ANALYSIS OF THE PRE-CRASH BENEFIT OF REVERSIBLE BELT PRE-PRETENSIONING IN DIFFERENT ACCIDENT SCENARIOS

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ABSTRACT

The goal of active belt systems is to reduce occupant movement in highly dynamic driving situations to increase both safety and comfort. In this paper the ability of such systems to reduce occupant displacement is quantified and the resulting increase in occupant safety is analyzed for different accident scenarios. These scenarios are characterized by the direction of occupant displacement as it results from vehicle dynamics prior to the accident such as braking or evasive steering and by the impact direction.
To identify the occupant displacement as initial condition for the chosen accident types, the inertial forces prior to the accident are reproduced in a test vehicle for the chosen scenarios. Different levels of reversible pre-pretensioning are used within these tests. A conventional belt system (no pre-pretensioning), a belt system with reactive pre-pretensioning (activation based on vehicle dynamics data) and a belt system with predictive pre-pretensioning (pre-triggered based on environmental sensors) are being compared. The occupant displacement is measured during these tests.
The results show, that a significant reduction of occupant displacement is possible using active belt systems. For instance forward head displacement during panic braking scenarios can be reduced significantly with reactive pre-pretensioning and even further with pre-triggered pre-pretensioning in comparison to the same scenario with a conventional belt system without pre-pretensioning.
The effect of reduced occupant displacement is studied using crash simulation and sled tests. In both cases the dummy is positioned according to the measured displacement values as initial condition. Characteristic injury values of these crash simulations and sled tests are compared to identify the effect of different levels of occupant displacement on injury probability.
Both simulation and sled tests demonstrate that a modified initial occupant position may result in an altered injury mechanism during the crash. The rapid deceleration in the tested panic braking situations for example leads to a forward displacement of the occupant that in case of a subsequent front crash may result in a bag slap (caused be the reduced distance between occupant and instrument panel). The improved occupant position using an active belt could decreases the probability of a bag slap for the same scenario.
Lateral displacement with a subsequent frontal collision could have even more severe consequences on occupant injuries. The simulation results show that because of the lateral displacement of the occupant the contact with the frontal airbag may be misaligned and therefore airbag effectiveness could be reduced. As a worst case scenario the probability for a contact to the instrument panel could increase. This effect is intensified as the routing of the belt is influenced by lateral occupant displacement, which may reduce the effectiveness of the belt system in a crash. Reduced occupant displacement can avoid or mitigate the risk of such an injury mechanism.
In case of a rear impact with initial forward occupant displacement the changed occupant position results in injury rating values many times higher than those in nominal position. Again, reduced occupant displacement can mitigate this effect.
In conclusion reversible pre-pretensioning allows the reduction of occupant displacement and proves to have a direct effect on occupant safety in the examined scenarios.

INTRODUCTION

Since their introduction into premium class vehicles in 2002, reversible belt pre-pretensioning systems spread into upper-class and mid-range vehicles and it is expected that they will be available in compact cars in the near future. Unlike pyrotechnical belt pretensioners, reversible systems are activated prior to an imminent collision if the driving situation is identified as critical. As a result, seatbelt effectiveness is increased. This is especially useful in situations, in which the occupant is moving out of his initial position prior to the accident. This movement can be reduced, if the reversible belt pretensioner is activated in time, thus increasing occupant safety.

Occupant movement prior to an accident can be caused by inertial forces that result from evasion maneuvers or emergency braking. The analysis of accident data shows that for a significant number of accidents there was an attempt for counter-measures beforehand, like braking or evasive steering. In case of rear-end collisions which account for 25% of all accidents with occupant injury in Germany [1] about 40 % of the drivers of the rear vehicle initiated emergency braking with an additional 12 % that partially applied the brakes [2]. For intersection accidents, which account for about 23 % of all accidents with personal injury/fatalities in Germany [1], about 40 % of the drivers of the vehicle causing the accident and about 40 % of the drivers of the colliding vehicle with the right of way tried to avoid the accident by braking [3]. This leads to the conclusion that a substantial number of accidents occurs with occupant movement during the last seconds prior to the impact.

Based on vehicle dynamics data (e.g. provided by the sensors of the Electronic Stability Control (ESC) in case of an instable vehicle dynamics) or the data of environmental sensors (as used for collision avoidance/mitigation systems like an Automatic Emergency Brake (AEB) in case of an imminent rear-end collisions) the current driving situation can be analyzed. If potentially dangerous situations can be identified early enough, reversible belt pre-pretensioning can be activated while or even before occupant movement starts. The result would be reduced frontal (braking) or lateral (evasive steering or skidding) occupant displacement. As a result of reduced displacement the occupant's position should be closer to the nominal position as foreseen in the vehicle interior design, increasing the effectiveness of the restraint system in total.

It is important to note that reversible pre-pretensioners are no replacement for pyrotechnical pretensioners, as their activation during the pre-crash phase can not be guaranteed for all cases [4]. Furthermore, reversible pretensioners work on a much lower force level and the webbing pull-in speed is significantly lower compared to pyrotechnical pretensioners [5], [6]. Therefore the benefit of reversible pre-pretensioning is seen in activation before t_0, while pyrotechnical units are triggered after t_0.

MOTIVATION AND STATE OF THE ART

As most automotive components occupant safety systems are subject to continuous development. Airbags and pyrotechnical belt pretensioners are currently standard features of most passenger cars. Reversible pre-pretensioners are a relatively new advancement to improve occupant safety furthermore.

The goal of reversible pre-pretensioning is to remove belt slack before inertial forces cause the occupant to leave the nominal position. This reduces occupant displacement during pre-crash braking or evasive steering. As the restraint system is designed with respect to the nominal position (e.g. given by regulation or consumer testing) this position is expected to provide the best occupant safety. Therefore one of the major objectives of this study is to determine whether and in which scale the efficiency of the restraint system is affected negatively if the occupant is not in nominal position due to inertial forces (unlike studies regarding the effect of pre-pretensioning in secondary collisions as in [7]). A comparison of these results for conventional and active belt systems provides information on the benefit of pre-pretensioning regarding injury severity.

A parallel trend to reduce the number of fatalities and to increase traffic safety is the advancement in active safety. Collision avoidance/mitigation systems are state of the art in upper class vehicles. Based on environmental sensors using e.g. radar and video, imminent collisions may be identified in advance and an Automatic Emergency Brake (AEB) can be activated. Usually these systems also include a driver warning and autonomous braking is only initiated if braking is the only way to prevent a collision (at higher velocities the stopping distance is longer than the distance required for evasive steering [8]. Since an AEB may only be activated if there is no other option to prevent a collision, only collisions below a certain velocity can be prevented autonomously. Still, the reduction of collision velocity reduces the risk of severe or fatal injuries at higher speed). That is why depending on the accident scenario AEB activation will either reduce relative velocity at t_0 or avoid the collision.

Consumer organizations like Euro NCAP accommodate the development of active safety systems like AEB on their roadmap (e.g. beyond NCAP [9]). Dekra and BMW performed a crash test with automatic emergency braking prior to the impact to demonstrate the benefit of the reduced collision velocity in 2010 [10]. A full testing methodology for integrated safety systems is being developed in the EC-funded research project "ASSESS", including rating criteria and tools [11]. These examples can be interpreted as a first step of an adaption of current standard testing procedures to an integrated active and passive safety evaluation in future vehicles.

Current standardized crash tests are performed without braking or evasive steering and therefore do not include initial dummy displacement. On the other hand static Out-of-position (OOP) tests in which the dummy is positioned close to the airbag module are integrated

in current U.S. legislation to evaluate potential harm by the deploying airbag for non-nominal seating positions. These tests are based on the fact that especially unbelted occupants or children without proper child restraint system on the front seats might be in an unfavorable position closer to the airbag module at the time of airbag activation. However, currently there is no standard procedure available to analyze and evaluate the potentially reduced restraint system effectiveness due to pre-crash occupant displacement.

The analysis of the relevance of initial occupant displacement with and without active belt systems on the efficiency of the restraint system in total provides information about the change of the injury mechanism if collision avoidance actions like evasive steering or emergency braking were attempted prior to the accident (either by the driver or by active safety systems) and thereby supports a further development and improvement of occupant safety systems.

APPROACH

The goal of this study is to analyze a potential real-world benefit of an active belt system. The study is divided into two major tasks. The first task is the analysis of the effect of active belt systems on occupant displacement. This is done in vehicle testing with real test persons. The test results can also be used as validation data for subsequent numerical pre-crash simulations with human body models (as done with similar tests within the cooperative project OM4IS [12]), but this will not be further discussed here.

Real test persons were chosen instead of test dummies because the kinematic of the dummy in the chosen scenarios turned out to be unrealistic in preliminary tests (Since the dummy is made for crash tests instead of driving scenarios it resists inertial forces in the order of 1 g stronger than the real occupant resulting in virtually no displacement). The resulting displacement values are then used as initial conditions for crash simulations and sled tests to identify the effect on occupant injury severity.

The driving scenarios chosen for the displacement analysis are examples for collision avoidance/collision mitigation maneuvers as they are attempted by the driver in critical situations if collisions are imminent: Emergency braking and evasive steering. These highly dynamic maneuvers can represent the dynamic status of a vehicle prior to an imminent crash. The deceleration or lateral acceleration of the vehicle causes inertial forces that affect the position of the occupants. The occupant position is identified during these tests using measurement equipment. All measurement is done for a test person on the passenger side as preliminary tests indicated that these values are more reproducible.

The second task is to identify the effect of occupant displacement on injury probability. For this a crash simulation is used for frontal and lateral impact while the rear impact scenario is analyzed in sled tests. In both cases the dummy or dummy model is positioned according to the measured displacement values from the vehicle tests as initial condition.

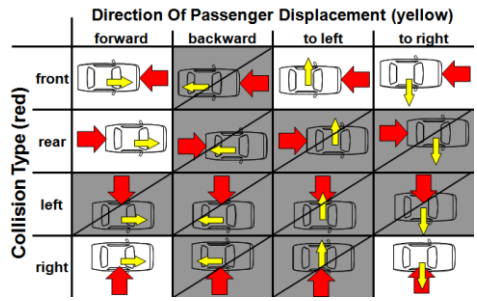

Figure 1. Combination matrix for collision type and displacement direction

As a result, major real world accident scenarios are represented by a combination of displacement direction and impact direction (See Figure 1). The accident scenarios with white background have been chosen for this study. Due to its limitation by the backrest of the seat backward displacement is not incorporated. All far side crash scenarios (impact from the left) are put aside as occupant injury is expected to be higher for a near side impact (see e.g. [13]). Rollover crashes have not been included in this matrix. Consequently the simulated or tested scenarios (passenger side) are

- Front impact with initial forward displacement
- Front impact with initial lateral displacement to the left
- Front impact with initial lateral displacement to the right
- Right side impact with forward displacement
- Right side impact with initial lateral displacement to the right
- Rear impact with initial forward displacement

The results provide information on how the injury mechanism is influenced by occupant displacement. This allows an estimation of the potential real-world benefit of reversible pre-pretensioning and offers indications for further improvement of active belt systems.

OCCUPANT DISPLACEMENT

Hypotheses

Dynamic driving as in collision avoidance maneuvers generates inertial forces which lead to a displacement

of the occupant. The goal of reversible pre-pretensioning systems is the reduction of occupant displacement to increase occupant safety. One hypothesis is that a reduction of occupant displacement can be achieved for both lateral and frontal displacement using reversible pre-pretensioning systems.

As for all safety measures, it is important to trigger pre-pretensioning as soon as possible as current pre-pretensioning systems do not provide enough force to move a displaced occupant back into position. As described earlier the intention is to preemptively remove belt slack to prevent high displacement values in the first place. That is why from the safety side point of view it is best to activate pre-pretensioning systems early (while avoiding unnecessary activations because of potentially unpleasant or even annoying reception). For rear end collisions a "predictive" activation of a reversible pre-pretensioning retractor based on e.g. radar sensors is already in series production. A second hypothesis therefore states that earlier activation improves the ability of a reversible pre-pretensioner to reduce occupant displacement.

Method and Tools

The tests were performed using one test person with weight and size similar to a 50%-dummy on the passenger seat (different persons for frontal and lateral displacement tests but no test person variation within one test scenario). As current reversible belt pre-pretensioning system the Active Control Retractor II (ACR2) was chosen, a retractor based reversible pre-pretensioner. The setup was tuned with a maximum ACR-generated belt force of up to 110 N for full retraction. The duration to reach the predefined shoulder force for full pre-pretensioning is approx. 120 ms, depending on driving situation and clothing.

Forward Displacement To measure forward displacement a vehicle equipped with a prototype Automatic Emergency Brake (AEB) was chosen. The AEB uses a 24 GHz radar sensor and a video camera. Based on these sensors the system recognizes the threat of an imminent collision and applies an emergency braking. By using an AEB instead of a driver the scenario is more reproducible regarding the brake pressure gradient (As long as the driver applies enough brake pressure to get all four tires into the Anti-lock Braking System (ABS) regulation for the duration of braking the deceleration is not influenced substantially by the driver). Also the activation time for the reversible pre-pretensioner can be adjusted gradually to identify the benefit of early activation based on environmental sensor data.

In braking tests the occupant was filmed from the driver side window using a video camera. The maximum frontal displacement for the occupants head and neck was identified from the video images using the intercept theorem and a defined scale on the vehicle as reference. Unlike the tests for lateral displacement this method only provides maximum displacement values and no progress of displacement over time. Vehicle dynamics data from the vehicle's inertial sensors and the brake pressure sensor were used to ensure comparability of all tests as described for lateral displacement testing.

For this test scenario a comparison was done between a conventional belt system, a reactive reversible pretensioning (ACR2 triggered simultaneously with emergency braking) and a pre-triggered reversible pretensioning (ACR2 triggered 120 ms before emergency braking by the AEB control).

Due to wet road surface all tests for forward displacement were performed with a resulting maximum vehicle deceleration of about 7 m/s². Braking maneuvers on dry concrete may well provide deceleration levels of 11 m/s² and may therefore result in higher inertial forces and possibly higher forward displacement.

Lateral Displacement The tests for lateral displacement analysis were performed in a current, representative compact class vehicle. The test person was filmed using a video camera and displacement values were identified with video tracking software as shown in Figure 2. The video tracking software uses reference markers for tracking. Two markers have been placed on the test person, one on the chest and one on the forehead. In addition one marker was used on the belt to visualize the belt movement (This marker is not used for measurement; the belt movement was measured using a separate belt pullout sensor). Figure 2 also shows two reference points near the vehicle's roof.

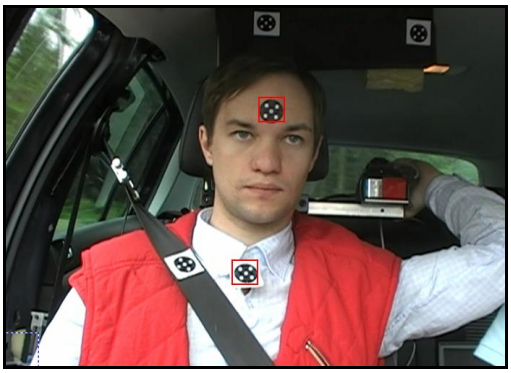

Figure 2. Measurement of occupant displacement using video tracking software

Using measurement sensors and the vehicles own sensors the following data was recorded in addition to the displacement values: belt force (near the shoulder), belt pullout, lateral and longitudinal acceleration, yaw rate, brake pressure, ACR2 motor current and ACR2 trigger signal. A flash is used to synchronize video and directly measured data. This way all signals (including lateral displacement) are measured over time and even complex scenarios like a double lane change can be analyzed. The measurement of vehicle dynamics data was also used to ensure that all repeated tests for one scenario are comparable and show similar values for lateral acceleration.

The first test scenario for lateral displacement analysis is the double lane change maneuver as defined in ISO 3888-2 [14]. The vehicle's velocity ahead of the course is regulated by cruise control. When entering the course the cruise control is turned off and the course is driven with engine brake. If a traffic cone is moved or knocked over during a run this run is considered invalid and repeated. Based on the recorded vehicle dynamics data all runs were checked for anomalies of velocity, lateral acceleration and yaw rate. Runs with high deviations were not used for the displacement analysis.

For the analysis the double lane change data is divided into parts to examine both sides of occupant displacement separately. Still the displacement values for left and right side are not independent from each other as the displacement during the first part of the maneuver may influence the further behavior of the test person. To allow an independent analysis of passenger displacement to both sides of the vehicle a curve with constant radius is introduced as a second maneuver.

The same curve is passed from both sides with all other parameters kept unchanged. With the exception of the course setup and the initial velocity the test procedure is identical to the double lane change maneuver, including the validation of vehicle dynamic data to ensure comparable test runs.

The occupant displacement with a conventional belt was compared to the reversible pre-pretensioner with partial and full retraction strength. In addition to a reactive system that identifies critical situations based on the vehicle dynamics a pre-triggered system is analyzed. The pre-triggering is done manually when entering the course. The pre-triggered variant provides a first impression of the potential additional benefit for further displacement reduction when integrating environmental sensors or e.g. road map data with reversible pre-pretensioners.

As driving the single curve maneuver does not create a critical situation there is no reactive activation of the belt pre-pretensioning system based on vehicle dynamics data. Therefore this scenario is only tested with a pre-triggered pre-pretensioner and a conventional belt-system as reference.

Results

<u>Forward Displacement</u> For the braking maneuver no partial pre-pretensioning was used. All tests were performed with either a conventional belt system or with a full pre-pretensioning with approx. 110N maximum pre-pretensioning force. A distinction is made regarding the timing of the pre-pretensioner in relation to the emergency braking. The reactive system variant is triggered simultaneous with the AEB while the predictive variant is pre-triggered approx. 120 ms prior to AEB activation. The situation interpretation algorithm of the AEB provides a calculated time-to-collision (TTC) based on obstacle distance and relative velocity. From this TTC value the timing of the emergency braking is deducted and the timing for activation of the ACR is preponed for 120 ms.

The results are shown in Figure 3 in form of box plots. The box plots show the maximum and minimum deviation values (as dotted gray lines), the 25th and 75th percentile (represented by the "box"), the median (as dotted black line) and the mean value (as solid red line). For each variant separate plots visualize the head and chest displacement.

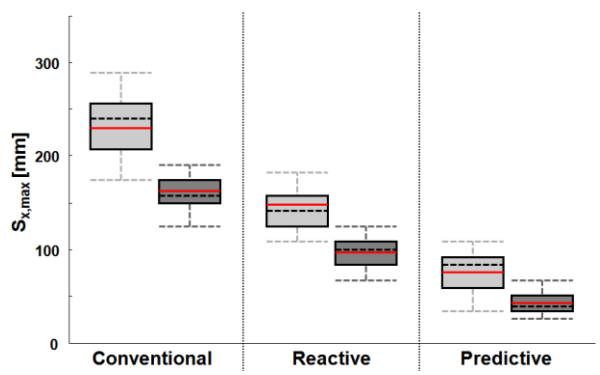

Figure 3. Maximum forward displacement in emergency braking maneuvers for head (light gray) and chest (dark gray), n=8 for each variant

Figure 3 shows that for a conventional belt system the maximum forward head displacement reaches maximum values of in average 232 mm. The corresponding chest displacement is 159 mm. This occupant displacement can be reduced significantly by the use of reversible pre-pretensioning. Simultaneous activation of the active retractor results in a displacement of 143 mm (head) and 92 mm (chest) respectively. The pre-triggered active retractor demonstrated a further reduction to 68 mm (head) and

46 mm (chest) respectively. The results of the unpaired two-sample t-test are highly significant for all variants and for both head and chest displacement. It should also be noted that the variance of displacement values is reduced by reversible pre-pretensioning.

Lateral Displacement The double lane change scenario as standardized evasive steering maneuver is divided into three parts for the analysis. This separation allows a detailed study of the displacement behavior in the different sections of the maneuver as illustrated in Figure 4.

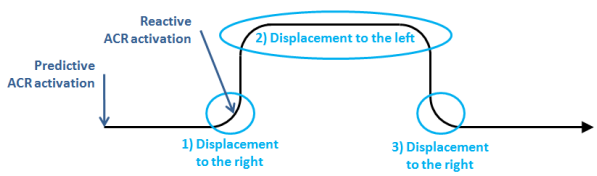

Figure 4. Illustration of the double lane change separated into three sections

The first section is characterized by the evasive steering to the left from the entry lane, resulting in occupant displacement to the right (towards the B-pillar - referring to the passenger as all data was recorded on the passenger side). The second phase includes the right curves when entering/leaving the evasive lane, resulting in occupant displacement to the left (towards the driver). The final left curve with occupant displacement to the right is considered as section three. Figure 5 shows the resulting occupant displacement (absolute values) as separate box plots for the three sections of the double lane change maneuver.

It is shown, that lateral head displacement values are consequently higher than the values for chest displacement. Also the variance of head displacement values is mostly higher than for chest displacement. That is why the following analysis primarily refers to the chest displacement because it allows higher significance levels.

For section 1 of the driving maneuver the reactive pre-pretensioner does not reduce the occupant displacement compared with the conventional belt system. This is due to the fact that the reactive system is activated near the end of section 1 (cp. Figure 4). That is why reactive pre-pretensioning may not affect lateral occupant displacement significantly in the first phase of the double lane change maneuver, while occupant displacement in the following segments 2 and 3 benefits from the reactive belt system. On the other hand, predictive (pre-triggered) pre-pretensioning showed significantly reduced occupant displacement in section 1, with an increased efficiency for the full retract with higher retraction force.

In section 2 of the double lane change reactive and predictive systems could provide a significantly improved occupant position. It can be seen that chest and head displacement values for partial pre-pretensioning with approximately 85 N can be reduced to a similar level for predictive and reactive pre-pretensioning activation. The full retraction force allows a higher reduction of occupant displacement (again for predictive and reactive triggering) with the exception of head displacement values for the pre-triggered variant.

The third chart in Figure 5 illustrates the occupant displacement towards the B-pillar in section 3 of the double lane change. A comparison of the results of the conventional seat belt with all tested active belt

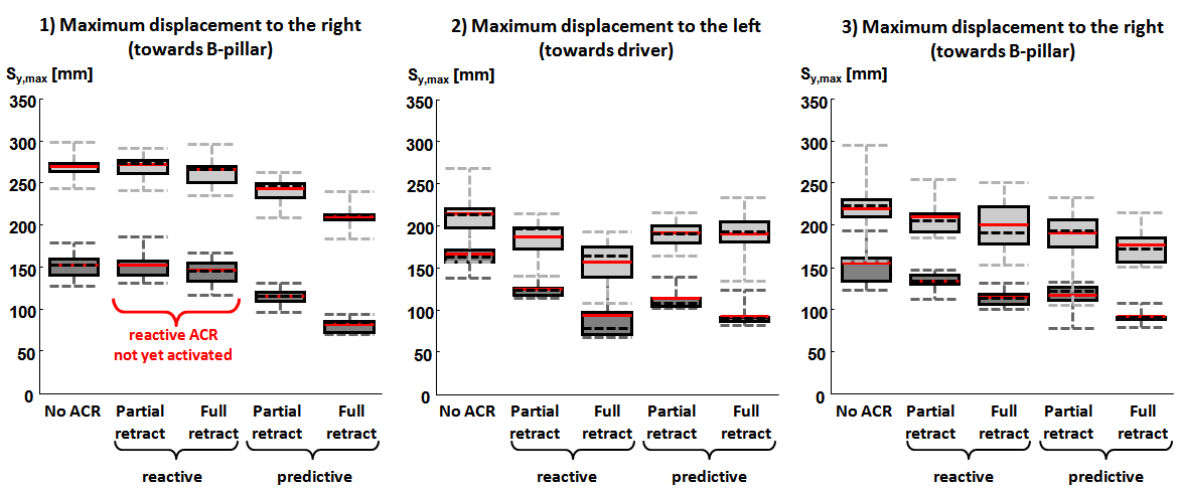

Figure 5. Maximum lateral occupant displacement for head (light gray) and the chest (dark gray), n=9

systems show a significant reduction of occupant displacement due to reversible pre-pretensioning. It can be seen that predictive triggering could further improve the occupant position compared to reactive triggering in section 3 although the displacement values for predictive and reactive systems are on a similar level in section 2 of the maneuver.

Table 1 sums up the displacement results of the double lane change maneuver for the passenger's chest, including the results of significance testing using unpaired two-sample t-test to compare displacement values for a conventional belt with the active belt variants. A significance level < 0.3 % is considered highly significant and marked with a blue background, a level < 5 % is considered significant and marked in light blue.

It can be seen that for chest displacement a significant or highly significant improvement is found for all systems except for reactive variants in section 1 as mentioned earlier.

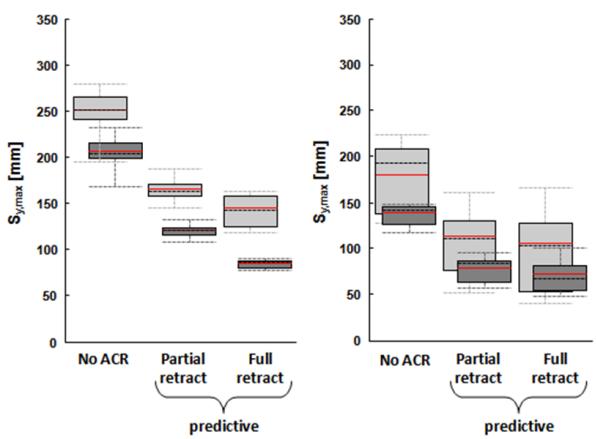

Figure 6. Maximum lateral head (light gray) and chest (dark gray) displacement for right (n=8) and left (n=9) curve

The box plots for lateral displacement for the constant curve are shown in Figure 6. The left chart shows the clockwise turn with displacement to the left (towards the driver), the right one presents the results of the counter-clockwise turn with displacement to the right (towards the door and B-pillar). Since reactive pre-pretensioning is not activated during these maneuvers (the driving situation is not rated "critical" based on vehicle sensors as no loss of vehicle stability is detected), reactive variants have not been included in the corresponding tests and box plots.

Similar to the results for the double lane change the variance of head displacement exceeds the variance of chest displacement. It can be seen that predictive pre-pretensioning could further reduce occupant displacement significantly. The higher pretensioning force of the full retract provides an additional benefit regarding occupant displacement. This effect is higher for displacement to the left than for displacement to the right. In general, lateral occupant displacement towards the center of the vehicle seems to reach higher absolute values as displacement towards the B-pillar in this maneuver. A comparison of the lateral acceleration values shows similar levels of inertial force. The passenger door as limiting factor and the asymmetric belt geometry are assumed to be the cause of this variation.

A comparison of the average displacement values and the results of the corresponding significance test can be found in Table 2.

Table 2
Max. lateral chest displacement in constant curve

		Chest Displacement		
			predictive	
		no ACR	Partial retract	Full retract
Left Curve	Significance Level		0,0000%	0,0001%
	Displacement	138 mm	79 mm	72 mm
Right Curve	Significance Level		0,0001%	0,0000%
	Displacement	207 mm	122 mm	86 mm

It can be seen that the improvement of occupant position is highly significant for all of the tested variants in curve driving.

Conclusion

For all scenarios the displacement (both forward and lateral) could be reduced significantly by the use of a reversible pre-pretensioner. In conclusion the

Table 1
Maximum lateral chest displacement in double lane change tests

			reactive		predictive	
		no ACR	Partial retract	Full retract	Partial retract	Full retract
Segment 1	Significance Level		93,9903%	42,8243%	0,0134%	0,0000%
	Displacement	152 mm	153 mm	145 mm	115 mm	81 mm
Segment 2	Significance Level		0,0065%	0,0014%	0,0005%	0,0000%
	Displacement	165 mm	124 mm	93 mm	113 mm	92 mm
Segment 3	Significance Level		3,7909%	0,0786%	0,1490%	0,0026%
	Displacement	155 mm	134 mm	115 mm	116 mm	92 mm

hypotheses stand the test. Occupant displacement can be reduced using active belt systems.
The comparison of reactive and predictive systems shows that earlier activation improves the ability of the analyzed reversible pre-pretensioner to reduce occupant displacement. The additional benefit of the pre-triggered active retractor can be seen best in the first phase of the double lane change maneuver or in the emergency braking tests.
In addition the lateral displacement also affects the routing of the belt webbing on the shoulder of the occupant. For test driving situations with high displacement towards the interior of the vehicle (during phase 2 of the double lane change and in the right curve) the belt slipped off the occupant's shoulder if no pre-pretensioning was used. As a result the geometry of the belt would be completely changed and the restraint effectiveness of the belt system would be significantly reduced. The effect of the changed belt geometry on occupant injuries was analyzed as part of the crash simulation.

INJURY ESTIMATION

Hypothesis

Besides the displacement study it is the goal of this work to determine in which way injury kinematics and the resulting injury severity are affected by the different levels of occupant displacement in case of a subsequent crash. As basis for the injury estimation the hypothesis is defined, that occupant displacement resulting from inertial forces increases the injury severity to be expected in a subsequent accident.
Since reversible pre-pretensioners do not allow to pull the occupant into nominal position but only help to reduce occupant displacement, the final position of the occupant is still displaced compared to the nominal position. The improvement of occupant safety due to reversible pre-pretensioning is addressed in the hypothesis, that the reduction of occupant displacement by reversible pre-pretensioning reduces consequential injury severity.
These hypotheses are being tested for both lateral and forward displacement in combination with side and frontal impact.

Method and Research Tools

Simulation Based on the results of the displacement studies a crash simulation is done for the predefined front and side impact scenarios (cp. Figure 1). The mean value of the maximum occupant displacement values for each belt system setup with the system variants

- conventional belt
- reactive pre-pretensioning based on vehicle dynamics data
- predictive pre-pretensioning based on environmental sensors

is used as initial dummy position for the start of the crash simulation at t_0 (t_0 = Time of the impact). The expected occupant injury in nominal position is identified within a reference simulation run. For better comparison to standardized testing (e.g. Euro NCAP) 50% male dummy models are used for simulation (Hybrid III for front crash, ES-2 for side crash).
The dummy models are positioned according to the displacement values. For lateral displacement hip displacement was not included in the simulation as it would increase simulation effort substantially (The dummy is seated in a predefined dent in the seat cushion. As the dent is in the center of the seat, lateral hip displacement would require a modified modeling of the seat cushion including a new position of the dent). The dummy model is seated in the middle of the seat and tilted to the side to fulfill the initial displacement conditions. Since displacement values for the chest showed a lower variance than for the head, chest displacement has a higher priority than head displacement if it is not possible to position the dummy model according to both measured conditions due to the rigidity of the virtual dummy. For simulations with forward displacement the dummy model is positioned according to displacement values for hip, chest and head with higher priority for the compliance with hip and chest displacement values than for head displacement. As a simplification inertial and belt forces prior to the accident are ignored in the simulation, because the forces before t_0 are significantly smaller than the forces during the crash. Also no initial dummy velocity is introduced to the crash simulations. The dynamic situation is only represented by the displacement of the dummy. The error made due to this simplification is analyzed in [15] for a front impact while braking.
For side impact different test scenarios are used for forward and lateral displacement. Forward displacement with a subsequent side impact is regarded as a typical intersection accident with crossing traffic after attempted but insufficient emergency braking (As described earlier, the percentage of intersection accidents with attempted emergency braking is significantly higher than for accidents with attempted evasive steering). This scenario is represented using an AE-MDB side barrier model. In contrast to that a virtual pole (as in the Euro NCAP pole side impact tests) is used for side impact simulation with lateral

displacement. This represents a skidding accident in which the vehicle is e.g. striking a tree with the side.
The simulation environment for side crashes is PAMCRASH 2009.1 with the ES-2 v4.1.2 dummy model. Side and curtain airbags are activated as well as the pyrotechnical belt pretensioner. The time-to-fire (TTF) is set to 6ms for the barrier crash and 10 ms for the pole crash. For front crashes the simulation software MADYMO V621 is used with the Hybrid III 50% male dummy model. The simulated restraint system includes the passenger airbag, a torsion bar load limiter and a pyrotechnical belt pretensioner. The belt is simulated using an FE belt model. Side crash analysis is done on the driver side under the assumption that the protection against side impact is similar for both sides. Front crashes were simulated on the passenger side because of the different airbag system and since the data was measured using a test person as front passenger.
Because of the reduced degrees of freedom and the rigidity of the dummy there is an intrusion conflict for some of the modified dummy positions. One conflict results from forward displacement of the side impact ES-2 dummy model. This virtual dummy does not allow a sufficient bending angle of hip and abdominal area to reach the aimed-at displacement values if seated correctly. To allow side impact simulation with the intended forward displacement the contact between feet and vehicle structure is taken out as well as the contact between the dummy's thighs and the front edge of the seat. The resulting position for maximum forward displacement is illustrated in Figure 7.

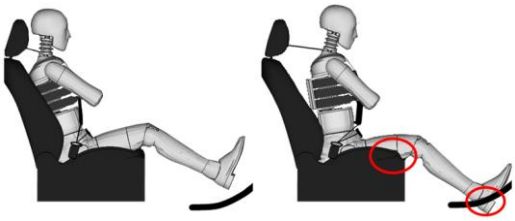

Figure 7. ES-2 dummy with/without forward displacement for side impact simulation
left: dummy in nominal position,
right: dummy with max. displacement and removed contact to seat/vehicle

To ensure that the elimination of these contacts and the resulting change in the distribution of forces does not affect the accident simulation all simulation runs in this specific scenario (including reference simulation runs with the dummy in nominal position) were also performed with cleared contact at the described areas.
For side impact simulation the maximum lateral displacement towards the B-pillar measured in previous testing could not be realized with the virtual ES-2 dummy due to the stiffness of the dummy's chest/shoulder area and because the vehicle used for testing is not the same one as used in the simulation. As a result only one position with lateral displacement is simulated for side impact to give a first impression of the change of injury kinematics in case of lateral occupant displacement.

Sled Tests For the predefined rear crash scenario with initial forward displacement (cp. Figure 1) a sled test is performed to identify the effect of occupant displacement on potential injury consequences. For this scenario the lowest crash pulse of the Euro NCAP whiplash testing protocol with a collision velocity of 16 km/h [16] was used as it represents a standardized evaluation method. The lowest pulse was chosen because the majority of cervical spine injury in rear end collisions occurs with a relative velocity less or equal to the velocity used in this pulse [17]. The crash pulse is recreated using the TRW Hy-G crash sled.
The whiplash tests are done with a BioRID dummy. The dummy is positioned with initial forward displacement as measured in the driving tests and secured with adhesive tape. A notch and the resulting notch effect ensure that the tape is torn upon impact and does not affect the dummy's behavior during the crash phase.

Figure 8. BioRID dummy in nominal position (left) and with forward displacement (center: with pre-pretensioning, right: with conventional belt) for whiplash sled tests

The initial dummy position for the three test setups representing the nominal position (Figure 8 left), forward displacement while braking with predictive pre-pretensioning (center) and forward displacement while braking with a conventional belt system (right) are illustrated.
Unlike the simulation tests the reversible pretensioner was activated during the whiplash test (only for the setup with displacement values measured with a reversible pre-pretensioner). As the belt force is reduced due to the rear impact, the pre-pretensioner can still reduce belt slack during the crash phase and therefore mitigate the rebound effect.

Results

Front crash forward displacement Forward displacement as initial condition for an impact from the front changes the injury kinematic in the simulation. Figure 9 illustrates the direct comparison of nominal position and maximum forward displacement (232/159 mm for head/chest as measured for emergency braking with a conventional belt) for a Euro NCAP forward collision simulation. The characteristics of head deceleration look less critical with forward displacement, but it has to be mentioned, that an initial bag-to-head contact during deployment (bag slap) occurs here.

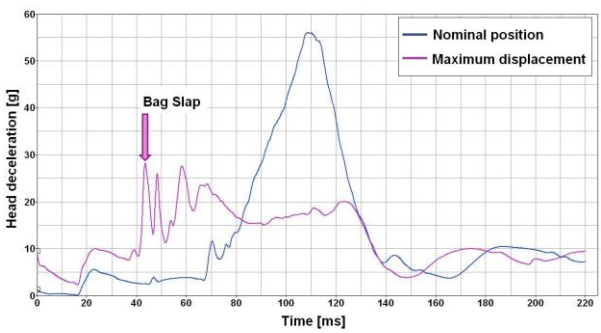

Figure 9. Comparison of nominal position and forward displacement - head deceleration over time

The peak of head deceleration at t_0 + 40 ms results from a bag slap, which has to be avoided completely, because it may cause additional injuries in the head and face area (It should be noted that the simulation of the unfolding phase of the airbag in the simulation environment used for these tests has limitations regarding accuracy and predictability for bag slap effects. Still the measured relative velocity of airbag and occupant head at the time of the first contact as ballpark figure allows the conclusion that the risk of a bag slap increases drastically with this level of forward displacement). The bag slap effect only occurred for the conventional belt system, the displacement measured for active belt systems did not result in a bag slap. Therefore, the potential occurrence of a bag slap for forward displaced occupants can be reduced using reversible pretensioning.

A comparison of the forward displacement values for the 50 % male with the nominal position of a 5 % female (usually the most critical standard test case regarding the bag slap) may exemplify this. While the head of the 5 % female in nominal position is approximately 138 mm more forward compared to the head of the 50 % male in nominal position (Average value of five arbitrary upper & middle class vehicles), the maximum pre-crash forward head displacement of the male test person (similar in size and weight to a 50% dummy) reaches a value of 232 mm.

Front crash lateral displacement As seen in the displacement analyses the belt may slip off the occupant's shoulder for lateral displacement towards the interior of the vehicle without reversible pre-pretensioning. This effect of the displacement study was included in the initial conditions of the simulation. The consequences are increased local belt forces for the abdominal region which could lead to a higher injury risk. Figure 10 shows the belt position for the conventional belt system (no reversible pre-pretensioning) after pyrotechnical pretensioning.

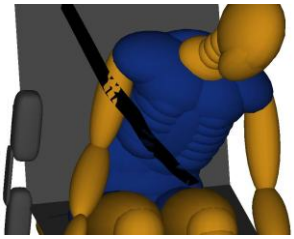

Figure 10. Belt position with maximum lateral displacement after pyrotechnical pretensioning (t0 + 94 ms)

The lateral displacement results in a non-central occupant to airbag contact. This limits the protection potential of the frontal airbag. During the simulation runs with initial forward displacement of the occupant in combination with the unfavorable belt position a dummy-to-IP contact was observed. In the head acceleration diagram this can be seen as a small peak in the head deceleration in Figure 11 for the curve without reversible pre-pretensioning.

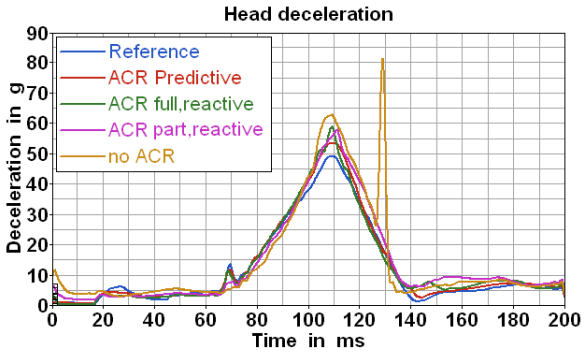

Figure 11. Head deceleration for lateral displacement towards vehicle interior

It can be seen that the head deceleration is best for nominal position and shows higher loads for higher initial forward displacement of the occupant. The simulation provides similar results for chest deflection values.
For initial displacements towards the B-pillar the belt webbing shows unfavorable routing close to the occupant's neck. When the pyrotechnical pretensioner is activated during the crash phase, this situation could lead to additional belt loads in the neck area, which would not occur for nominal seating positions. However, in the simulation model the pyrotechnical pretensioner was able to pull the occupant back and reduce the initial outboard lateral displacement (cp. Figure 12), resulting in a better restraint performance as seen for lateral displacement towards the interior.

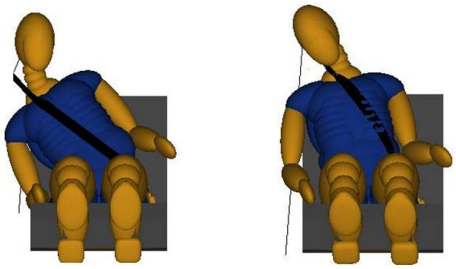

Figure 12. Belt position with maximum lateral displacement before (left) and after (right) pyrotechnical pretensioning

For these simulation runs, some injury criteria for the front crash like chest deflection show even slightly better numbers than for the nominal seating position. This is due to the fact, that the changed belt routing does not directly contact the sternum area, where the chest displacement measurement is located in the dummy and has therefore no real-world significance. But it has to be noted that the unfavorable belt routing close to the neck might lead to additional neck or spinal loadings compared to the nominal case, which do not show in standardized rating criteria for the front crash.

<u>Side crash (barrier) with forward displacement</u> In this scenario the most apparent change due to forward displacement prior to a barrier crash is the changed position of the occupant in relation to the side airbag. As seen in Figure 13 the given width in x-direction of the airbag shows limited ability to cover the whole thorax area for increasing forward displacements. Therefore, the occupant is moving out of the protection zone of the airbag resulting in an increased injury potential in the thorax area.

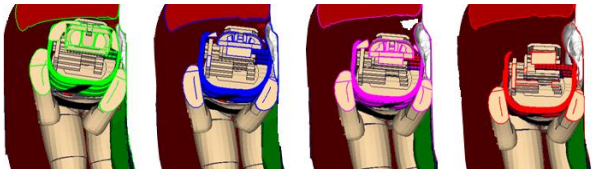

Figure 13. Section view from above – side crash with different levels of forward displacement during airbag deployment (left: nominal position, right: max. displacement).

With rising forward displacement also the abdomen load is increased. This is caused by a contact with the armrest as the occupant is moving out of the protection zone of the airbag. The direct contact with the armrest and the corresponding increase in abdomen force are shown in Figure 14.

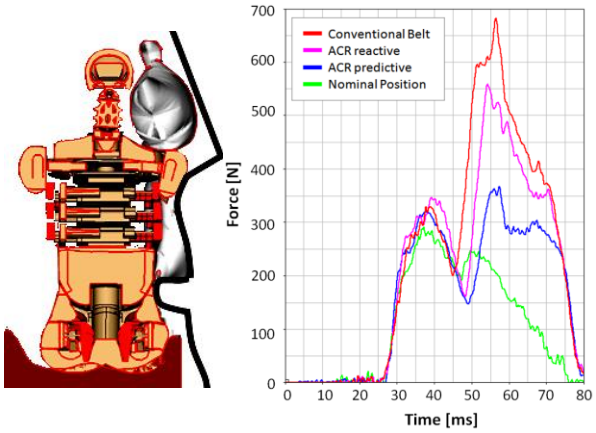

Figure 14. Contact with the armrest (left) and abdomen force for different levels of forward displacement (right)

<u>Side crash (pole) with lateral displacement</u> Most of the standard injury criteria show lower values in the simulation for an initial outboard displacement of the occupant due to the shoulder load path. The maximum shoulder force for the virtual ES-2 dummy is increased from 2.3 kN to 5.1 kN. However, shoulder load is not considered a standardized injury criteria in usual side impact assessment As the shoulder load increases, some other injury criteria show lower values because of the stiffness of the simulated dummy. Therefore the standardized injury assessment criteria cannot be used to evaluate the effects for this test scenario properly.
In addition it was not possible to recreate all occupant positions measured in vehicle testing with lateral displacement as mentioned earlier. That is why the nominal position as reference was only compared to the maximum of lateral displacement that could be reached using the dummy in the simulated vehicle, which is

lower than the maximum measured value. The result of this simulation is seen in Figure 15.

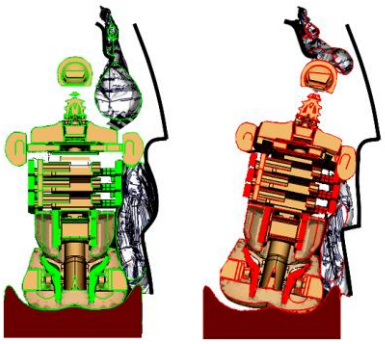

Figure 15. Side crash without (left) and with (right) lateral displacement

It can be seen that both the side airbag and the curtain airbag are not positioned properly due to lateral displacement. During deployment the curtain airbag hits the occupant's head causing a significant head-acceleration in vertical direction. This effect might be even higher with a real occupant with higher initial head displacement (the stiffness of the dummy's neck prohibits higher head displacement values as initial conditions in the simulation). The belt pressure for the side airbag (not illustrated) indicates that the deployment phase of this airbag is affected as well. It is expected that with additional hip displacement the deployment of the bag would have been hindered even more by lateral occupant displacement (Lateral hip displacement was not included in the initial conditions though inertial forces in e.g. the double lane change affect head, chest and hip position).

Rear crash with forward displacement As mentioned earlier the injury estimation for the rear impact crash scenario was done using sled tests with a pulse similar to the specifications of the Euro NCAP whiplash protocol for the lowest severity test. Therefore all whiplash test results should only be compared among each other.

The analysis shows that the values of most injury criteria used for the whiplash rating are highly increased as a result of forward occupant displacement. Figure 16 shows the resulting curve for the neck injury criterion (NIC) as an example.

In comparison to the reference value (dummy in nominal position), the NIC is increased to 240% for the dummy position representing reversible pre-pretensioning and to 410% for the dummy position representing a conventional belt system. Similar tendencies (but with lower differences) are found for the criteria

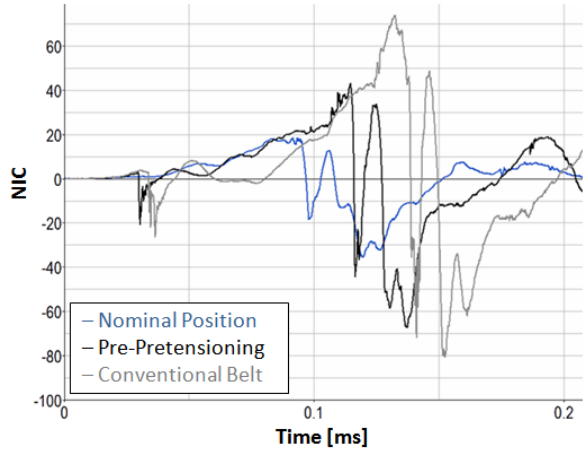

Figure 16. NIC for whiplash tests with/without forward occupant displacement.

- Rebound velocity: 115% respective 143%
- Upper Neck Sheer: 142% respective 175%
- Upper Neck Tension: 160% respective 262%
- T1 acceleration: 154% respective 216%.

In contradiction to these results the Nkm values are reduced with increasing occupant displacement (95% respective 84%). The reason for this behavior is still in discussion.

Subsuming the whiplash test results show that increased forward occupant displacement as e.g. by braking in a rear crash leads to increased injury probability.

Conclusion

The results of the crash simulation using lateral and forward occupant displacement as initial conditions show how the crash phase of the accident is affected by the changed occupant position. For the simulated vehicle with maximum forward displacement a bag slap occurred in the simulated front crash. Due to the fact, that only one vehicle was studied in this study and because of limitations of the simulation this cannot be generalized for all vehicles and occupant sizes. For initial forward displacement in a front crash the potential for a bag slap is increased and the reduction of forward displacement by e.g. reversible pre-pretensioning could mitigate or even eliminate this risk. Lateral displacement in a front crash affects the belt geometry. This may cause additional neck and spinal loads for initial outboard lateral displacement towards the B-pillar as the belt moves closer to the neck and may press on the neck area. For initial lateral displacement towards the center of the vehicle the changed occupant position and the changed belt geometry result in a reduced protection effectiveness of

the restraint system. As shown in the simulation results, higher loads in the abdominal area could occur. Furthermore, the potential for occupant-to-IP contacts would be increased for this scenario. The general conclusion is that a reduction of displacement reduces the tendency of unfavorable belt geometry and its subsequent consequences.

The side impact simulation with initial forward displacement shows that the occupant might move out of the protection zone of the side airbag and therefore the effectiveness of the side restraint system could be decreased. The increase in abdomen forces due to the armrest is regarded as specific for the simulated vehicle.

For initial outboard lateral displacement in side impacts the proper deployment and positioning of curtain and side airbag could be disturbed. In case of the curtain airbag the deployment could even lead to additional vertical head accelerations. Furthermore, after deployment the curtain airbag is not positioned properly, which could further reduce the protection effectiveness. These observations are not specific to the vehicle under investigation, but can be transferred to other vehicles as a general effect including the additional load in vertical direction.

The negative effect of high occupant displacement values and the potential improvement using reversible pre-pretensioning is also proven for the whiplash scenario. If the rear impact occurs, while the vehicle is still braking, the resulting forward displacement may result in load values many times higher than the stress in nominal position. This effect can be mitigated significantly using reversible pre-pretensioning.

Recapitulating the use of reversible pre-pretensioners is favorable in all the cases because the reduction of the initial occupant displacement also reduces the negative influence of initial displacements to the effectiveness of the restraint system. The potential occurrence of effects like bag slap or a contact to the instrument panel can be reduced if the occupant remains closer to the nominal seating position, as this is the reference position the restraint system can show its best protection effectiveness. This confirms the hypotheses stated earlier.

DISCUSSION AND OUTLOOK

To reduce the effort for vehicle testing and crash simulation and due to the restrictions of some of the tools some limitations apply to this study. The displacement values introduced with this paper have been measured using one male test person as a passenger and one sample vehicle with an ACR2 as reversible pre-pretensioner for each scenario. Further tests regarding the influence of varied test persons (e.g. including test persons similar to a 5% female), different vehicles or a comparison of driver and passenger displacement would increase the transferability of the study. Similar tests are ongoing as part of the cooperative project OM4IS with the intention to develop a simulation model that is validated for both the pre-crash and the crash phase [12].

Other pre-pretensioning systems may differ from the tested one in pretensioning speed/strength, activation thresholds and basic function. For instance the Active Buckle Lifter performs pre-pretensioning at the buckle instead of the retractor, which results in a different distribution of belt force for lap and chest/shoulder area with possibly different displacement values.

Regarding the simulation results the predictability of the tools has to be taken into account. Especially, quantitative values for contact situations have limited transferability. The use of a human model is expected to allow a more realistic positioning of the occupant according to the measured displacement values and the behavior during the crash phase is expected to allow more realistic kinematics for a human model. Still the simulation data is very well able to demonstrate possible effects of reversible pre-pretensioning on injury severity. And the general effects that were identified remain valid for other vehicles and scenarios.

In case of the whiplash sled tests it has to be noted, that the pulse is similar to Euro NCAP requirements so injury values should not be used for an absolute rating, while a comparison among these tests is still valid. This comparison proves the drastic increase of the probability of potential injury with increasing forward displacement and illustrates the positive effect of reversible pre-pretensioning systems in this scenario. This constitutes a substantial finding compared to previous publications regarding the benefit of reversible pre-pretensioning [18].

Subsuming the ability of active belt systems to reduce occupant displacement and to mitigate the negative effects on potential injury has been shown. This benefit can be increased even more if the activation of such safety measures is done before vehicle dynamics cause inertial forces. E.g. the activation of the ACR2 prior to an Automatic Emergency Brake can reduce forward displacement significantly compared to simultaneous triggering. Therefore an early recognition of critical situations is an important factor to further minimize unfavorable pre-crash occupant displacement.

Rollover crash scenarios are not included in this study. Since a positive effect is assumed also for these scenarios, it is planned to include such test scenarios in further analysis regarding the benefit of active seat belt systems.

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