# PRE-CRASH TRIGGERED PRETENSIONING OF THE SEAT BELT FOR IMPROVED SAFETY

**Bengt Pipkorn**
Autoliv Research
SWEDEN

**Jacob Wass**
Sigma Industry West
SWEDEN

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## ABSTRACT

The potential injury reducing benefits of pre-crash belt slack reduction of a motorized seat belt system was evaluated. The evaluation was carried out for 1 second pre-crash braking followed by a 56km/h full frontal rigid wall crash. For the evaluation a validated active human body model and a model of the THOR dummy were used. The active human body model is capable of, and validated for, predicting occupant kinematics during pre-crash braking and occupant response for crash loading. In the study substantial belt slack was introduced by adding 100mm thick foam pads between the occupant and belt. Pads were added between the chest portion of the seat belt and the chest and between the lap portion of the belt and the pelvis. The effect of 300N and 600N pre-crash pretensioning (pre-pretensioning) of the belt on occupant kinematics and chest deflection during 1 second braking followed by a 56km/h full frontal rigid wall crash was evaluated. In addition the effect of in-crash triggered pyrotechnic pretensioning of the belt was also evaluated.

It was found that pre-crash forward excursion of the occupant during braking was reduced by pre-pretensioning the belt. The forward excursion was reduced for both the occupant without slack and the occupant with 100mm slack. For pre-crash braking followed by a crash generally chest deflections were reduced with pre-crash pretensioning of the belt. Reductions were obtained for the occupant without slack as well as for the occupant with 100mm slack. However, greater reductions was obtained for the occupant with 100mm slack than for the occupant without slack. It was also generally found that additional reductions in chest deflection was obtained for the in crash activated pyrotechnic pretensioners.

## BACKGROUND

Seat belts decrease automobile-related fatalities and injuries [1] & [2]. They achieve this benefit by reducing the peak loads applied to the occupants, applying these loads to anatomical structures better able to handle high loads, and limiting occupant excursion—and thus the probability of contact—inside the vehicle. Seat belts function optimally when worn snugly. When not snug, the additional slack in the seat belt was shown to increase the displacement of the head, chest, hips, and knees in high-speed frontal impacts [3] [4] [5]. Prior to a collision, seat belt slack can be introduced by poor seat belt adjustment, bulky clothing, or tension-relieving devices incorporated into some seat belt retractors. In a study it was found that for approaching 10% of the vehicle occupants the slack in the shoulder belt was greater than 75mm [6]. During a collision, seat belt slack can be introduced by tightening of the webbing on the spool after the retractor locks [7]. Whether introduced before or during a collision, the larger displacements caused by seat belt slack increase both the potential for occupant contact with interior structures and the severity of contacts that can occur even with a snug belt.

Today, real-world occupant protection is more than simply conventional passive safety technologies, such as seatbelts and airbags. During the last decade, rapid development of auto-brake technologies has taken place. Today most vehicle manufacturers offer some form of collision avoidance systems on their vehicles, at least as an option package [8]. In conjunction with the autonomous emergency braking (AEB) system, the motorised pre-pretensioner (PPT) system was introduced in order to reduce the degree of an occupant leaving the designed-position [9]. To comprehensively assess the benefit of introducing so-called integrated safety systems (e.g. motorised PPT systems in conjunction with AEB) an appropriate occupant model must be used. The occupant model should represent occupant responses, not only for in-crash loading, but preceding pre-crash loading. In order to predict human posture maintenance and human-like reflexive responses during pre-impact braking, a finite element human body model with proportional integral derivative (PID) controlled Hill-type active muscle system model was developed by Östh et al. (2012) [10]. The neuromuscular feedback control was implemented for the Total HUman Model for Safety (THUMS) AM50 version 3.0 [11], with some enhancements to the model [12]. The developed model – the so-called SAFER AHBM – with an active muscle system, was able to capture the kinematic responses during AEB events, and muscle activation magnitude was similar to that of the volunteers [13]. The SAFER AHBM uses a 1D Hill-type model, as muscle representation, with muscles controlled by PID feedback, via stabilising muscle activation generated in response to external perturbation. Using the SAFER AHBM tool that can predict occupant kinematics pre-crash and the loads on the occupant in-crash the potential injury reducing benefits from reducing the slack in the belt by pre-pretensioning the belt during the braking phase of a vehicle can be evaluated.

The aim of this study is to quantify the effect of seat belt slack on occupant response during pre-crash braking (1 sec) followed by a 56km/h crash.

## METHOD

For the study the SAFER active human body model and a model of the THOR dummy [15] were used as occupant substitutes. The occupants were positioned in the driver side interior model of a mid size vehicle. The human body model and THOR dummy model were restrained by a state fo the art belt system comprising a seat belt retractor with a motorised pre-pretensioner, a pyrotechnic retractor pretensioner, a lap belt pre-tensioner, a retractor belt force limiter and a driver side airbag. The force limiter value of the retractor pretensioner was 4.0kN. Dashpanel, floor and toepan were also included in the model.

Slack was introduced by adding 100mm thick soft foam pads between the seat belt and the thorax and pelvis of the occupant substitute. The foam pads were so soft that pulling the seatbelt between the shoulder of the occupant and the D-ring by hand would result in completely compressed foam pads and eliminated belt slack. Seat foam properties were used for the foam pads in the model (Figure 1).

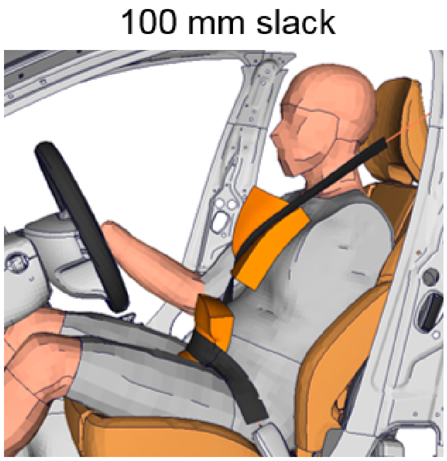


**Figure 1.**
**Foam Pads to Introduce Slack**

For all evaluations the brake pulse was applied for 1.0 second at approximately 1g. The ramp up time for the pulse was 500ms. The 1.0 seconds pre-crash braking was followed by a crash at 56km/h (Figure 2). The retractor locked after 575ms. The 1 second pre-crash braking was followed by a full frontal crash at 56km/h in a rigid wall (Figure 3).

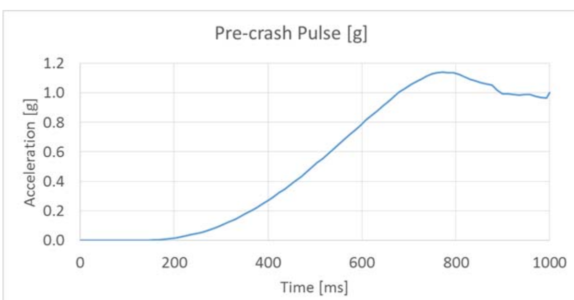


**Figure 2.**
**Brake Pulse**

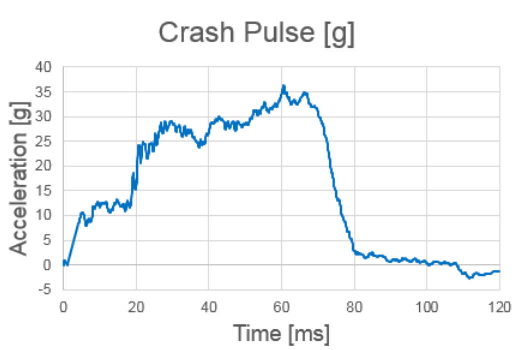


**Figure 3.**
**Crash Pulse**

Initially the incluence of braking only on occupant kinematics and chest deflection was evaluated. Thereafter the influence on occupant kinematics and chest deflection for various level of pre-pretensioning force was evaluated. The levels were 0, 300N and 600N. Lastly the influence of the pyrotechnic pretensioners on occupant kinematics and chest deflection was evaluated.

Chest deflection for the active human body model was extracted at 4 locations (Figure 4). The upper locations were at the 4:th rib and the lower locations were between the 6:th and 7:th rib. For the THOR dummy model chest deflections were extracted from the 4 IRTRACCs. Greatest resulting deflection of the four measurement locations was selected for presentation in this paper.

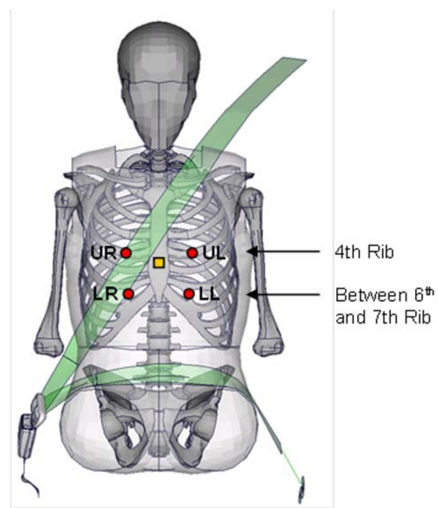


**Figure 4.**
**Chest Transducer Locations for the Active Human Body Model**

## RESULTS

### Active Human Body Model

For 1 second pre-crash braking greatest head and sternum excursions were obtained for the configuration with 100mm slack and no pre-pretensioning (Figure 5). For the configuration with 100mm slack the excursion with 300N and 600N pre-pretensioning was less than for the configuration without slack. For 100mm slack small difference in head and sternum excursions for 300N and 600N was obtained.

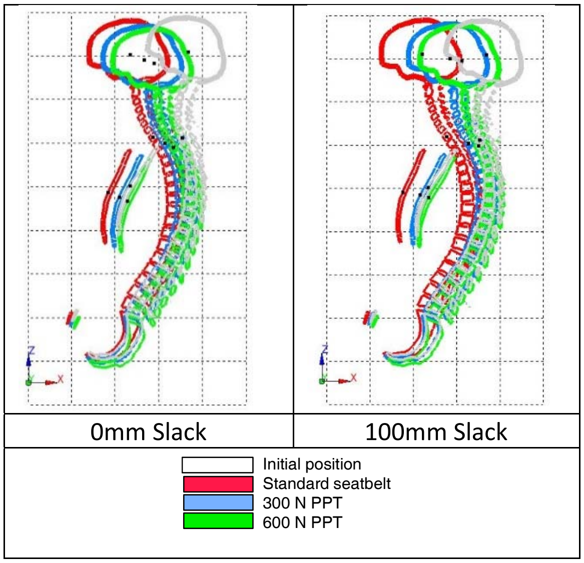


**Figure 5.**
**Position at Crash after 1sec Pre-Brake**

For the crash only configuration in which pre-crash braking was not included it can be observed that for the belt system without slack the pyrotechnic pretensioners reduced chest deflection by approximately 4mm (Figure 6). For the belt system with 100mm slack the pyrotechnic pretensioners reduced chest deflection also by 4mm.

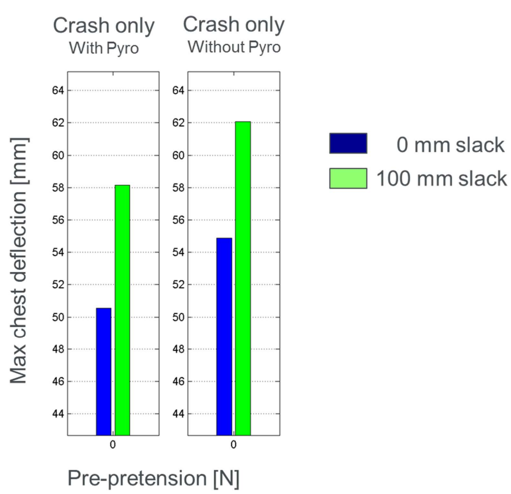


**Figure 6.**
**Chest Deflection for Crash Only**

For 1 second pre-crash braking with pyrotechnic pretensioners and without pre-pretensioning of the belt chest excursion was 6mm greater for the occupant with 100mm slack (Figure 7). Chest deflection was reduced by 2mm for 300N and by 5mm for 600N pre-pretensioning. For 0mm slack small reductions in chest deflection was obtained for pre-pretensioning.

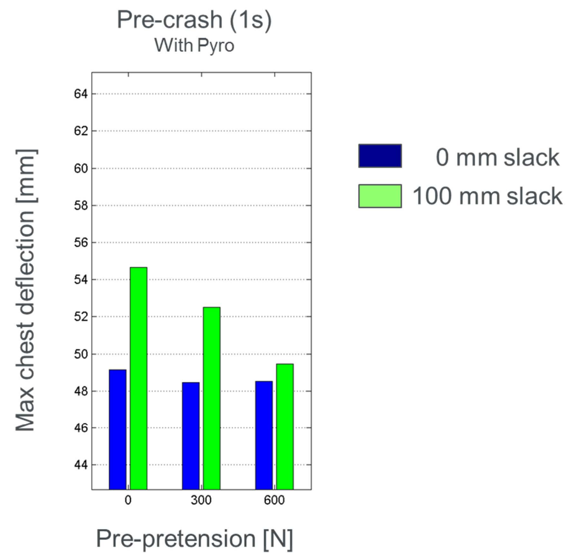


**Figure 7.**
**Chest Deflection Pre-Pretensioning for Pre-Crash Braking with Pyrotechnic Pretensioner**

For 1 second pre-crash braking without pyrotechnic pretensioner and 0mm slack chest deflection was reduced when pre-pretensioning was added (Figure 8). For 100mm slack chest deflection was reduced by 5mm and 7mm respectively when 300N and 600N pre-pretensioning was added.

For 100mm slack and no pre-pretensioning chest deflection was reduced with the pyrotechnic pretensioner (Figure 7). For 100mm slack and pre-pretensioning no reductions in chest deflection was observed for the pyrotechnic pretensioners (Figure 8 and 9).

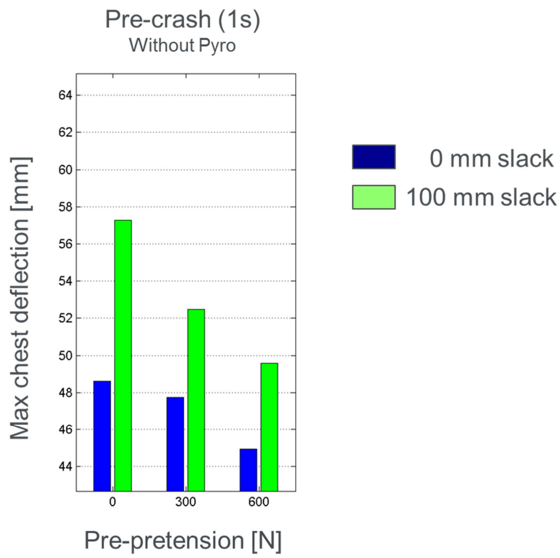


**Figure 8.**
**Chest Deflection for Pre-Pretensioning for Pre-Crash Braking Without Pyrotechnic Pretensioner**

**THOR Dummy Model**
With the purpose of confirming the observations from the analysis with the active human body model the THOR dummy model was exposed to the identical load conditions as the SAFER active human body model in the present study, 1 second braking followed by a 56km/h rigid wall crash. Generally the same trends was observed for the THOR dummy model as was observed for the active human body model. In the loadcase without pre-crash braking chest deflection was reduced by pyrotechnic pretensioners by approximately 7mm for both without and with 100mm slack (Figure 9).

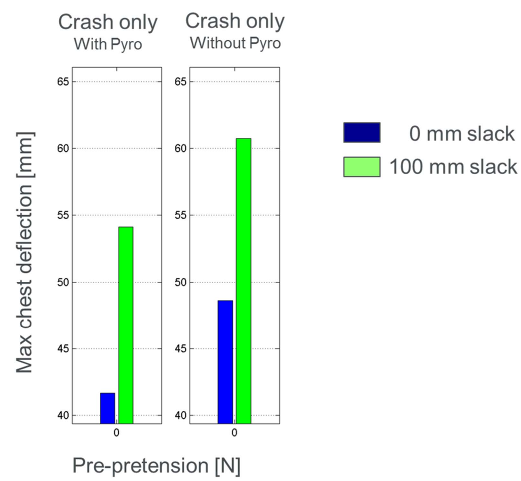


**Figure 9.**
**Chest Deflection for Crash Only**

For the pre-crash activated pre-pretensioning chest deflection was reduced with pre-pretensioning for the occupant without slack (Figure 10). However, when the pre-pretensioning force was increased from 300N to 600N no additional reductions in chest deflection was obtained. For the occupant with 100mm slack chest deflection was reduced from 58mm to 48mm with 300N pre-pretensioning. For 600N pre-pretensioning chest deflection was reduced to 42mm.

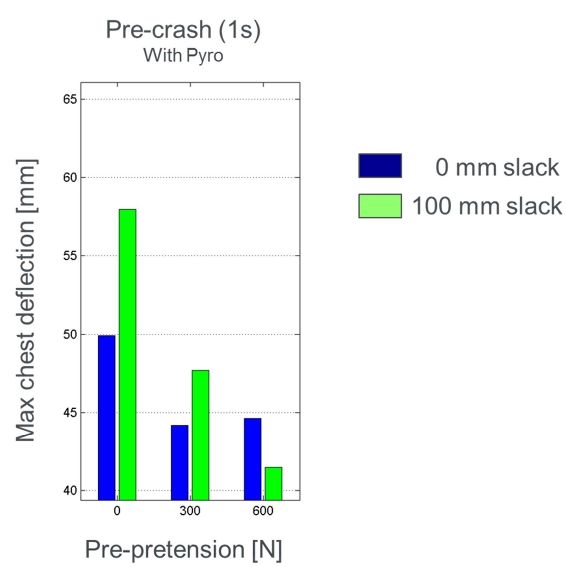


**Figure 10.**
**Chest Deflection Pre-Pretensioning for Pre-Crash Braking with Pyrotechnic Pretensioner**

For the evaluation without pyrotechnic pretensioners chest deflection was reduced from 55mm to 49mm with 300N pre-pretensioning for the occupant without slack (Figure 11). For an increased pre-pretensioning force to 600N chest deflection was reduced to 45mm. For an occupant with 100mm slack chest deflection was reduced from 63mm to 50mm with 300N pre-pretensioning and to 44mm with 600N pre-pretensioning.

For the evaluation of pyrotechnic pretensioners chest deflection was greater both without slack and with slack when the pyrotechnic pretensioners were not used (Figure 10 & Figure 11). However, for the occupant without slack and 600N pre-pretensioning no reductions in chest deflection was observed while for the occupant with 100mm slack chest deflection was reduced from 44 to 41mm.

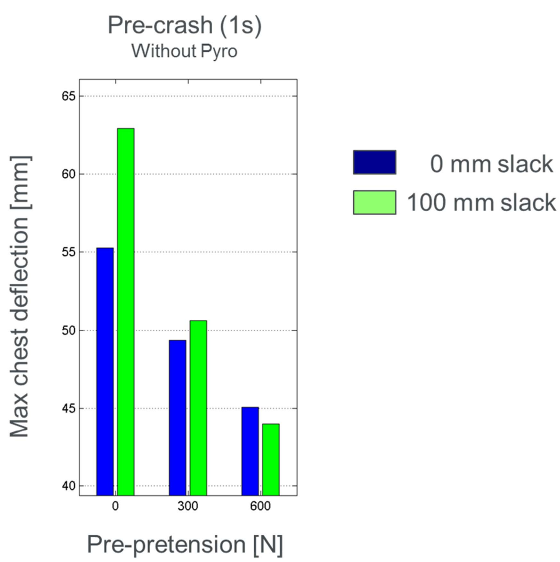


**Figure 11.**
**Chest Deflection for Pre-Pretensioning for Pre-Crash Braking Without Pyrotechnic Pretensioner**

## DISCUSSION

Generally 300N and 600N pre-pretensioning was found to reduce maximum forward excursion of both the active human body model and the THOR dummy model (Figure 12). Greatest total excursion was obtained for 100mm slack and no pre-pretensioning. The result from increased excursion was increased load on the chest from the airbag. The result from increased load on the chest was increased chest deflection. In the study no modifications to the airbag were included.

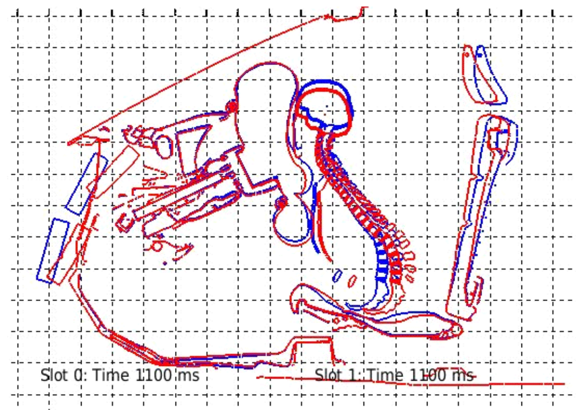


**Figure 12.**
**Active Human Body Model Peak forward excursion (100ms into the crash):**
**Blue - 100mm slack no pre-pretensioning**
**Red - 100mm slack with and 600N pre-pretensioning**

For both the active human body model and the THOR dummy model chest deflection was reduced for an occupant with 100mm slack when 300N and 600N pre-pretensioning was added (Figure 7, 8, 10 and 11).

For the active human body model without pre-pretensioning chest deflection was reduced for the occupant both without slack and with 100mm slack for the 1 second pre-crash braking loadcase compared to the crash only loadcase (Figure 6, 7 and 8). For the THOR dummy model the trend was the opposite. Chest deflection was increased for the occupant without slack and with 100mm slack without pre-pretensioning when pre-crash braking was added (Figure 9, 10 and 11). In the active human body model the hands were holding onto the steering wheel and the arm muscles were tensed to reduce forward motion during the pre-crash braking phase. The hands were released from the steering wheel at 30ms into the crash phase. Therefore the pre-crash kinematics predicted with the active human body model can be assumed to be more similar to human kinematics during pre-crash braking than the THOR kinematics for which pre-crash bracing with the arms was not included.

Reducing THOR dummy chest deflection from 57mm to 42mm for an occupant with 100mm slack by adding 600N pre-pretensioning in addition to the pyrotechnic pretensioning was found to reduce the risk to sustain an AIS3+ injury from 75% to 26% for a 45 year old occupant [13].

The THOR dummy model was included in the study to enable potential future mechanical verification of the results from the active human body model. Therefore, the ability of the THOR dummy to predict human kinematics in pre-crash braking was evaluated by mimicking the volunteer tests carried out by Östh et al. (2013) [14] with the THOR dummy (Figure 13). In the tests a passenger vehicle was travelling at 70km/h the velocity was reduced to 0km/h by appling the brakes during 2 seconds. The volunteers and THOR dummy were positioned in the passenger seat and restrained by a motor driven reversible seat belt. Head x-, y- and z-displacements and head rotations for THOR were compared to corresponding measurements for the volunteers. The volunteer tests were also virtually mimicked with the THOR dummy model (version 1.0) [15].

**Figure 13.**
**THOR in Passenger Seat**

A CORA (correlation and analysis) evaluation was carried out for the active human body model and the THOR dummy [16]. Both the mechanical and mathematical THOR dummy model were included in the evaluation. CORA uses two different methods to assess the correlation of signals. While the corridor method calculates the deviation between curves by using corridors, the cross correlation method analyses specific curve characteristics like phase shift or shape of the signals. The rating results ranges from "0" (no correlation) to "1" (perfect match).

The CORA rating for the active human body model was good while the rating for the THOR dummy model was fair (Figure 14) [17]. For the THOR dummy model there was poor agreement for the head z-displacement. All other displacements for both the THOR dummy model and the active human body model were in the fair to good biofidelity range. The CORA biofidelity rating was considered relevant despite the fact that the settings for the CORA evaluation varied between this study and the study carried out by Barbat et al. (2013) [17].

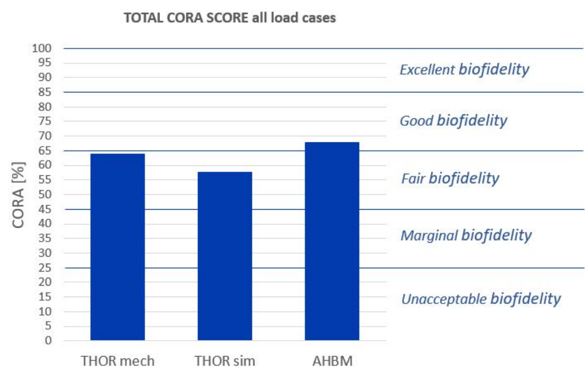


**Figure 14.**
**CORA Score Active Human Body Model and THOR (both mechanical and mathematical)**

Based on the CORA rating the active human body model was considered a more relevant tool than THOR dummy model to be used for evaluation of the influence of pre-crash occupant kinematics from pretensioning the belt during pre-crash braking.

Reductions in chest deflection and corresponding reduction in injury risk was obtained by pre-pretensioning the seat belt. Reversible motorised pre-pretensioners can be activated in pre-crash emergency braking situations. In the event when there will not be a crash that after an emergency braking situations the pre-pretensioner can release the force in the belt. However, it is likely that there will always be pre-crash situations in which the sensor system is not capable of detecting the imminent crash and hence the automatic pre-crash system will not be activated prior to the crash. Therefore in crash triggered pyrotechnic pretensioners will increase the level of safety for the vehicle occupants.

Occupant size also affects the magnitude of the dynamic occupant response [3]. These factors need to be considered when applying the current results—obtained with a 50th percentile male dummy and a single seat, seat belt and collision pulse—to collision conditions other than those tested here.

Using an active human body model provides unique possibilities to an integrated evaluation of active and passive safety technologies. Specifically in this study, occupant responses in frontal impacts with a preceding event of emergency braking of various characteristics were evaluated.

The active human body model used in the study represents an average driver exposed to an auto-brake situation. The model was tuned to correspond to an average driver based on the results from the volunteer tests carried out by Östh et al. (2013) [14]. The model can be tuned to predict the response of a specific group of individuals, such as elderly, or to predict the response of one specific individual. The model can also be tuned to a self-braking driver or a passenger.

In the study the effect on occupant response by pre-crash pretensioning the seat belt for 1 second pre-crash braking followed by a 56 km/h full frontal rigid wall crash for an average 50%-ile occupant was evaluated. Future analysis will include evaluations of both longer and shorter pre-crash braking durations other occupant sizes and other occupant crash pulses. In addition future evaluations will also include potential variations of the airbag for improved safety.

Therefore future developments analysis and developments should contain variation in occupant sizes and individual characteristics in reactions and muscle tonus, as well as including other pre-crash manoeuvers besides braking. All these variations are challenging from a model development perspective as well as in terms of generating validation data.

Future evaluations with the active human body model will include evaluating the influence on occupant kinematics of pre-pretensioning during avoidance maneuvers and avoidance maneuvers combined with braking.

**CONCLUSIONS**

Reducing seat belt slack by belt pre-pretensioning during pre-crash emergency braking can reduce chest deflection and injury risk in a 56km/h rigid wall crash.

Additional reductions in chest deflection can be achieved with in crash triggered pyrotechnic pretensioning of the belt.

**REFERENCES**

[1] Campbell BJ. 1987. "Safety belt injury reduction related to crash severity and front seated position." J Trauma, Vol. 27, pp. 733–739.

[2] Evans L. 1996. "Safety-belt effectiveness: the influence of crash severity and selective recruitment." Accid Anal Prev., Vol. 28, pp. 423–433.

[3] Hontschik H, Müller E, Rüter G. 1977. "Necessities and possibilities of improving the protective effect of three-point seat belts" (770933), Proc. 21st Stapp Car Crash Conf., pp. 795–831

[4] Viano DC, Culver CC, Prisk BC. 1980. "Influence of initial length of lap-shoulder belt on occupant dynamics—A comparison of sled testing and MVMA-2D modeling" (801309), Proc. 24th Stapp Car Crash Conf., pp. 377–415.

[5] Biss DJ. 1988. "Safety performance evaluation of slack effects in threepoint safety belts using the Hybrid III dummy in frontal and frontal oblique sled tests." Proc. 16th Annual Workshop on Human Subjects for Biomechanical Research, pp. 69–114.

[6] Ciccone, M & Wells, J. 1988, "Improper Shoulder Belt Use by Maryland Drivers", HUMAN FACTORS, 1988,30(3),359-366.

[7] Bacon D. 1989. "The effect of restraint design and seat position on the crash trajectory of the Hybrid III dummy, in Hybrid III: The First Human-

like Crash Test Dummy" (PT-44), Eds. SH Backaitis, HJ Mertz, Society of Automotive Engineers, Warrendale, PA, pp. 641– 647.

[8] Ljung-Aust, M., Jakobsson, L., Lindman, M., Coelingh, E. 2015 "Collision avoidance systems – Advancements and efficiency." SAE World Congress, Detroit, USA. SAE Technical Paper 2015-01-1406

[9] Schoeneburg P R, Baumann K, Fehring M. 2011. "The Efficiency of PRE-SAFE Systems in Pre-braked Frontal Collision Situations." Proceedings of the 22nd ESV Conference, Washington, D.C.

[10] Östh J, Brolin K, Bråse D. 2015 "A Human Body Model with Active Muscles for Simulation of Pretensioned Restraints in Autonomous Braking Interventions." Traffic Injury Prevention, 2015, 16(3):pp.04–13.

[11] Labs, T.C.R.D. THUMS (Total HUman Model for Safety) AM50 Occupant Model: Version 3.0-080225

[12] Östh J, Brolin K, Carlsson S, Davidsson J, Wismans J. 2012 "The Occupant Response to Autonomous Braking: A Modeling Approach That Accounts for Active Musculature." Traffic Injury Prevention, 2012, 13:pp.265–77.

[13] Saunders J, Parent C, Ames E, 2015 "NHTSA Oblique Crash Test Results: Vehicle Performance and Occupant Injury Risk Assessment in Vehicles with Small Overlap Countermeasures." Proceedings of the 24th ESV Conference, Gothenburg, Sweden.

[14] Östh J, Ólafsdóttir JM, Davidsson J, Brolin K. 2103 "Driver Kinematic and Muscle Responses in Braking Events with Standard and Reversible Pre-tensioned Restraints: Validation Data for Human Models." Stapp Car Crash Journal, 57:1-41

[15] HUMANETICS. 2015 "THOR-50th Dummy Model LS-Dyna, Release Version 1.0

[16] Gehre, C, Gades, H, Wernicke, P. 2009, "Objective rating of signals using test and simulation responses." Proceedings of the 21:st ESV.

[17] Barbat, S, Fu, Y, Zhan, Z, Yang, R-Y, Gehere, C. 2013, "Objective Rating Metric for Dynamic Systems", Proceedings of the 23:rd ESV.