Occupant Protection in Alternative Seating Positions

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1 Abstract

Autonomous driving at SAE level 4 and 5 will allow for seating configurations completely different from today's. This affects the direction of the seat with respect to the driving direction as well as e.g. inclinations of the seat down to sleeping positions. This study focusses on different seat directions in a car undergoing a frontal crash with and without vehicle rotation. Computer simulations are done using different dummy models and a standard seat model. In the baseline cases occupants are restrained by standard seat-integrated 3-point-belt systems with pretensioner and load limiter. Worst cases are identified and potential improvements of the restraint systems are investigated.

The study shows increased injury risk due to high loading of the neck and partially the chest as well as the belt sliding off the shoulder of the occupant in some cases. These risks are addressed by including alternative restraint systems as inflatable belt systems, criss-cross-belt and improved seat and head rest geometry in the models. It could be shown that these systems are able to reduce the injury risk and the occupant displacement considerably.

2 Introduction

Studies have shown that occupants riding in future vehicles allowing for highly or fully autonomous driving (AD, SAE level 4 or 5 [1]) would like to use this freedom to be seated in positions differing from today's [2, 3]. Jorlöv et al. investigated these customer expectations and identified positions preferred for longer rides as shown in Fig 1.

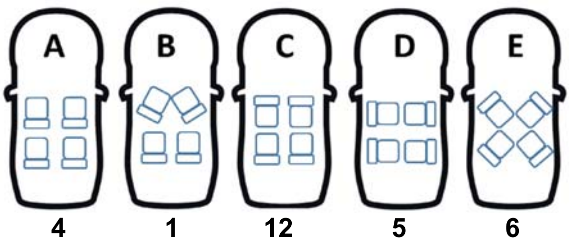

Fig.1: Seat arrangements derived in Jorlöv et al. and number of preferences [2].

The traffic at least in the first years of autonomous driving will be of mixed nature. It was already estimated that new technologies need about 30 years to spread to 95% of the fleet [4]. Manually driven cars and autonomously operating cars will share the same roads and crashes will still happen [5, 6].

If AD vehicles with seat configurations given in Fig. 1 undergo a full frontal crash, the occupants in these vehicles will experience this crash differently, depending on their seating position. Occupants in vehicle A and rear occupants in vehicles B and C face a frontal crash. Front occupants in vehicle B have an angled frontal crash and in vehicle C a rear crash. All occupants in vehicle D suffer a (far) side crash. Finally occupants in vehicle E are subjected to a mixture of angled frontal and side crash in the rear and a mix of side and rear crash in the front.

Additionally, there might be no standard airbags available in crash direction for occupant restraint in vehicles with rotatable seats because surfaces, which could take the restraint load from the airbag might not be available. Consequently, no standard airbags are included in this study.

This paper investigates the kinematics of the occupant in three crash configurations and seven different seating positions by FE simulations. Seating positions include frontal and lateral cases. Rear cases were not involved. Based on identified worst cases and restraint insufficiencies the potential of improving the occupant restraint was analyzed for different restraint systems.

3 Methods

The generic models used in this study consist of the appropriate occupant (HIII 50% for frontal crash directions and ES-2re left hand side for lateral crash directions), a standard seat, a vehicle floor and the restraint system (see Fig. 2). The dummy models are taken from the LSTC database [7]. The seat and the floor are based on NCAC Toyota Yaris model [8]. The floor, the seat base and the seat back are modelled rigid. The seat foam is modelled deformable. Velocity (Δv) of the modelled crash was chosen to be 16,2 m/s for frontal cases using HIII and 11,1 m/s for lateral cases using ES-2re.

In the baseline case the occupants are restraint with a seat-integrated 3-point belt system including pretensioner and load limiter. The mounting direction refers to driver belts with retractor behind left shoulder and buckle on the right side. The load level was chosen to be 4 kN for the frontal cases and 5 kN for the lateral cases. The higher load level for the lateral cases was selected due to high displacements of the occupant with lower load levels.

Fig.2: Generic models used in the study.

Two parameters were varied for the worst case analysis with the baseline models – seat rotation and vehicle rotation during the crash.

The seat rotation with respect to driving direction was set at levels 45°, 30°, 0°, -30°, -45°, -60° and -90° as shown in the left upper part of Fig. 3. Taking into account the symmetry of the driver and passenger configurations with mirrored belt attachments and opposite rotation directions, investigated directions from 0° to -90° cover all seating positions except the more rearward facing ones in Fig. 1. 30° and 45° were included to investigate the influence of the opposite mounting direction of the belt attachments on the results. Algebraic sign of the angles is based on the seat rotation direction around z axis – counterclockwise positive and clockwise negative. Therefore, negative angles describe a rotation of the driver towards the passenger.

Instead of rotating the complete model into these directions, the seating direction including the vehicle floor was kept constant (positive x direction) and the loading direction was varied by rotating the virtual vehicle around the occupant, resulting in configurations shown in the lower left part of Fig. 3. Frontal cases modeled with the HIII dummy included 45°, 30°, 0°, -30° and -45°, and lateral cases with the ES-2re -45°, -60° and -90°.

All these configurations have been tested without rotation of the vehicle during the crash. Additionally, the influence of rotation of the vehicle during the crash was investigated for all seat configurations. This included vehicle rotation around z axis (yawing) in positive direction (counterclockwise) and in negative direction (clockwise) as shown on the right side of Fig. 3. These rotations could represent vehicle movement in crashes with full overlap, 40% overlap on the left vehicle side and 40% overlap on the right vehicle side, respectively.

Basis of the worst case analysis was the performance of the restraint systems rated according to Euro NCAP protocols [9, 10] and the occupant kinematics. Since the models do not contain any vehicle environment, which could come into injury-inducing contact with the occupant, the lower the applied load the higher would be the rating. This is contrary to the target of occupant restraint. Hence, an additional criterion needed to be implemented, which is able to rate the performance of the improved systems to keep the occupant in place with optimal loading. Excursion of the head of the occupant was chosen as additional criterion to rate the restraint performance.

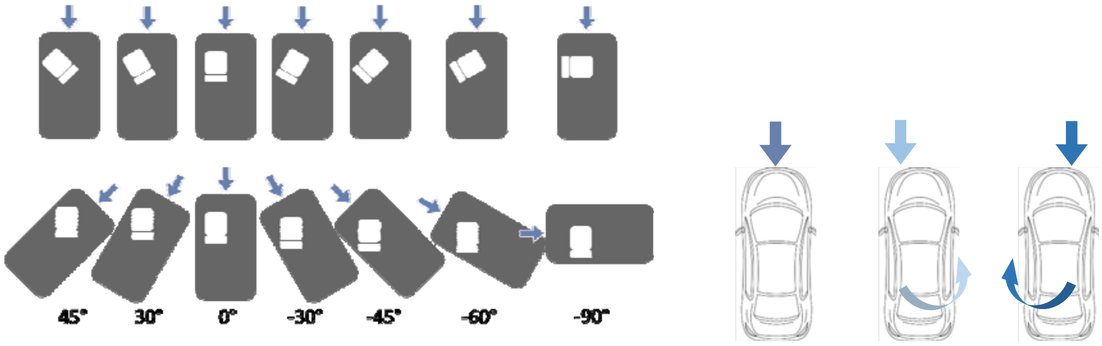

Fig.3: Left: Upper part – Seat configurations included in the study. Lower part – Applied crash loading direction in the models and naming convention used in the study.
Right: Applied vehicle rotation – no rotation, positive and negative rotation, respectively.

4 Results

4.1 Frontal Cases – Baseline

The kinematics of the baseline case with a seat rotation of -30° and a positive vehicle rotation around z during the crash is shown in Fig. 4 as example for the modelled crash conditions in frontal direction (-45°..+45° seat rotation) using HIII. Since the restraint system consists mainly of the seatbelt, very concentrated loading on the chest and neck of the occupant is found.

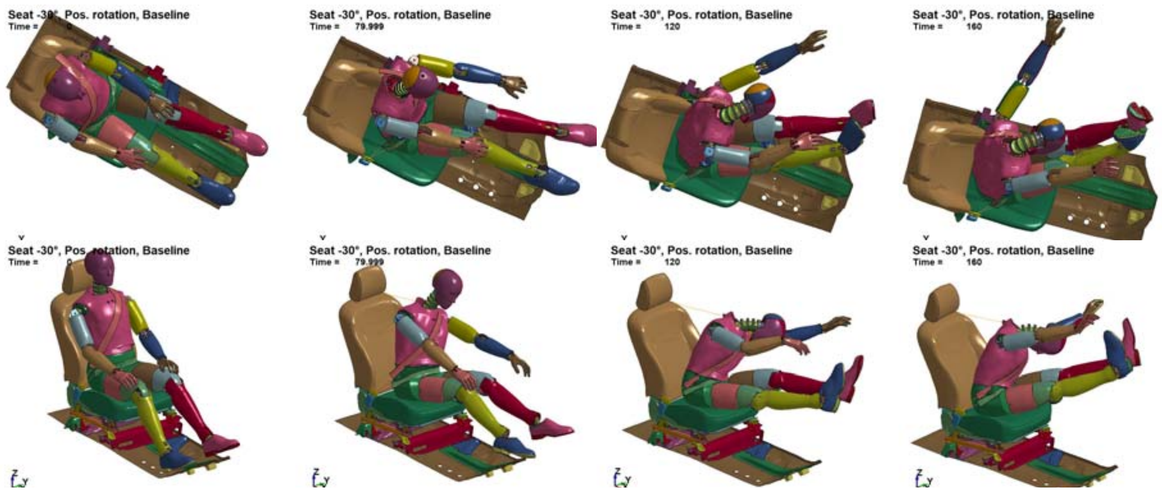

Fig.4: Kinematics of the occupant in the baseline case with seat rotation -30° and positive vehicle rotation for times 0 ms, 80 ms, 120 ms, and 160 ms. Impact direction in the top view pictures is from the right side.

An overview of the injury risk rated based on Euro NCAP [9] is given in Fig. 5. Independently from the rotation of the vehicle (no/ positive / negative) worst cases were found to be -30° and -45° seat rotations, which refers to rotations into direction of passenger side. The analysis of the simulation cases showed low head loading due to no contact, reflected by a_{3ms} of 35 g to 45 g and HIC values in the range of 100 to 200. Major injury risks have been found for the neck and chest area. Neck moments M_y in the worst cases reach values in the range of 50 Nm to 70 Nm, being closed to or even above the lower performance limit (LPL) of 57 Nm. These worst cases also showed high chest deflections in the range of 35 mm to 45 mm partially exceeding the LPL, which is 42 mm. [11]

Seat rotation +30° combined with vehicle rotation in negative direction (e.g. overlap on the right vehicle side) showed the seatbelt slipping off the shoulder of the dummy. The same effect was found for +45° seat rotations independently from vehicle rotation. This leads to reduced restraint of the occupant in these cases and needs to be avoided by more robust restraint systems. [11]

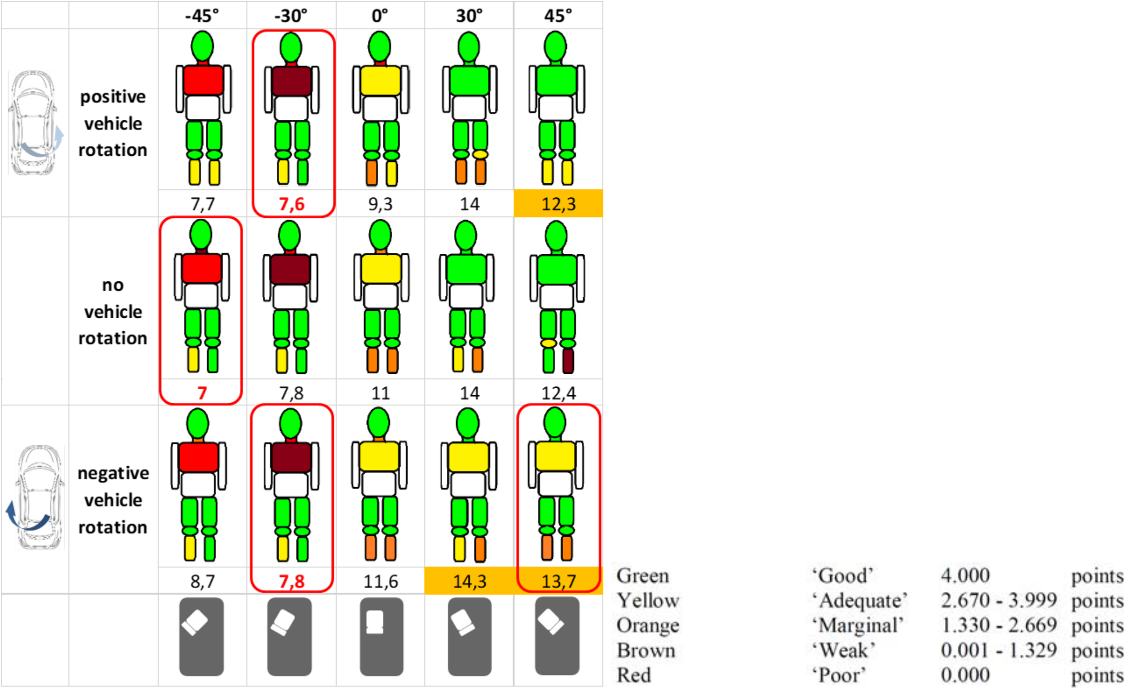

Fig.5: Ratings based on Euro NCAP [8] for all baseline cases; Red marked cases show highest loading; Orange marked cases show belt slip; Red frames show cases included in further analysis.

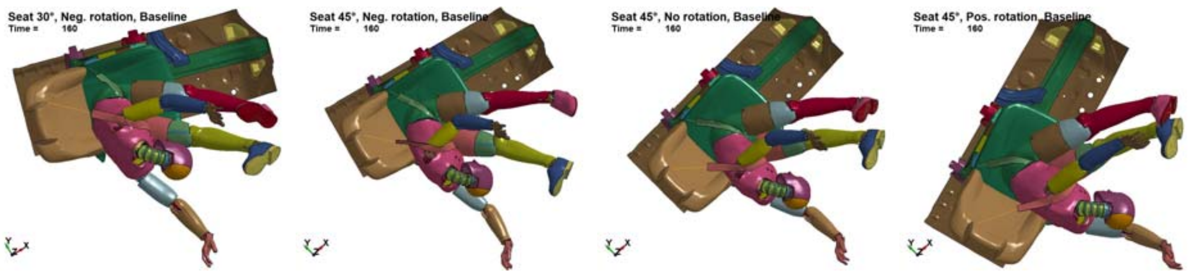

Fig.6: Top view of occupant and belt position at 160 ms for all cases with seatbelt slipping off the shoulder. Angle of seat rotation and applied vehicle rotation are given on top of the pictures. Impact direction is from the right side.

Based on the presented analysis of the worst cases and the kinematics of the occupant and the belt the following four cases were chosen for the application of improved restraint systems and further investigation. These cases are marked with red frames in Fig. 5:

1. -30°, positive vehicle rotation,
2. -45°, no vehicle rotation,
3. -30°, negative vehicle rotation, and
4. 45°, positive vehicle rotation.

The results of the baseline study showed potential for improvement of the restraint system. The improved restraint systems should provide a better distribution of the load on the chest reducing the injury risk in this region, address the high neck moments, and be more robust against slipping off the shoulder of the occupant.

4.2 Frontal Cases – Alternative Restraint Systems

To address these findings two alternative restraint systems have been investigated: (a) an inflatable belt system in the thorax area to get a better distribution of the load and (b) an additional belt part resulting in a criss-cross-shape as introduced in [12, 13] to avoid belt moving off the shoulder. Both systems in the model are equipped with pretensioners and load limiters of 4 kN. Analysis of the results has shown that the pretensioner could have been removed in the Airbelt case, since the take-in was very low.

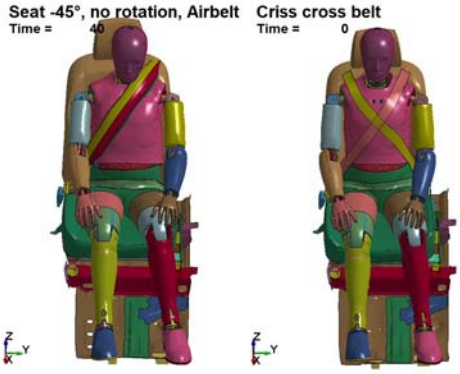

Fig.7: Models including the investigated improved seatbelt systems Airbelt and Criss-Cross-Belt.

Fig. 8 shows the kinematics of an occupant restraint with the improved systems for the case with seat rotation of -30° and positive vehicle rotation. Comparison to the kinematics in the baseline case in Fig. 4 shows strongly reduced forward movement of the occupant with both improved systems. Forward displacement of the right shoulder and the head is slightly lower for the Criss-Cross-Belt compared to the Airbelt (see also Fig. 9).

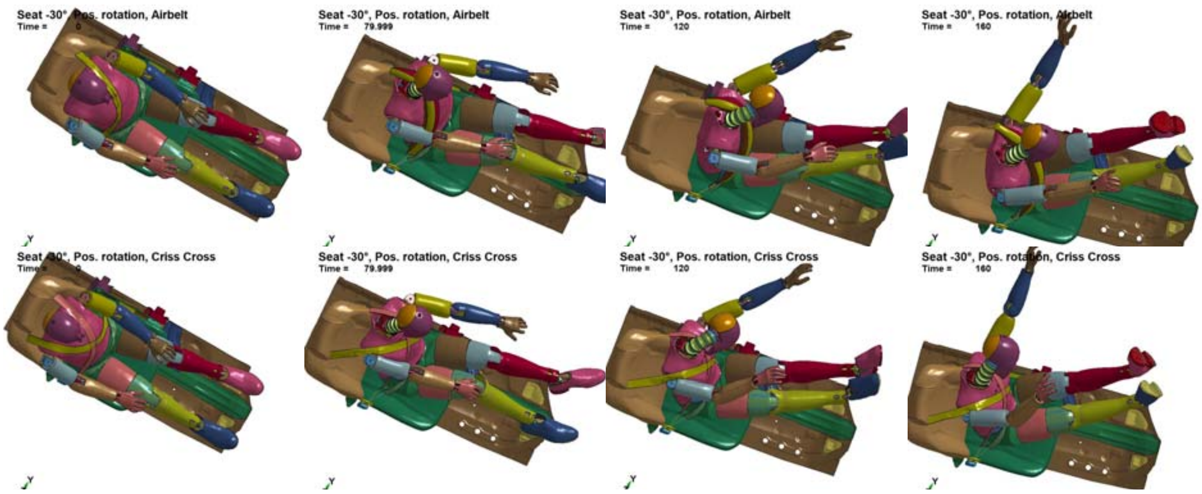

Fig.8: Top view of the kinematics of the occupant with the improved restrained systems for the case with seat rotation -30° and positive vehicle rotation for times 0 ms, 80 ms, 120 ms, and 160 ms. Impact direction is from the right side. Upper: Airbelt. Lower: Criss-Cross-Belt.

	-30° pos. rot	-45° no rot.	-30° neg. rot.	45° neg. rot		-30° pos. rot	-45° no rot.	-30° neg. rot.	45° neg. rot
Baseline					**Airbelt**				
	7,6	7	7,8	13,7		12,9	12,1	14	9,5
	561 mm	529 mm	727 mm	814 mm		432 mm	451 mm	618 mm	551 mm
Green 'Good' 4.000 points Yellow 'Adequate' 2.670 - 3.999 points Orange 'Marginal' 1.330 - 2.669 points Brown 'Weak' 0.001 - 1.329 points Red 'Poor' 0.000 points					**CC Belt**				
						7,1	6,6	7,3	7,6
						400 mm	480 mm	544 mm	466 mm

Fig.9: Ratings based on Euro NCAP [9] and head displacements for the baseline and the improved systems in the investigated cases. Orange marked case shows belt slip.

The detailed analysis of the injury risk shows an improved load distribution for the inflatable belt system in the chest area, resulting in better rating for the chest deflection in three of the cases (see Fig. 9). Only the fourth case, where the belt slipped off in the baseline, shows higher loading with the Airbelt, which is based on the improved restraint. Due to the larger diameter of the inflated belt, the loading is maintained even if the belt moves to the very left side of the shoulder (see Fig. 10 left). Since the investigated Airbelt is asymmetrical (as the baseline belt), this slipping can not be completely avoided.

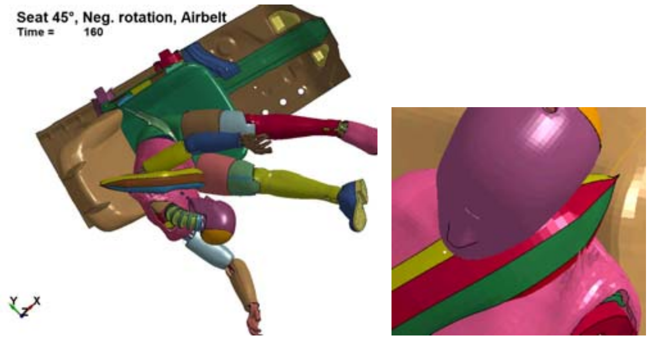

Fig.10: Left: Top view of occupant and belt position at 160 ms showing the improved restraint of the occupant with Airbelt for seat at 45° and negative vehicle rotation. Impact direction is from the right side. Mid left: Detailed view showing head support of the Airbelt [11].

Fig. 9 also shows reduction of the neck moment for three cases. The Airbelt supports the head similar to an airbag in these cases, where the movement of the head is directed towards the Airbelt (see Fig. 10 right). The fourth case (Seat 45°, neg. rotation) shows an increased neck moment. A more detailed analysis of the kinematics of the baseline case shows a very straight side nicking of the head (see Fig. 11 left), which is not represented in the rated neck moment around y axis. If the occupant is restraint by the Airbelt the direction of the head motion is changed resulting in more rotation around y axis (see Fig. 11 right), which is causing higher moment around y axis and thus lower rating.

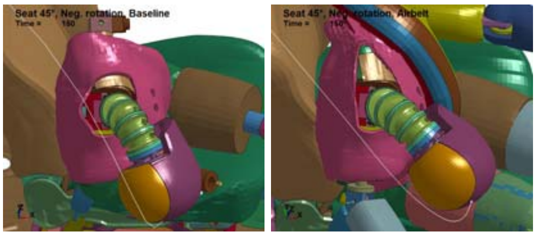

Fig.11: Comparison of the head movement for the baseline case (left) and the Airbelt (right) marked by trajectories (Seat 45°, Negative vehicle rotation).

The analysis of the simulations using the Criss-Cross-Belt shows that the complete slipping of the belt system from the shoulder of the occupant is avoided due to the symmetric setup of this system. One side slipping can occur (see Fig. 8 lower line), but occupant restraint is retained. Unfortunately, Euro NCAP rating could not be improved with the investigated system – chest and neck loading is still too high. However, the strongly reduced forward displacement will allow for reduction of the load limiter level, which should lead to better ratings in the chest area. Reduction of the neck moments is an open item for the Criss-Cross-Belt system.

4.3 Lateral Cases – Baseline

The kinematics of the baseline case with seat rotation -45° and positive vehicle rotation is shown in Fig. 12 as an example for lateral direction (-45°..-90° seat rotation) using ES-2re. The severity of the crash as well as the untypical kinematics and loading of the occupant compared to standard side crashes can be seen. The loading is completely different from a standard lateral impact, where the load is distributed over the whole dummy side from pelvis to head by means of side airbags and curtains. This results in a controlled movement of the complete dummy and a distributed loading. In the modelled case the restraint system consists mainly of the seatbelt, and very concentrated loading on the neck and pelvis and strong side nicking of the head of the occupant is found. [14]

The analysis of this baseline case shows head, chest and abdominal values below higher performance limits (HPL) of Euro NCAP [9]. Severe spine loading reflected by T12 M_x higher than LPL and T12 F_y closed to LPL is found, which finally results in modifiers for the chest (Fig. 13 left). [14]

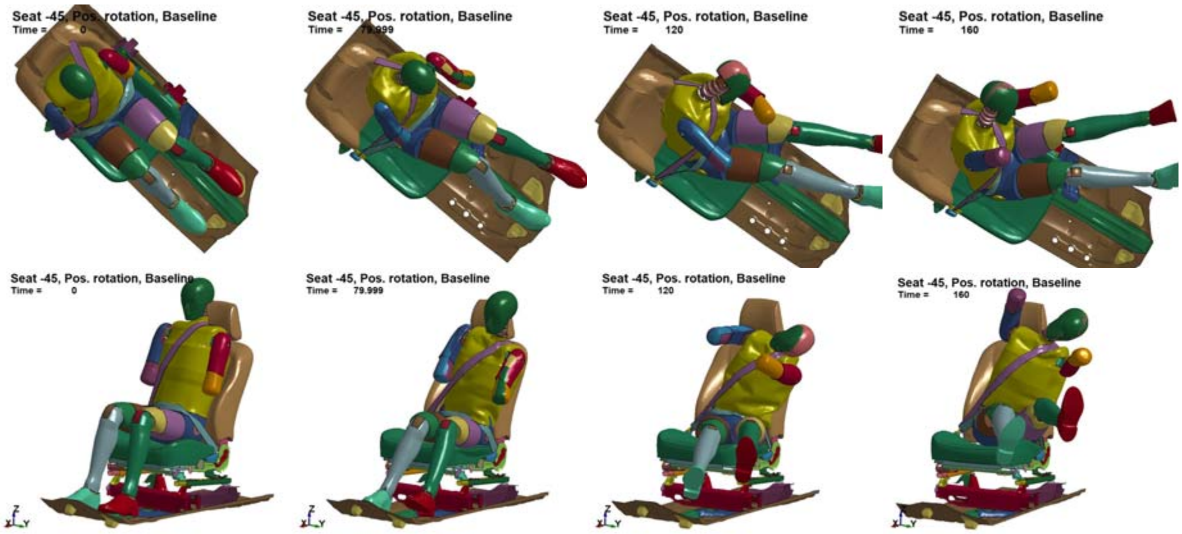

Fig.12: Kinematics of the occupant in the baseline case with seat rotation -45° and positive vehicle rotation for times 0 ms, 80 ms, 120 ms, and 160 ms. Impact direction in the top view pictures is from the right side.

		-45° pos. rot.
Head	HIC36	220
	3ms Acceleration g	37,8
Chest	Compression mm	21,7
	Viscous Criterion m/s	0,27
Abdomen	Total Abdominal Force kN	0,21
Pelvis	Pelvis Symphysis Force kN	2,13
Backplate Loading	Load y-direction kN	0,21
T12 Modifier	Load y-direction kN	1,93
	Moment x Nm	260
Head	Displacement mm	479

Green	'Good'	4.000	points
Yellow	'Adequate'	2.670 - 3.999	points
Orange	'Marginal'	1.330 - 2.669	points
Brown	'Weak'	0.001 - 1.329	points
Red	'Poor'	0.000	points

	Region	-45°	-60°	-90°
positive vehicle rotation	Head	4,00	4,00	4,00
	Chest	2,00	2,00	4,00
	Abdomen	4,00	4,00	4,00
	Pelvis	4,00	4,00	4,00
no vehicle rotation	Head	4,00	4,00	4,00
	Chest	2,00	2,00	4,00
	Abdomen	4,00	4,00	4,00
	Pelvis	4,00	4,00	3,42
negative vehicle rotation	Head	4,00	4,00	4,00
	Chest	2,00	2,00	3,80
	Abdomen	4,00	4,00	4,00
	Pelvis	4,00	4,00	4,00

Fig.13: Left: Detailed injury values for baseline case with -45° seat rotation and positive vehicle rotation. Right: Ratings for all baseline cases based on Euro NCAP [10].

Similar results were found for all cases with -45° and -60° rotation of the seat independently from the vehicle rotation (no/ positive / negative). Pelvis symphysis force exceeded HPL slightly for the case with seat rotation -90° and no rotation of the vehicle. Backplate F_y exceeded HPL slightly for the case with seat rotation of -90° and negative vehicle rotation. All ratings based on Euro NCAP are given in Fig. 13 on the right.

Based on the presented analysis and the target to include different seat angles and different rotations, the following three cases were chosen for the application of improved restraint systems and further investigation. These cases are also marked with red frames in Fig. 13 right:

1. -45°, positive vehicle rotation,
2. -60°, no vehicle rotation, and
3. -90°, negative vehicle rotation.

The results of the baseline study showed high necessity for improvement of the restraint system. The improved restraint systems should provide a better distribution of the load along the side of the occupant, address the high spine moments and reduce the head motion.

4.4 Lateral Cases – Alternative Restraint Systems

Several changes to the seat belt and seat have been investigated, including (a) inflatable belt systems, (b) improved geometry of the seat and (c) improved geometry of the head restraint. Best results were found with the Airbelt in the shoulder area and with the seat with enlarged sides and improved head restraint. Therefore, these results will be presented in detail. [14]

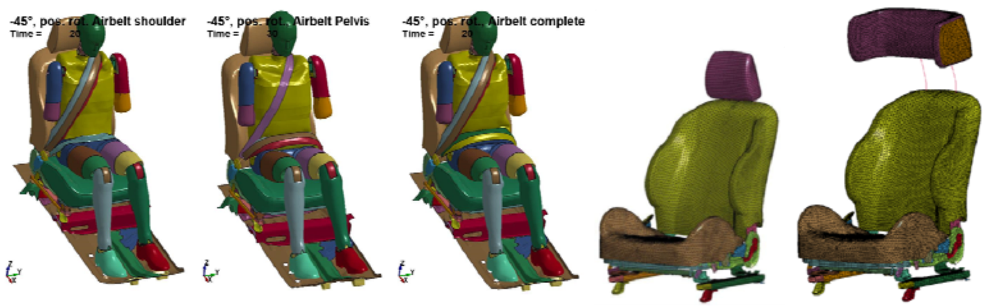

Fig.14: From Left to Right: Airbelt in the shoulder, in the pelvis and in both area(s), Seat with enlarged sides, Seat with enlarged sides and improved head restraint [14].

As in the frontal cases the usage of the Airbelt system in the shoulder area leads to a better distribution of the load, better occupant kinematics and improved restraint of the head in the lateral cases (see Fig. 15 upper part). T12 modifiers could be prevented and the head displacement could be strongly reduced – reducing the risk of contact to interior parts or other occupants. An Airbelt enlarged into the pelvis area also could have potential to further distribute the loading. Unfortunately, the diameter of the investigated system was too high and led to loading in the abdominal area. This system needs further analysis in a future study.

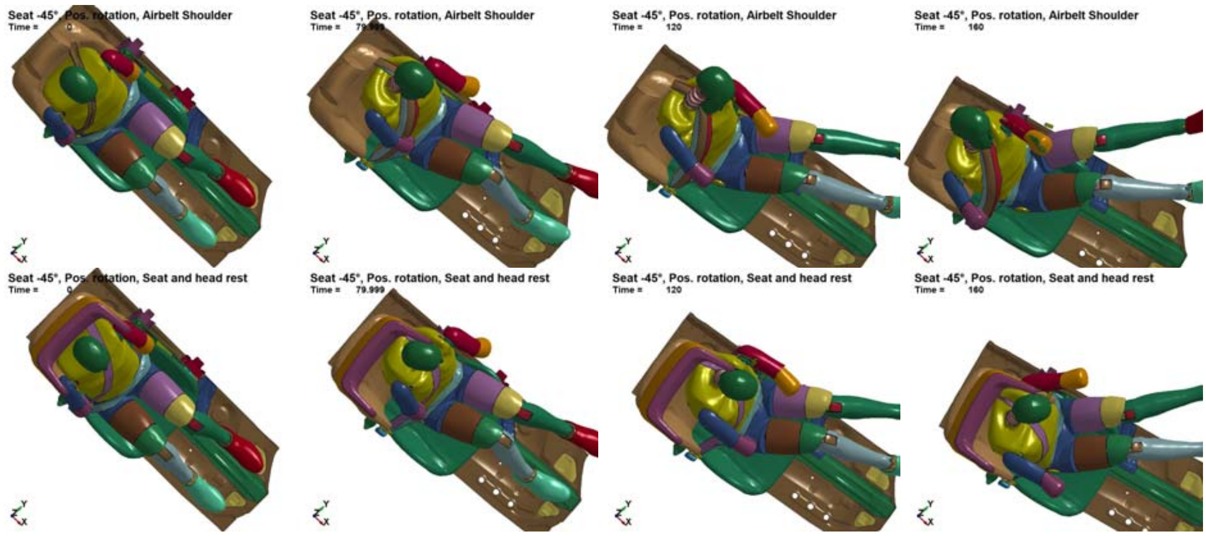

Fig.15: Top view of the kinematics of the occupant with the improved restrained systems for the case with seat rotation -45° and positive vehicle rotation for times 0 ms, 80 ms, 120 ms, and 160 ms. Impact direction is from the right side. Upper: Airbelt. Lower: Improved seat.

The seat geometry was modified to increase the contact area to the occupant. As can be seen in Fig. 14 the sides of the seat pad and the side wings were expanded and the geometry of the head rest was completely changed. The improved head rest consists of a 5 mm metal sheet in the back and soft foam padding towards the occupant. In this model the load limiter level was increased to 6 kN to reduce movement of the occupant out of the head restraint.

Detailed analysis will be presented for the case of -45° seat rotation and positive vehicle rotation, since this would be the most difficult case for restraint improvement with this system. Nevertheless, the system showed improved restraint of the occupant and strongly reduced head displacement (Fig. 15 lower part) compared to the baseline case. Spine loading could be improved, which is reflected in T12 modifier reduction (-60°) or avoidance (-45°, -90°). The contact area of the occupant to the seat could be increased. This results in moderate loading of the lower rib by the modified seat. Fig. 17 provides an insight into the loaded area in the baseline (left) and the modified seat for seat rotation of -45° and positive vehicle rotation. The contact area between the occupant and the seat could be increased in the femur, chest and head region. The yellow rating for the chest in this case is caused by a rib compression of 26,2 mm.

	Region	-45°, pos. rot.	-60°, no rot.	-90°, neg. rot.		Region	-45°, pos. rot.	-60°, no rot.	-90°, neg. rot.
Baseline	Head	4,00	4,00	4,00	**Airbelt Shoulder**	Head	4,00	4,00	4,00
	Chest	2,00	2,00	3,80		Chest	4,00	4,00	4,00
	Abdomen	4,00	4,00	4,00		Abdomen	4,00	4,00	4,00
	Pelvis	4,00	4,00	4,00		Pelvis	4,00	4,00	3,96
Head displacement		479 mm	468 mm	476 mm	Head displacement		363 mm	356 mm	372 mm

	Region	-45°, pos. rot.	-60°, no rot.	-90°, neg. rot.
Improved Seat	Head	4,00	4,00	4,00
	Chest	3,16	2,33	4,00
	Abdomen	4,00	4,00	4,00
	Pelvis	4,00	4,00	4,00
Head displacement		239 mm	312 mm	211 mm

Green	'Good'	4.000	points
Yellow	'Adequate'	2.670 - 3.999	points
Orange	'Marginal'	1.330 - 2.669	points
Brown	'Weak'	0.001 - 1.329	points
Red	'Poor'	0.000	points

Fig.16: Ratings based on Euro NCAP [9] and head displacements for the baseline and the improved systems in the investigated cases [14].

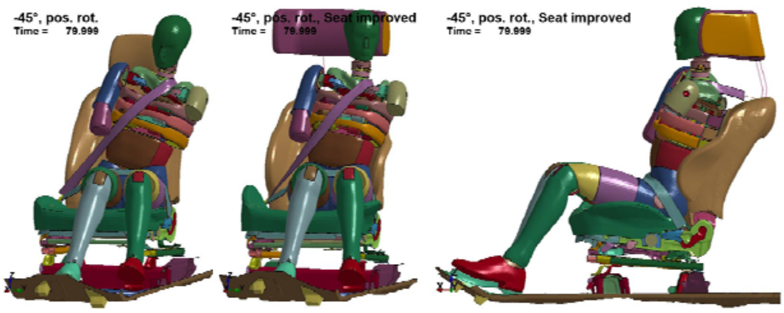

Fig.17: Contact area of dummy to seat at 80 ms for -45°, pos. rotation baseline vs. improved seat (Dummy jacket and lower arm removed for visualization).

Analyzing Fig. 17 it also can be anticipated that the contact area between seat and occupant could be further increased, leading to a better distribution of the load between lower, mid and upper rib of the occupant. This will be included in a future study.

5 Summary

This preliminary study investigated restraint systems under the boundary of varying seat positions in a frontal crash with and without vehicle rotation. Since load response surfaces for airbags in crash direction might not be available in AD vehicles, no airbags are included in the modelled system. High loading of chest and neck as well as sliding of the seat belt was observed in frontal cases. Loading of occupants using only seatbelts and driving sideways was found to be completely different from loading in a standard side crash with airbags. Major concern for the lateral cases was spine loading, kinematics of the head, and missing load distribution. Cases for further analysis were defined based on injury rating and kinematics and improvements in the restraint systems were analyzed.

Inflatable belt systems in the shoulder part improved load distribution at the occupant for frontal as well as lateral crash conditions, but could only partially address sliding of the belt in frontal angled cases. Support of the head could be provided by the Airbelt in some cases. Criss-Cross-Belt systems avoid the complete sliding of the belt from the shoulder, but could not reduce the loading of the chest with the applied load limiter level. Seat and head rest were modified to protect occupants driving sideways. These modifications showed improvements in restraint.

Further improvement of the systems could be investigated in a future study, combining the advantages of the considered systems, including further improvements and using the same system in all crash conditions. The main target could be further progress in load distribution, head support in frontal cases and chest support in lateral cases.

The study provided a preliminary insight into challenges of occupant protection in future vehicles driving highly automated or fully autonomous (SAE levels 4 and 5) with alternative seating positions. It could be shown that the seat needs to be included in the analysis of restraint systems for future vehicles. It will be part of the restraint system.

The analysis of the results of this study also raises questions, which have to be addressed in future research:

- Which crash and seat configurations need to be tested to assure occupant restraint in AD vehicles in mixed traffic?
- Today's dummies might not be the tools of choice for these configurations. In computer simulation studies human body models could be used to investigate the injury risk. But which tools should be used in real testing (as long as it is not completely replaced by virtual testing)?
- As shown in the study, especially the neck was exposed to high loading not only in the rated direction. Which additional injury measures do we need to include in the rating of occupant restraint for these new conditions?
- How does the kinematics of the used dummies compare to the kinematics of humans in these unusual crash conditions?

6 Thanks

I would like to thank Celine Schwarz, Markus Kipping, Florian Ruf and Nikolai Fischer for their focused and very dedicated work on this project.

7 Literature

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