

EVALUATION OF THE PROTECTIVE PERFORMANCE OF A NOVEL RESTRAINT SYSTEM FOR HIGHLY AUTOMATED VEHICLES (HAV)

Tetsuya Matsushita

Hiro Saito

Autoliv Japan Ltd.

Japan

Cecilia Sunnevang

Martin Östling

Autoliv Research

Sweden

Abhiroop Vishwanatha

Avinash Tabhane

Autoliv India Pvt. Ltd.

India

Paper number 19-0321

ABSTRACT

As automated driving further penetrates the market, opportunities continue to arise for new vehicle interior designs, and new seating positions might be allowed. Flexible seating with a wider range of positions will require new restraint systems, independent of the steering wheel or instrument panel. The aim of this study was to evaluate a novel seat-integrated restraint system created for future potential seating position, compared to the current conventional restraint system in forward-facing seat condition.

The seat-integrated restraint system was evaluated using a virtual simulation model correlated to physical sled tests. The CAE model included a generic seat, the seat integrated belt system with a 2kN load limiter, and the new Dual Shoulder Airbag system (DSA). The DSA was mounted to the seat back on both sides of the seat. The DSA was also connected below the seat pan to raise the occupant's pelvis-thigh area during a crash, to avoid submarining in the reclined position. For reference, a standard system (3-point 4 kN load limiter belt and driver airbag) was used. Occupant injury assessment reference values (IARV) were evaluated using the AM50_THOR, AF05_Hybrid III, and AM95_Hybrid III models and compared to IARVs from the current and new proposed New Car Assessment program in the U.S (US NCAP). The IARVs compared were HIC15, BrIC, Nij and Chest deflection. The load cases evaluated were full rigid-barrier frontal crash (FRB) and NHTSA Oblique Impact (NOI), with crash pulses representing a mid-size sedan. The occupant protection was evaluated for the standard seating position (23 degrees from vertical) as well as for a reclined position (45 degrees from vertical).

The new restraint system resulted in lower IARVs than the reference system in every case except HIC15 and Nij in the NOI condition.

A comparison of the standard and reclined positions revealed that every IARV was increased in the latter.

No submarining occurred for any of the restraint systems.

The new proposed airbag system has the potential to offer equivalent or lower IARVs compared to the reference system in frontal crash mode (forward-facing seat condition).

INTRODUCTION

Over the last decade, highly automated vehicles (HAV) have been a focus of future mobility innovations for many players—like automobile manufacturers, automotive suppliers, IT professionals, mobility-service providers, and governments. They are also working to develop related technology enabling more flexible seat layout, as there will no longer be a need for someone to drive the vehicle. This trend has been summarized by Filatov et al. (2019) [1]. Mercedes introduced the “F015 Luxury in Motion” research vehicle [2], equipped with four rotating seats which allow occupants to select their orientation according to their preference. Volvo introduced “Concept 26” [3], which allows the driver's seat to be repositioned away from the steering wheel and instrument panel when the car is in automated driving mode. Volkswagen's “ID BUZZ electric minivan” [4] also employs the rotated-seats concept. Several component manufacturers have introduced similar concepts. Some representative seat-layout images of these trends (seats that are deeply reclined, far from the steering wheel, and

rotated) are shown in Figure 1. In fact, many people have realized that one of the benefits of HAV technology is that the vehicle interior can transform from a cabin just for driving and riding into a living space, where many daily activities like reading, working, and relaxing can be performed. Jorlöv et al. (2017) [5] and Östling et al. (2019) [6] investigated which seat layout consumers prefer in automated driving mode in static conditions using normal chairs. They found that consumers' preference depended on the situation, but they generally preferred seats that could rotate and recline. Thus the developers of HAV technology and consumers both seem to want the same thing: that the technology of flexible seating be developed further. The ensuing challenge is to make flexible seating as safe as the seating in current vehicles.

Current occupant restraint systems comprising seatbelts and airbags are designed to protect passengers in traditional seating positions from either frontal or side impacts. The occupants are moved by the inertia force produced by crash deceleration, and the airbags are located in line with the forces, in order to prevent occupant contact with the vehicle interior (i.e., they are located at the steering wheel, the instrument panel, the side window, and between the seat and the door's inner panel). Seatbelts are normally anchored through the upper part of the B-pillar, although some vehicles place the thru-anchor on the top of the seatback.

Given the future possible sitting positions (Figure 1) and the current airbag layout (Figure 2), it should be pointed out that the current conventional system might need adjustments. The occupants in the rotated seats have no airbags directly in front, and a seatbelt anchored onto the B-pillar cannot be routed to restrain them in their initial position. Further, the reclined posture is related to increased likelihood of submarining, as described in Östling et al. (2017) [7].

A novel concept has been created in response to these challenges that has the potential to protect the occupant in any type of crash event, independent of seat position. This concept was evaluated in this study, using the current and upcoming New Car Assessment program in the U.S (US NCAP) as a reference for both loading conditions and injury assessment reference values (IARVs). The target was to achieve IARVs equivalent or below to that of the current conventional restraint system in a frontal 56 km/h crash [8]. To make the comparisons with the current conventional system as valid as possible, the new-concept model maintained the knee bolster and instrument panel, and only the forward-facing seat condition was applied. Every evaluation was performed by numerical simulation.

In this study the main objective is to compare the proposed new system to the current standard system. As a result, although the most representative future seat position would be rotated, as in Figure 1, only the traditional forward-facing seating position has been evaluated. In addition to rotated seats, reclined posture is anticipated in future vehicles, so both the reclined posture and the standard one have been evaluated. The effect of occupant size has also been evaluated. Three crash test dummies were selected: AF05_HybridIII (small female), AM50_THOR (average male), and AM95_HybridIII (large male).

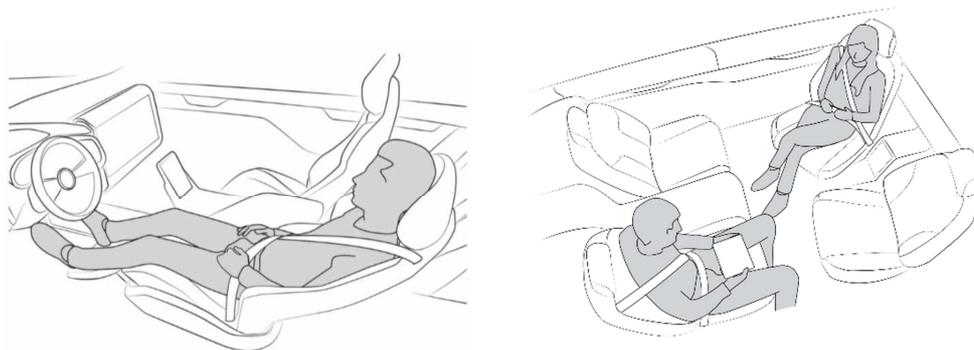


Figure 1. Examples of future flexible seat layouts

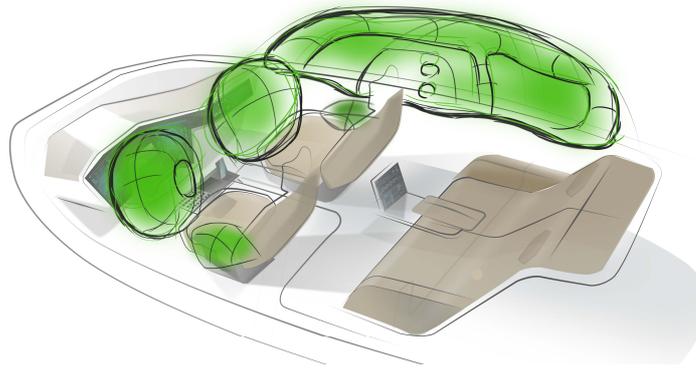


Figure 2. Diagram of current airbag layout

METHOD

The novel system, with seat-integrated restraints, was evaluated to determine whether it could achieve target IARVs for occupants seated in the potential seat positions in the two most frequent load cases of frontal crashes. The conditions are explained in more detail in the “Evaluation condition” section.

To evaluate restraint performance, the IARVs for HIC15, BrIC, Nij, and Chest deflection, developed for the head, brain, neck, and chest regions, respectively, were used.

HIC15 has been authorized and applied to many regulations and assessment programs for a long time. Nij has also been authorized for a long time. AF05_HybridIII applied Nij as is, and AM50_THOR applied the same formula with updated reference values of F_{zc} : +4200N (tension), -6400N (compression); M_{yc} , +88.1Nm (flexion), -117Nm (extension). These values were proposed in the NHTSA US NCAP upgrade protocol’s second request for comments (RFC) in 2017 [9]. (The first RFC in 2015 proposed different values, based on Nightingale et al. (2009) [10], which were then updated to the second version.) BrIC is a new criterion, continuously being developed; in this study the one proposed by Takhounts et al. (2013) [11] was used. For Chest deflection, AM50_THOR has four measuring points that quantify displacement in the x, y and z directions. The maximum of the four resultant peak deflections (R_{max}) was applied to quantify Chest deflection. The HybridIII dummies have a single point located at the center of the sternum quantifying displacement only in the x direction. For this reason, Chest deflection cannot be directly compared between the crash dummies.

Since the IARVs for BrIC, Nij, and R_{max} (for THOR only) are still under discussion, they, too, were used for comparison purposes—not for the actual injury assessment.

Every evaluation was obtained by numerical simulation using LS-DYNA software V971 R7.1.2 (Livermore Software Technology Corporation, Mich., U.S.A.). The conditions are explained below.

Numerical models

The applied vehicle environment geometry was a generic vehicle interior, representing a mid-size sedan (MY 2010). For occupants, THOR v1.3 US NCAP model as average size for male, Hybrid III AF05 v7.0.6 as a small female size, both are produced by Humanetics Innovative Solutions, Inc. and AM95 v3.03 which is produced by LSTC as a large-size male, have been used. The models were positioned according to the seating protocol designated in US NCAP. The vehicle model’s seat had a deformable seat pan and rigid seatback; the dimensions were obtained from the same vehicle used for the interior geometry setting. In addition, the knee bolster, steering wheel (SW) column, and toe board were all assigned simple force deflection properties which reflected physical testing data. Each property is shown in Figure 3.

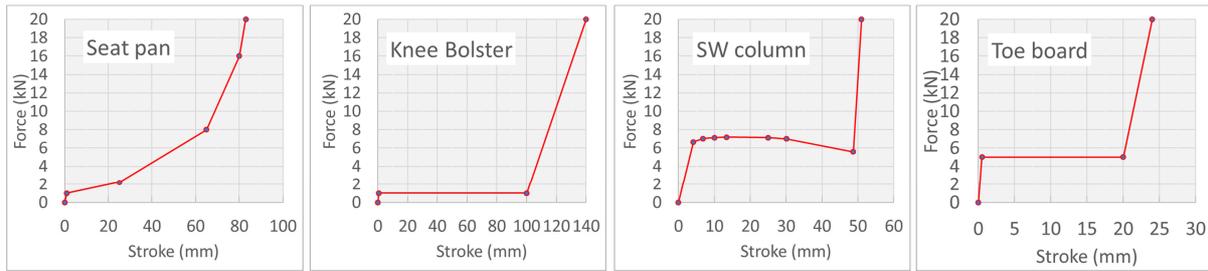


Figure 3. Vehicle interior force deflection properties

The numerical model was validated using measured forces from the belt system as well as head acceleration from the dummy. Accordingly, B3 force (seatbelt force at shoulder), B6 force (seatbelt force at lap anchor), head acceleration on interaction with the driver airbag, and left and right femur forces on interaction with the knee bolster are compared with physical test results (Figure 4).



Figure 4. Comparison between CAE results and physical test results

The Reference restraint system

The conventional restraint system (hereinafter called “Reference system”) was set up with the vehicle conditions which achieved a 5-star rating in current US NCAP protocol. The system was developed to meet the current US NCAP requirements with HybridIII. It comprises a conventional 3-point seatbelt installed in the B-pillar, with a pre-tensioner activated 10 ms after the crash start (TTF 10 ms), a load limiter of 4 kN (at shoulder), a 60-liter driver airbag with a peak pressure of 55 kPa (left in Figure 5) and a 30mm-diameter vent hole. The airbag, activated at the same time as the pre-tensioner, is supported by a steering wheel with a collapsible steering column, which allows the steering wheel to collapse approximately 50 mm. Further, the driver airbag has an adaptive function: an additional vent hole can be activated when a softer airbag is desired. This function is typically used for the small female crash dummy.

Concept description for novel restraint system

Seat-centric One of the features of HAV interiors is the more relaxed sitting position, with a deeply reclined seat back, more legroom, and rotating seat arrangement. The relative positioning of an occupant and the interior parts—except the actual seat—can be changed according to occupant preference. Because the occupants are always seated, the relative position of the seat is always constant, unlike other interior parts such as the steering wheel or instrument panel.

In principle, the in-crash protection system comprising seatbelts and airbags is affected by the relative position of the occupant, as its function is to absorb the kinetic energy from the occupant, who either strikes the airbag or

pulls out the seatbelt. To keep this relative position between the restraint system and the occupant, it is natural that the novel protection system be fitted into the seat, a so-called seat-centric restraint system.

System composition The proposed concept (hereinafter called “New system”) is shown to the right in Figure 5. The New system comprises a 3-point belt with the same function as the Reference system, but installed in the back of the seat (the so-called Belt-in-Seat: BiS). The BiS also has a pre-tensioner (TTF10 ms) and a load limiter, but the latter’s force is only 2kN (at shoulder). Further, the new system is equipped with a novel type of airbag, the Dual-Shoulder-Airbag (DSA), which deploys from the seatback and goes around both sides of the occupant’s shoulders; see Figure 5. Each DSA has a volume of 45 liters and a peak pressure of 50 kPa with no vent holes. The DSAs are triggered at the same time as the BiS pre-tensioner. Each DSA is supported by a virtual vertical reaction plane (VRP); their size and locations are indicated in Figure 6. These VRP represents some fabric membrane to be deployed with DSA in real vehicles and were introduced to simplify simulations. The distance between the two planes (670mm) is twice the distance from the dummy’s center to the door’s inner panel. The plane is rigid and the friction coefficient with the DSA is zero. The DSAs are connected to the seat pan through an Engage belt (EnB); see Figure 5. Through this connection, the seat pan is pulled up by the EnB when the DSAs are triggered, pulling the femurs up. The main factor to be evaluated is the effect of the DSA. The methods to retain them could vary, because although one side of the door inner panel can be the one, for the other side there is no part to retain it, so some new device or structure must be developed in future. Hence, generic VRPs are used at this time.

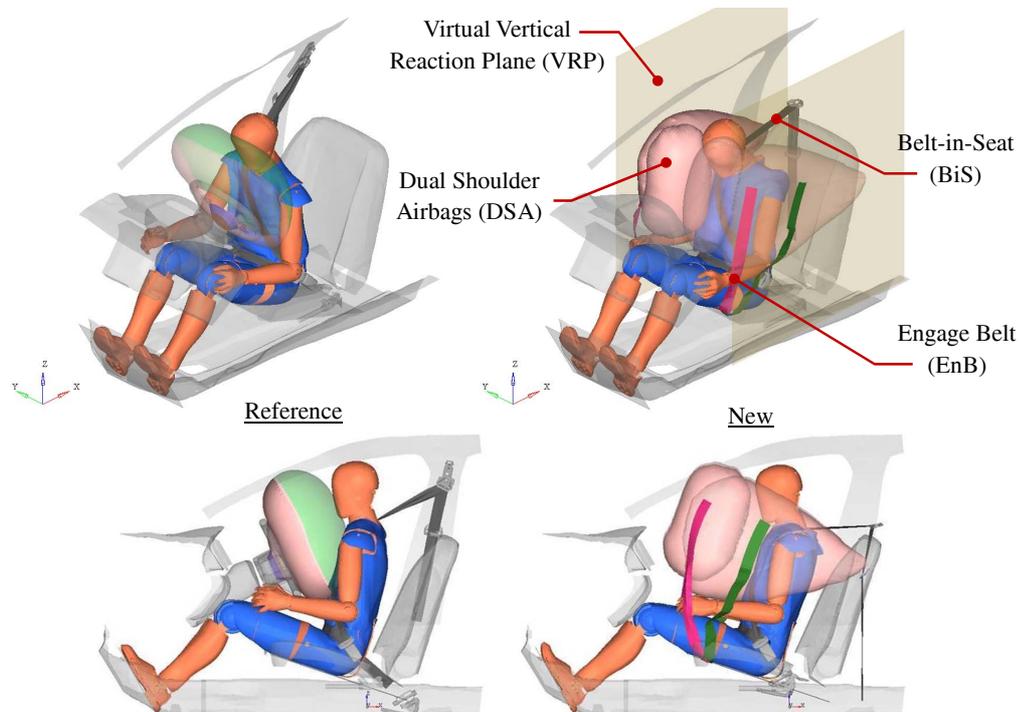


Figure 5. Restraint system comparison
Left: Reference system, Right: New system

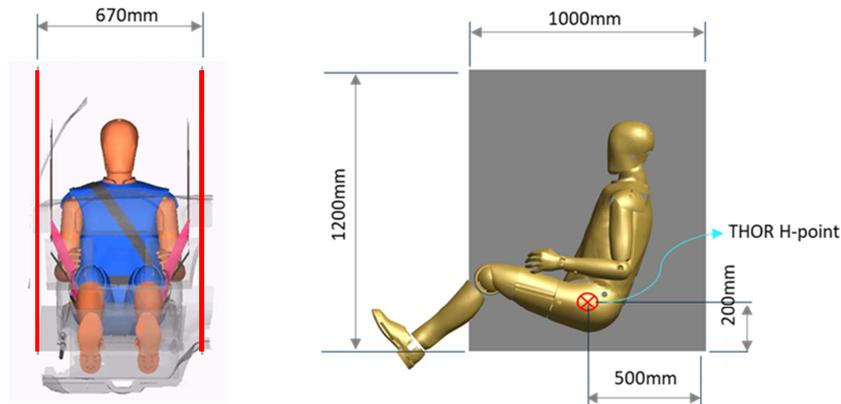


Figure 6. Virtual vertical reaction plane (VRP) setting

How it works In a direct or oblique frontal crash, the BiS enables the seatbelt to fit an occupant with the same relative positioning regardless of seat arrangement, and the DSA provides a more distributed loading in order to stop upper body excursion. Distributed loading has been shown to reduce injury risk [12][13]. Therefore it is proposed that the New system is more protective in more severe crashes, because there is less localized loading of the chest and more distributed loading across the chest, including of the shoulders. The DSA would play a main role in stopping the upper body in a crash, reducing the localized seatbelt force on the chest to less than that of the Reference system. To restrain the head and neck sufficiently, each DSA also has a sub-chamber located at the front. The sub-chamber restrains the head and neck less stiffly compared to the main chamber. This is an important design feature, since the mass of the head is lower than the mass of the chest.

The seat pan is pulled up by the DSA via the EnB, pulling the femurs up. This action, which complements the lap part of the seatbelt, would also be effective in a reclined position, avoiding or reducing the probability of submarining. Submarining, which occurs when the lap belt passes over the pelvis and penetrates the abdominal area, can cause serious injuries (further explained in Luet et al. (2012) [14]).

The DSA can adapt to differences in occupant size. It is retained by the VRP, which is always in the same location relative to the seat, independent of occupant size. The DSA inflates in the gap between the occupant and the VRP, so the gap changes depending on the occupant size: the bigger the occupant, the smaller the gap; the smaller the occupant, the bigger the gap. If the inflator output level is the same, then with a bigger occupant (and a smaller gap) the DSA's inner pressure would be higher when it makes contact, resulting in a stronger restraint force—and the opposite would hold for a smaller occupant. The DSA connects to the seat pan via the EnB; the pulling force at the seat pan is changed by the inertial force of the occupant's femur. The bigger occupant generates more EnB tension to pull the DSA closer, while the smaller occupant generates less tension. Hence, the DSA could achieve occupant adaptivity with a single inflator setting and airbag design. We have named it the "self-adaptive function". Figure 7 illustrates the concept.

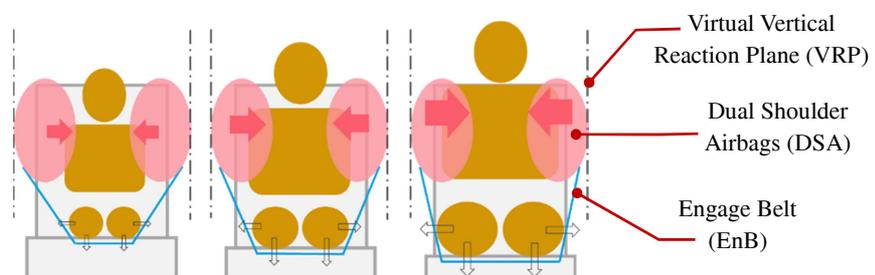


Figure 7. Image: Self-adaptive function reacting to occupant size

Evaluation condition

Test Matrix Table 1 shows the test matrix with ten simulations to evaluate the potential of the New system compared to the Reference system. The parameters are System type (Reference/New), Load case (FRB/NOI), Occupant posture (Standard/Reclined), and Occupant size (AF05/AM50/AM95). Note that for the four simulations with NOI and/or the reclined seat back, only the AM50_THOR was used, because the Hybrid dummies are too stiff to capture the dynamics accurately.

Table 1.
Simulated configurations of load case, occupant posture, and occupant size

ID#	System	Load case	Occupant Posture	Occupant Size
1	Reference	FRB	Standard	AM50_THOR
2				AF05_Hybrid-III
3				AM95_Hybrid-III
4			Reclined	AM50_THOR
5		NOI	Standard	AM50_THOR
6	New	FRB	Standard	AM50_THOR
7				AF05_Hybrid-III
8				AM95_Hybrid-III
9			Reclined	AM50_THOR
10		NOI	Standard	AM50_THOR

FRB: Full-Rigid-Barrier frontal crash, NOI: NHTSA-Oblique-Impact

Parameters The settings of the system model are described in Table 2. The detailed deformation properties of the vehicle interior are shown in the “Numerical model” section. Significant factors that differ between the systems are airbag type, seatbelt load limiter level, and the fact that no steering wheel was used when evaluating the New system.

Table 2.
Parameter descriptions: System

		Reference system	New system
Vehicle interior	Knee bolster	Common (deformable)	
	Toe board	Common (hardly deformable)	
	Seatback	Common (rigid, no rotation)	
	Seatpan	Common (deformable)	
	Steering wheel	Yes	N/A
	Steering column	with (deformable)	N/A
Restraint devices	Driver airbag	Yes	N/A
	Seatbelt	3points thru B-pillar	3points belt (BiS)
	Load limiter at shoulder	4 kN	2 kN
	Shoulder airbags	N/A	Yes

	Engage Belt (EnB)	N/A	Yes
--	-------------------	-----	-----

The Load case parameter is the kind of frontal crash (FRB or NOI); they are both expected to apply to the next, upgraded US NCAP test protocol [15]. In an FRB the vehicle impacts a full-width rigid barrier directly in front at 56km/h. In an NOI the vehicle is impacted by a moving deformable barrier (MDB) traveling at 90km/h, angled at 15 degrees with respect to the vehicle. The overlap ratio between the MDB and the struck vehicle's front end is 35%. The Oblique MDB (OMDB) used in this study weighs 2486kg. The impact pulses of each load case were simulated by the same mid-size sedan. The setup is illustrated in Figure 8. We applied a RH driver and a LH struck side (the farside NHTSA Oblique impact). The reason for this choice is that this type of impact does not involve the side-curtain airbag, which is becoming standard equipment. If a nearside impact were evaluated, the side-curtain airbag would be involved (if present) and it could create some noise in the analysis. However, since this study is evaluating a frontal crash protection system, the farside impact was selected.

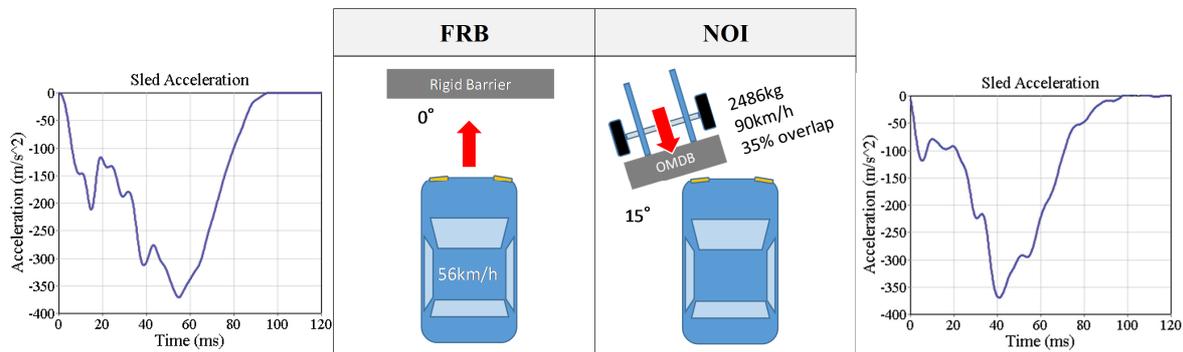


Figure 8. Parameter description: Load case

The parameter for the Occupant posture can be either Standard (23 degrees from vertical), or Reclined (45 degrees from vertical) (See Figure 9).

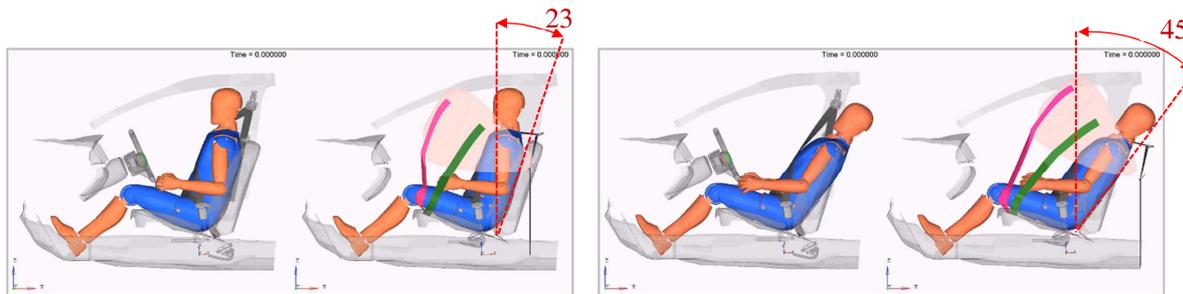


Figure 9. Parameter description: Occupant posture

The parameter for Occupant size is either a small female, an average male, or a big male. The AF05_HybridIII, representing a small female, has been used for a long time in regulation and assessment all over the world (e.g., US NCAP and Euro NCAP). The AM50_THOR represents an average size male; THOR is a newly developed dummy with higher biofidelic properties than the HybridIII series. The AM95_HybridIII represents a big male. The three types are shown in Figure 10.

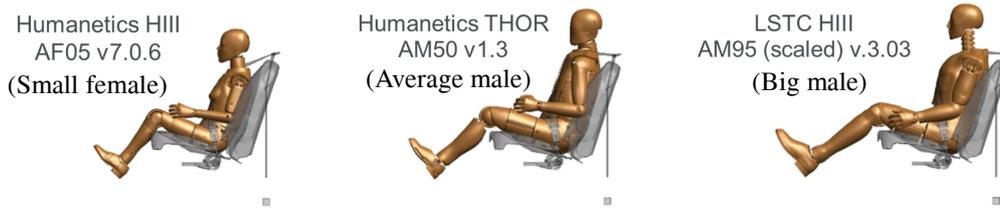


Figure 10. Occupant size of each type

RESULTS

Comparison based on Occupant size

For configurations 1, 2, 3, 6, 7, and 8 (see Table 1), the three occupants were compared in the standard posture (see Figure 11).

The New system resulted in lower IARVs than the Reference system in every case.

The Chest deflection graph shows that the New system has lower IARVs, and the range of values between the different occupant sizes is narrow. It is assumed that the distributed loading including shoulder and low seatbelt tension at chest contributed to these values.

The Reference system resulted in higher IARVs, which may be due to the THOR dummy's differences from HybridIII.

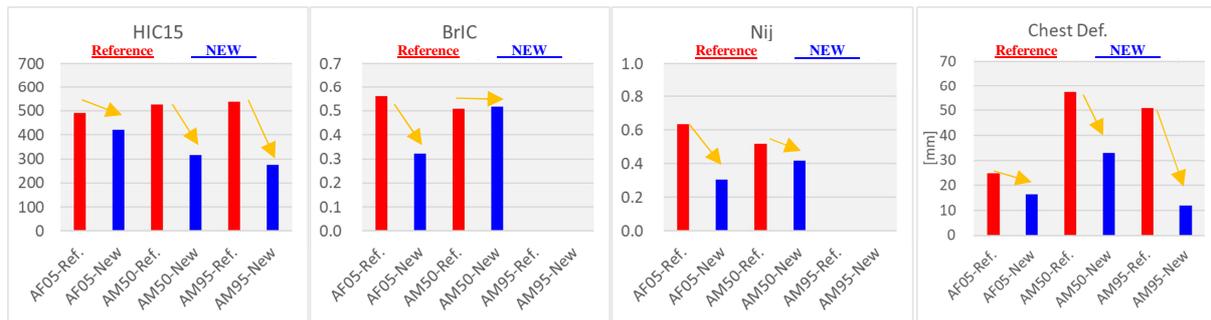


Figure 11. IARVs comparison based on Occupant size

Comparison based on Occupant posture

For configurations 1, 4, 6 and 9 (see Table 1), the two types of posture (Standard and Reclined) were compared for the FRB load case (see Figure 12).

Both systems produced higher IARVs in the Reclined posture than in the Standard posture in every case except Chest deflection in the Reference system. The head and neck region in particular showed a substantial difference. The New system resulted in lower IARVs than the Reference system in every case.

For Chest deflection Rmax, the New system showed lower IARVs and a narrower range of values between postures. As in the previous chapter, these results can be explained by the shoulder restraint scheme and the low level of seatbelt tension at the chest. However, it must be stated that the THOR_AM50 is not validated for the reclined sitting posture so the values should be interpreted with caution.

The velocity of the head region deceleration started later with the Reference system (i.e., the free-flight motion continued longer), because the relative distance between the head and the driver airbag in the Reclined posture is much greater than in the Standard posture. The New system creates equivalent relative distances between the head and the DSA in both Standard and Reclined postures, while the performance gap at HIC15 is much smaller than that of the Reference system.

As a side note, there is currently no regulation and assessment program to evaluate the risk of reclined posture.

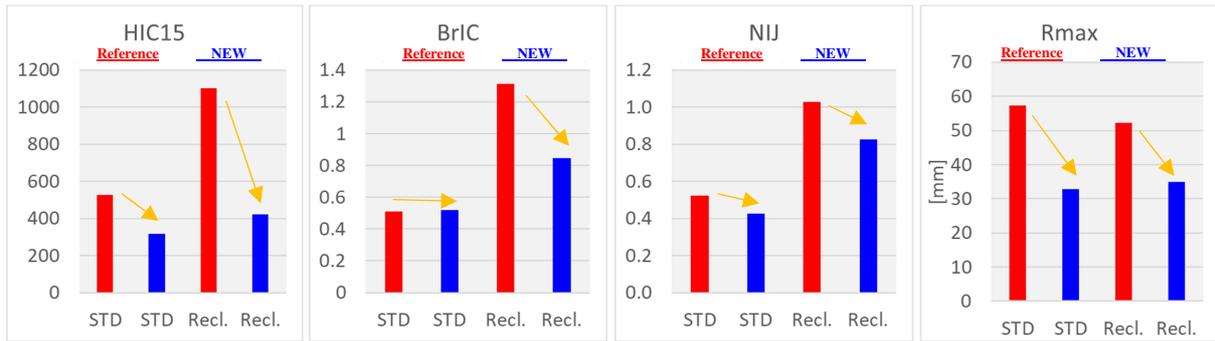


Figure 12. IARVs comparison based on Occupant posture

Comparison based on Load case

For configurations 1, 5, 6 and 10 (see Table 1), the two load cases of FRB and NOI in standard posture are compared (Figure 14).

The New system did not show substantial decrease of IARVs compared to the Reference system. HIC15 and Nij were higher for the New system, although Chest deflection and BrIC resulted in lower IARVs. For BrIC, the New system had a lower value than the Reference system, but a higher magnitude.

The Reference system in this study was not equipped with any unique feature designed specifically for the NOI load case; the head rotated clockwise around the Z axis after contacting the airbag. Although the New system caught the head in the valley between the sub- and main chambers of the DSA as intended, the head rotated counterclockwise around the Z axis (See Figure 15).

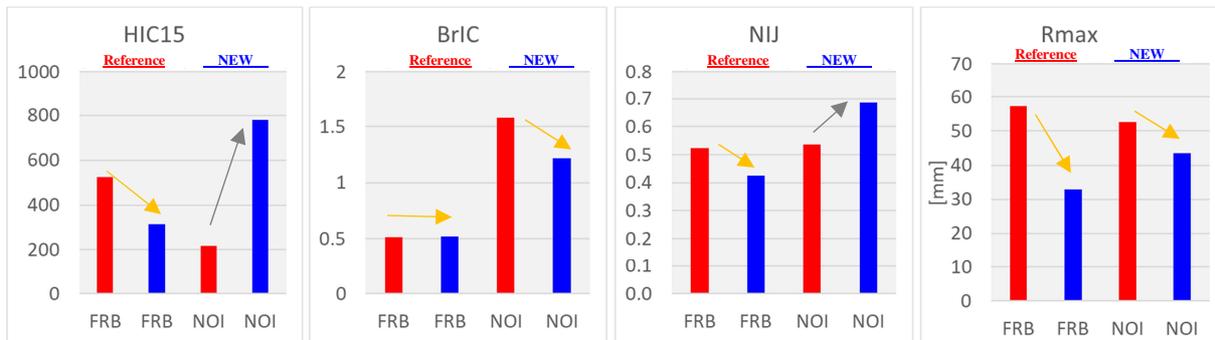


Figure 14. IARVs comparison based on Load case

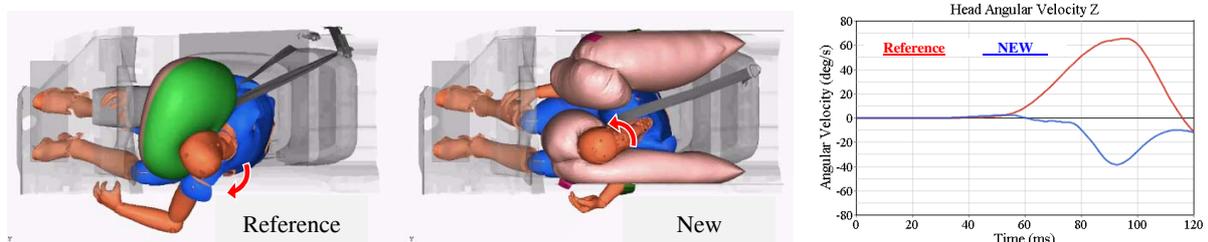


Figure 15. Occupant motion behavior comparison and Head angular velocity Z

Comparison focusing on rib deflection

As mentioned, AM50_THOR has four measuring points for Chest deflection (Figure 16). Figure 17 shows the result of the Chest deflection at each point: Upper-Right (UR), Upper-Left (UL), Lower-Right (LR), and Lower-Left (LL). The graphs on the left illustrate the Reference system, the graphs on the right illustrate the New system. The upper two graphs permit a comparison of the two Occupant postures in the FRB condition. The lower two graphs permit a comparison of the two load cases for Standard posture. The Reference system produced higher IARVs at UL and LL, corresponding to the seatbelt route across the chest, while the LR, far from the seatbelt route, has a very lower IARV. These results mean that there was a local rib cage deformation at the chest. For the New system, there was less local deformation, indicating that loading at the chest was more broadly distributed.

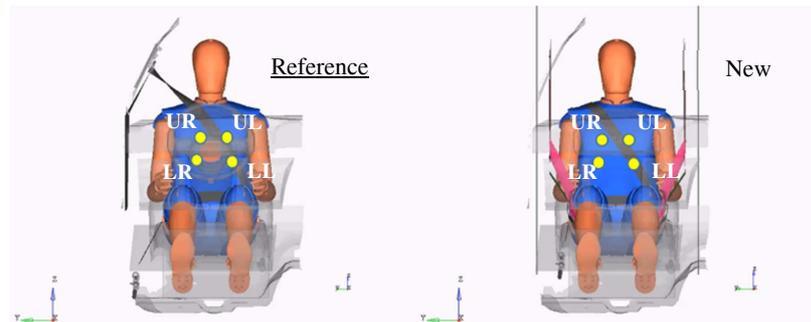


Figure 16. Seatbelt route w.r.t. Chest deflection measuring points (yellow dots)

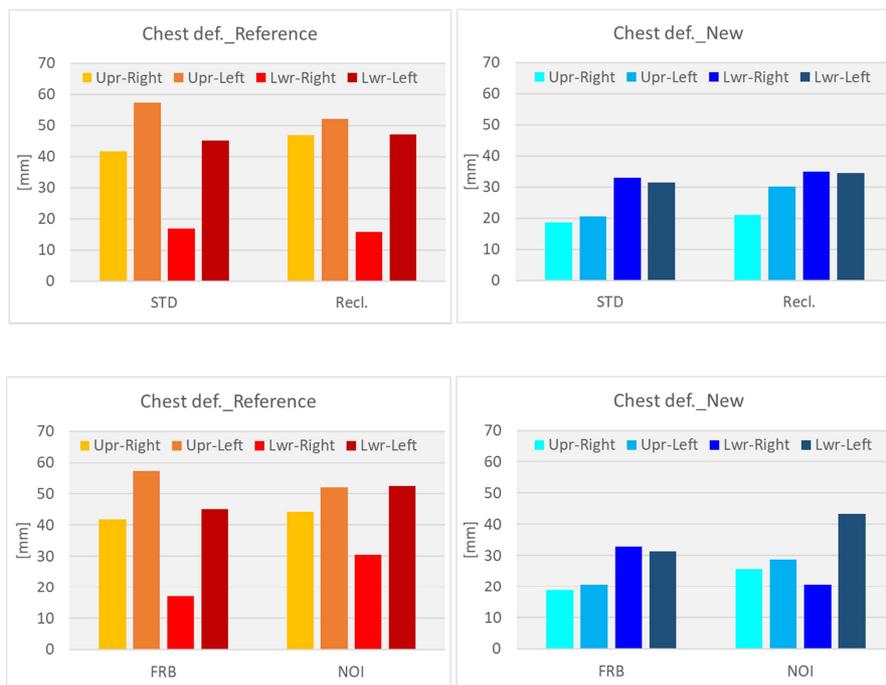


Figure 17. Chest deflection results from three cases (Left: Reference system, Right: New system)

Contact force measurement

Figure 18 shows the contact forces between occupants and restraint devices in the Reclined posture. The Chest contact force (between the DSA and the occupant) shows that restraint starts earlier with the New system compared to the Reference system; the seatbelt contact forces for both chest and pelvis are lower in the New system than in the Reference system, due to the low load-limiting force on the seatbelt. In spite of the lower

seatbelt-to-pelvis force of the New system (Figure 18, lower right), the higher seat pan force (Figure 18, lower left) was indicated; it is a key feature of the New restraint system.

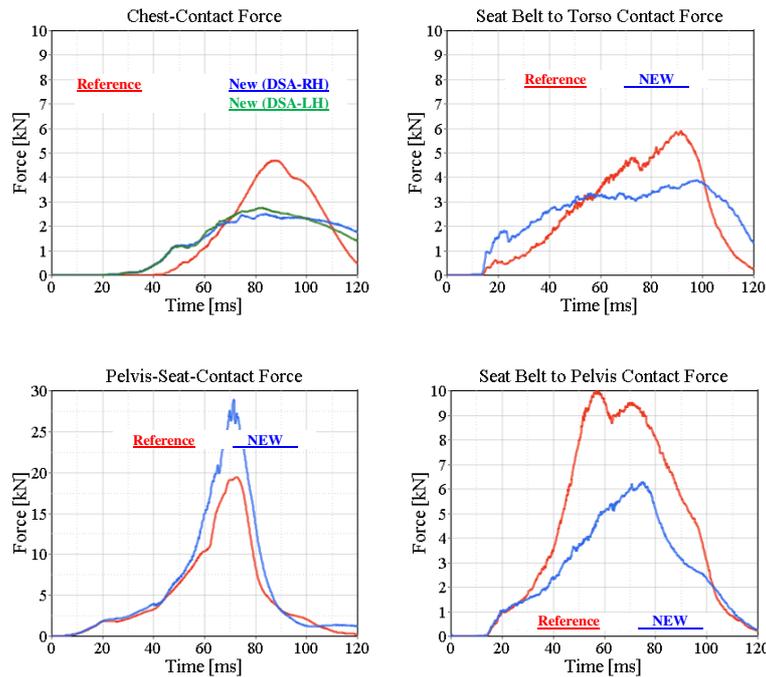


Figure 18. Contact forces between the restraint system and the occupant in reclined
Upper left: Chest Contact Force, Upper Right: Seat Belt to Torso Contact Force,
Lower left: Pelvis-Seat Contact Force, Lower right: Seatbelt to Pelvis Contact Force

Submarining check

When the submarining phenomenon occurs, the force exerted by the lap part of the seatbelt tension drops suddenly as it slips over the ASIS, the top-front part of the iliac wing, into the abdomen. (This acute force decrease is one of the assessment criteria proposed in Euro NCAP [16]). The ASIS has a dented shape where the lap belt fits, transferring the restraint force from the seatbelt to the pelvis. Accordingly, the lap belt force was checked in configurations 1–10, and the ASIS load was checked for AM50_THOR. Like the lap belt force, if the ASIS load shows a sudden drop, it means that submarining has occurred. None of the configurations showed submarining. Representative graphs of the Reclined condition are shown in Figure 19.

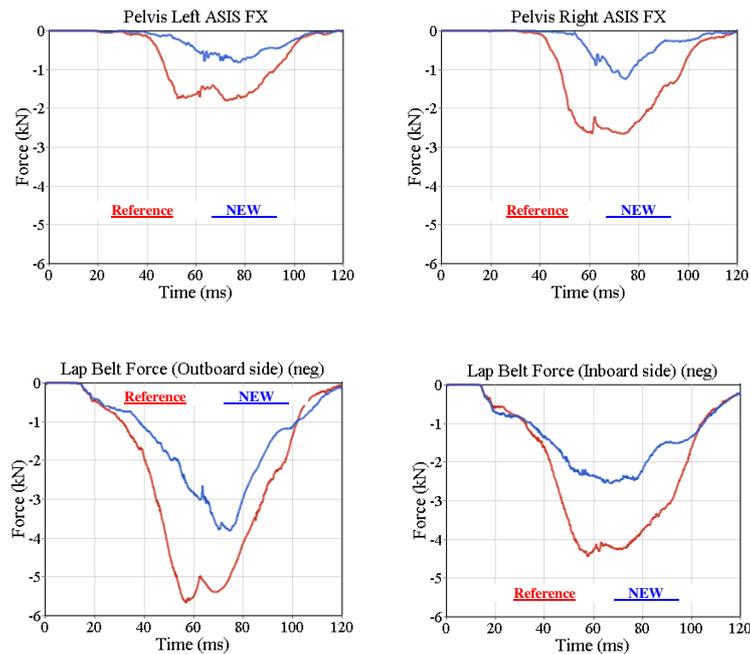


Figure 19. ASIS load and Lapbelt Force in Reclined posture

DISCUSSION

The New system had lower IARVs than the Reference system in almost all cases. However, it had higher IARVs for the head, as determined by the HIC15 and Nij results in the NOI condition. The main element of Nij is NTE (tension-extension), which means the head has been rotated back in a bouncing motion; a softer airbag could lower the Nij value. In fact, the HIC15 value could also be lowered with a softer airbag.

For BrIC in the NOI condition, the New system resulted in a lower value than the Reference system. In the New system, the VRP is a rigid wall, which may cause a high-reaction lateral force against the head, resulting in rotation around the z axis and a high BrIC value. In this study we used a virtual VRP, but for the next step a VRP made of real material could be used to support the DSA. If the VRP could retain the DSA while allowing some deformation, it could create a softer head impact with the DSA, improving head-protection performance.

Considering the evaluation of the New system, we would like to make the following two points.

First, the New system's distributed loading including the shoulder provides a great advantage over the Reference system. The DSA restrains the chest more broadly, including the shoulders, and thereby loads the chest less localized. Thanks to this decrease, the seatbelt load-limiting force can be reduced (it was 2kN in this study). This design contributed to lower Chest deflection values in every case. For the AF05 and AM95_HybridIII dummies, the DSA did not impact any measuring point directly at all. The AM50_THOR, with four points to be measured, permits a more realistic evaluation of how chest loading is distributed: the results show that chest loading is more broadly distributed in the New system. The main contributor to the restraint is not the seatbelt; it is the DSA. The findings of Knobloch et al. (2016) [17], who used an accident database to make comparisons between several restraint systems, indicate that a restraint system designed to provide distributed loading reduces rib fracture risk. Thus this New system, by distributing the loading across the chest more effectively, could contribute to reducing risk in real-world accidents.

Second, in the reclined posture, the New system can restrain the occupant earlier than the Reference system does, due to DSA which equipped seat, the early restraint to chest; it is to reduce more amount of potential kinetic energy of upper body before head contacting to airbag, can reduce the velocity of head contact to airbag, head injury risk could be reduced. The New system generated a high contact force from the seat pan; it is assumed that the DSA pushes shoulders down. At the same time, the contact force from the lapbelt to the pelvis was low due to the low load limit. The combination of high seat pan contact force and low lapbelt force may help us achieve sufficient pelvis-stopping force while reducing abdominal injuries.

LIMITATIONS

This study shows the potential of the New system. The system was, however, only evaluated by numerical simulations of mechanical crash dummies and not verified by mechanical tests. The DSA needs to be validated with real physical material in order to develop it into a manufactured system. It should also be validated using more complex Human Body Models.

The only seat condition evaluated was forward-facing, which involves the knee bolster and toe board, which help restrain the lower body. If these parts were removed (for example, in the case of a rotated rear facing-seat), it would be more difficult to restrain the lower body.

The New system uses a unique restraint concept, which deploys from left and right sides of an occupant instead of from the front, thereby providing more distributed loading, also including the shoulders. The existing crash dummies and its model in this study has been developed and verified with the conventional restraint system and airbag, both of which restrain the chest from the front. As pointed out by Shaw et al. (2009) [18], rib cage deformation (as commonly defined by relative uniaxial displacement toward the spine) is insufficient to characterize the observed multiaxial deformation patterns.

In addition, it is possible that early restraint, even in the reclined posture, might increase the axial spine force and leading to spine compression. In another study of the effect of reclined posture, Valevan et al. (2018) [19] described three types of challenges through their CAE simulation with a crash dummy model: 1) high head acceleration, 2) submarining, and 3) increased spine force. The New system could be a countermeasure against 1) due to its early restraint start. It could also address the challenge 2); the DSA could pull femurs up via EnB to stop the pelvis with shorter displacement. However, we have not measured the spine force, so we cannot evaluate the third challenge. Further, spine flexibility greatly affects the load level, and even the state-of-the-art dummy THOR may not be the proper tool since it has not yet been evaluated in terms of spine force.

CONCLUSION

The New system was confirmed to have the potential for equivalent or lower IARVs compared to the Reference system in frontal crash mode in the forward-facing seat condition.

In the Full-Rigid-Barrier (FRB) load case, the IARVs of AF05/AM95_HybridIII and AM50_THOR with standard posture were compared; the New system provided lower chest IARVs through the combination of distributed restraint by the DSA and the low seatbelt load.

Using AM50_THOR, the effect of occupant posture in the FRB case was evaluated. It was confirmed that the New system has advantages in reclined-occupant protection by early restraint start of the seat-centric concept. In addition, the robust performance for chest protection was indicated also in this parameter of occupant posture.

AM50_THOR was also used to evaluate the effect of load case on restraint system performance.

REFERENCES

[1] Filatov, et al. "Effects of Innovation in Automated Vehicles on Occupant Compartment Designs, Evaluation, and Safety: A Review of Public Marketing, Literature, and Standards" presented at WCX SAE World Congress Experience, SAE International, issn: 0148-7191, 2019

[2] The Mercedes-Benz F 015 Luxury in Motion. - Mercedes-Benz, <https://www.mercedes-benz.com/en/mercedes-benz/innovation/research-vehicle-f-015-luxury-in-motion/>, Oct. 2018.

[3] Volvo - Concept 26, <https://www.futureofdriving.com/concept26.html>, Oct. 2018.

[4] Volkswagen I.D. Buzz EV Concept Photos and Info | News | Car and Driver, <https://www.caranddriver.com/news/volkswagen-id-buzz-ev-concept-photos-and-info-news>, Oct. 2018.

[5] Jorlöv S., Bohman K., and Larsson A., 2017. "Seating Positions and Activities in Highly Automated Cars—A Qualitative Study of Future Automated Driving Scenarios." In Proceedings of IRCOBI conference. Antwerp, Belgium

- [6] Östling M., and Larsson A., 2019. "Occupant activities and sitting positions in automated vehicles in China and Sweden." "Proceedings of 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Eindhoven, Netherlands.
- [7] Östling M., Sunnevång C., Svensson C., and Kock H.O., 2017. "Potential future seating positions and the impact on injury risks in a Learning Intelligent Vehicle." 11. VDI-Tagung Fahrzeugsicherheit, 29th of November 2017, Berlin, Germany.
- [8] National Highway Traffic Safety Administration. 2012. "Laboratory Test Procedure For New Car Assessment Program Frontal Impact Testing.
- [9] National Highway Traffic Safety Administration (2017) New Car Assessment Program; Request for comments; [Docket No. NHTSA-2015-0119].
- [10] Nightingale R., et al. "THOR Head and Neck IARVs," SAE THOR Evaluation Task Group, 2009
- [11] Tackhounts E., et al. "Development of Brain Injury Criteria (BrIC)" Stapp Car Crash Journal, vol. 57 (November 2013), pp. 243-266
- [12] Forman J., et al. "Biomechanical Considerations for The Optimization of an Advanced Restraint System: Assessing The Benefit of a Second Shoulder Belt" IRCOBI Conference - Prague (Czech Republic) - September 2005
- [13] Bostrom O., et al. "Mechanism of Reducing Thoracic Deflections and Rib Strains Using Supplemental Shoulder Belts During Frontal Impacts" The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea, May 27-30, 2013.
- [14] Luet C., Trosseille X., Drazetic P., Potier P., Vallancien G.: Kinematics and dynamics of the pelvis in the process of submarining using PMHS sled tests. Stapp Car Crash Journal, 2012, Vol. 56: pp. 411 - 442
- [15] National Highway Traffic Safety Administration (2015) New Car Assessment Program; Request for comments; Docket No. NHTSA-2015-0119.
- [16] European New Car Assessment Program (Euro NCAP) Assessment protocol – Adult Occupant Protection, Version 8.0.3, October 2018. <https://cdn.euroncap.com/media/41746/euro-ncap-assessment-protocol-aop-v803.201811061520101516.pdf>
- [17] Knobloch K., et al. "Sternal Fractures Occur Most Often in Old Cars to Seat-Belted Drivers Without Any Airbag Often With Concomitant Spinal Injuries: Clinical Findings and Technical Collision Variables Among 42,055 Crash Victims", The Annals of Thoracic Surgery, 82(2): 444-450
- [18] Shaw G., et al. "Impact Response of Restrained PMHS in Frontal Sled Tests: Skeletal Deformation Patterns Under Seat Belt Loading" Stapp Car Crash Journal, vol. 53 (November 2009), pp.1-48
- [19] Valevan S., et al. "Development of occupant restraint system for future seating positions in fully or semi autonomous vehicles", FISITA World Automotive Congress, Paper No. F2018-APS-056