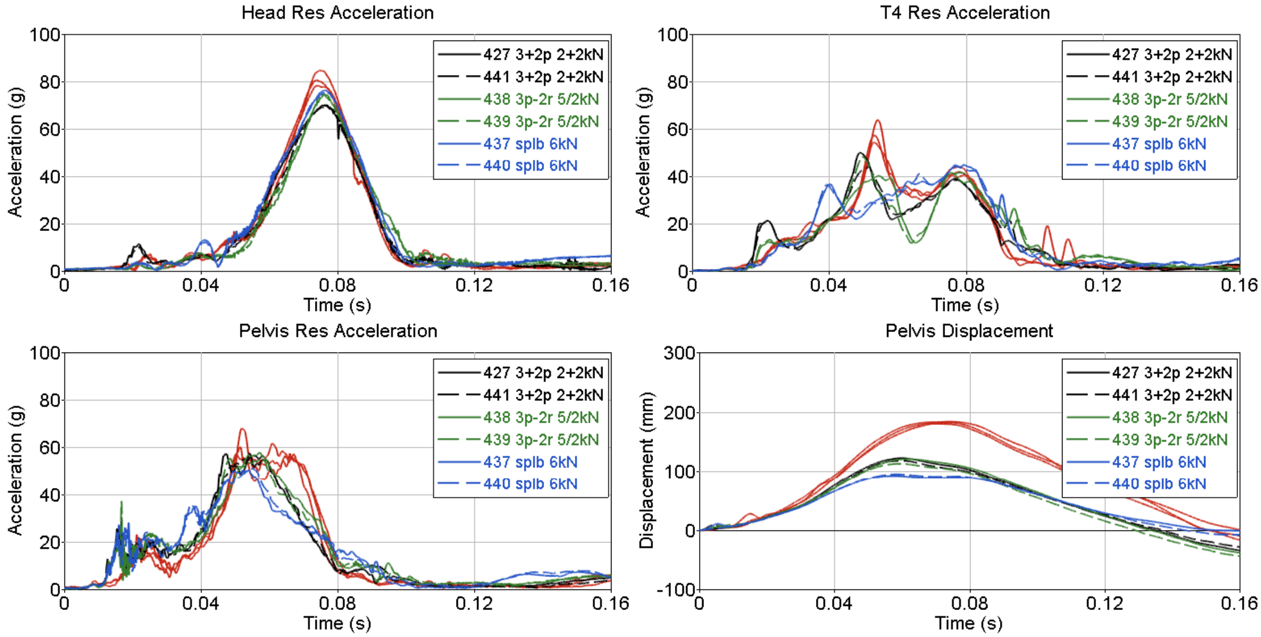

Fig. A4. Head, chest and pelvis resultant accelerations, and pelvis displacements (3-point belt tests 407–409 in red), 56 km/h.

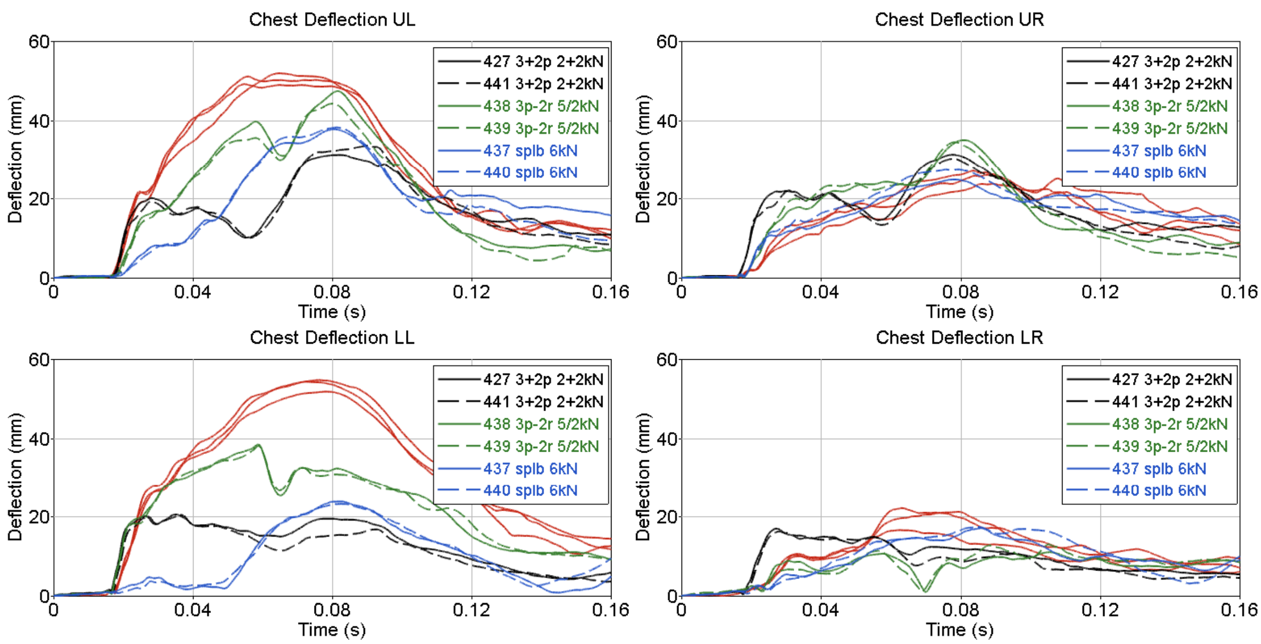

Fig. A5. Chest resultant deflections (3-point belt tests 407–409 in red), 56 km/h.

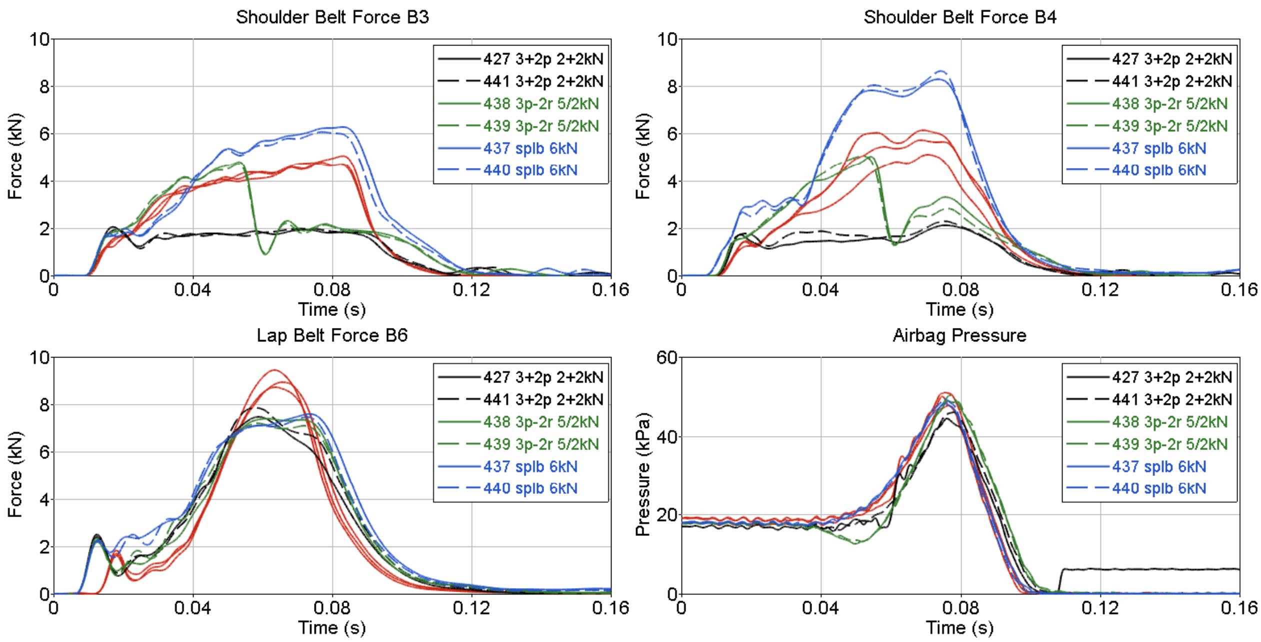

Fig. A6. Belt forces and airbag pressure (3-point belt tests 407-409 in red), 56 km/h.

TABLE A4
THOR HIC15, NIJ, THORACIC SPINE FORCES AND MOMENTS (AVERAGE OF 2-3 TESTS), 35 KM/H.

Belt Type	HIC15	Nij	Thoracic Spine Fz Compression (N)	Thoracic Spine Fz Tension (N)	Thoracic Spine My (Nm)
3-pt	107	0,26	-286	353	155
3-pt 2-ret	92	0,20	-1004	1116	86
3+2 2-ret Criss-Cross	83	0,19	-1085	944	81
Split Buckle	118	0,28	-600	507	97

TABLE A5
THOR HIC15, NIJ, THORACIC SPINE FORCES AND MOMENTS (AVERAGE OF 2-3 TESTS), 56 KM/H.

Belt Type	HIC15	Nij	Thoracic Spine Fz Compression (N)	Thoracic Spine Fz Tension (N)	Thoracic Spine My (Nm)
3-pt	686	0,37	-4526	1036	193
3-pt 2-ret	533	0,28	-3076	2843	156
3+2 2-ret Criss-Cross	499	0,33	-5174	1930	147
Split Buckle	595	0,38	-3980	1404	85