ASSESSMENT OF PASSENGER SAFETY IN FUTURE CARS - IDENTIFYING THE REAL-WORLD NEEDS TOWARDS SAFETY SYSTEM DEVELOPMENT

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ABSTRACT

Future cars will likely include further collision mitigation systems, seat positions and seating configurations compared to current cars, in addition to an increased degree of shared mobility solutions. At the same time the population is becoming older and the diversity in car passenger dimensions is growing. This calls for assessment tools and evaluation methods beyond the current standardized crash test methods. This paper summarizes the results of a Swedish research project on how to assess the protection of the heterogeneous population of passengers (i.e., non-drivers) in future car crashes, focusing on restraint interaction. With the overall purpose of further improving passenger protection, the specific aims were to achieve method developments based on the enhancement of tools (physical and virtual human substitutes) as well as to create knowledge on passenger protection needs.

This comprehensive research project combined multiple competencies and international collaborations, and a large number of studies have been performed using different methods. The applied methods include real-world crash data analyses to identify scenarios and situations, crash testing and simulation, and additionally user-studies conducted in cars to evaluate sitting posture, beltfit, kinematics, comfort, experiences and attitudes. Furthermore, the project included studies on crash test dummies (ATDs) and Human Body Models (HBM). Moreover, adult morphed HBMs were developed in various sizes, ages and sexes, for investigating various protection principles.

In novel studies, crash interventions strategies were applied to predicted residual crash configurations. User-studies provided evidence of self-selected passenger postures in real car settings and, thus, deviations from standardized ATD positions. The importance of body shape was highlighted in a beltfit user-study including older adults. Essential booster design parameters were identified for children in upright and reclined seat positions. Restraint principles were investigated for adults in reclined seat positions and with the seat in rearward positions, away from the frontal airbag and knee bolster, along with an evaluation of the capabilities of the assessment tools.

The adult HBM morphed to various sizes, ages and sexes were validated for prediction of in-crash kinematics in different impact scenarios, and provided enhanced insights in passenger protection assessment compared to the three standardized sizes of ATDs. Simulations with PIPER6y, a child-sized HBM, emphasized the importance of vehicle-booster-user system interaction.

The results from the research project provided input to safety system development, ATD/HBM design, assessment methods development, and a number of identified research challenges for future work. Specifically, there is a need to further explore car passenger interaction with the restraint system in terms of seat positions and variations in body sizes, shapes and postures. The inclusions of the heterogeneous population into more advanced tools such as HBMs are essential, acknowledging that when moving closer to "zero injuries", the situations to address are more unique and specific. Although a large range of studies using different methods was conducted, many challenges still remain to cover the entire scope of passenger safety in future cars.

INTRODUCTION

Assessing protection for passengers in cars is of increased importance moving towards automated driving (AD) and a higher degree of car and ride sharing (Jakobsson et al., 2019). In unsupervised AD, the driver becomes a passenger. Car sharing and increased use of taxis and other ride sharing, call for effective, comfortable, and safe protection systems, customized for a wide range of ages and sizes as well as a wider range of seat positions and seating configurations. In addition, the advanced driver-assistance systems (ADAS) will influence the crash frequency, as well as the pre-crash dynamics and the crash configurations, when activated and altering but not avoiding the crash.

It is expected that future passengers will choose their seat position and sitting posture with even more freedom than today, presenting a larger spread in real-world postures in crashes compared to today. For example, passengers may choose more reclined seat positions. This poses the challenge of assessing safety for novel sitting postures and seat positions where current tools (physical and virtual human substitutes) may not be biofidelic, nor the sitting postures and beltfit are understood.

The position of the shoulder and lap-belt over the body (beltfit) is highly related to the seat position and the occupant's posture, shape, and anthropometry. The aging population is growing, and beside their fragility and frailty, there are challenges with respect to the lap-belt position (Fong et al., 2016). Similar challenges are also seen for obese passengers, for whom their abdomen size influences lap-belt position, (Reed et al., 2012, Park et al., 2016). A high positioned lap-belt increases the risk for submarining (Howes et al., 2015).

Many passengers are children. Children have specific needs due to their body shape and development, which will remain in future cars. The smallest children are optimally protected using rearward facing child seats, while children from approximately 4 years of age can use the car's seat belt (Jakobsson et al., 2005). However, these older children need to use belt-positioning boosters to adapt to the seat belt (Reed et al., 2008). Specifically, the increased usage of transportation modes such as car sharing and ride sharing will require for children flexible and easy-to-use solutions in order to maintain high utilization and protection.

To enable future mobility services (such as AD and shared mobility) and to ensure the protection of a heterogeneous passenger population, safety assessment methods and tools need to be evaluated and where applicable be developed or updated. Tools for car passenger protection assessment are mainly crash test dummies (ATDs) and virtual human body models (HBMs). ATDs are available as physical tools as well as virtual counterparts. They are available in a limited number of sizes and do not reflect the variety of body shapes. HBMs, being more anatomically similar to humans, have greater potential to be omni-directional, representing human kinematics in all impact directions. In addition, they are representing a wider range of anthropometries for both sexes. They also have the potential to predict injury risk at the organ or tissue level and to recreate more humanlike interactions, e.g., detailed shoulder to shoulder-belt interaction. However, as for ATDs, the HBMs need to be validated for new sitting postures as well as for the injury risk predictions in focus.

This paper summarizes the results of a Swedish research project on how to assess the protection of the heterogeneous population of passengers in future car crashes, focusing on restraint interaction. Future car crash challenges include, among others, the influence of ADAS, potential novel seating in future unsupervised AD, increased use of shared mobility, and injury prediction when moving towards "zero injuries". Using various methodologies of applied research, the objectives of the project were to investigate variations in passengers' seating and perceptions, to address and develop assessment methods and tools for evaluating protection principles, and to contribute to identifying future research and development needs. The following research questions were formulated:

- What are the challenging passenger protection needs in current and future passenger cars?
- What do passengers' sitting postures and beltfit look like in today's cars and what are their seating preferences in future car usage?
- How can existing tools help to address the real-world needs for passenger safety assessment?
- Can morphed versions of existing HBMs represent a larger portion of the population and how do we choose the target population?

The project considered passengers of age 4 years and older in passenger cars. Younger children who are not using the car's seat belt as part of their protection were excluded. Only passengers were included as they are free to choose a greater variation of seat adjustments, seat positions and sitting postures, which results in more interesting learnings than for drivers. Passengers are also a more relevant population for future car safety challenges.

The research effort combined expertise from industry and academia, involving senior researchers as well as doctoral and master students. The project started in 2017 and the structure and way of working followed prior research projects (mainly addressing child car passengers) presented at the 22nd and the 25th ESV conferences (Jakobsson et al., 2011 and 2017). In total 25 publications, 13 academic theses and some insights from unpublished studies are briefly summarized in four chapters. The chapter **Real-world data** covers methodologies ranging from crash data analysis and occupant preference predicting, to user-studies on postures and beltfit. The chapter on **Tools** includes studies on the development of a heterogeneous population of HBMs and assessment of ATDs, while the chapter **Assessment of protection principles** covers physical sled tests and virtual simulations applying the HBMs and the ATDs. The chapter **International outreach** demonstrates a method for international multidisciplinary exchange.

REAL-WORLD DATA

Real-world crash data was analyzed to identify scenarios relevant for future crashes. User-studies of various kind were executed to investigate seating preferences in future travel modes, as well as passengers' sitting postures, movements, beltfit and comfort experiences in current passenger cars.

Predicting future crash scenarios
Crash data was used as input to determine future safety-critical scenarios. Lubbe et al. (2018) and Östling et al. (2019a and 2019b) used the German In-depth Accident Study (GIDAS) data and National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) data from USA, respectively, to identify future unavoidable crash scenarios for ADAS equipped cars and what crashes fully automated vehicles will be exposed to in mixed traffic analysis. The unavoidable crashes identified in the NASS-CDS data were further analyzed to identify remaining injuries (Östling et al., 2018). Analyses of crash data also served the purpose to derive statistics about passenger car seat occupancy and occupant age, sex, height, and weight. A comparison between Sweden, Germany and USA was performed using crash data from each of these countries. Front passenger seat occupancy ranged from 24% in the US data, 26% in the German data to 37% in the Swedish data. A relatively higher share of children in the front passenger seat was seen in the two European datasets compared to the US data.

An example of results from one of the studies looking at predicted future crash scenarios is shown in Figure 1. An estimation of most frequent remaining crash scenarios was derived using real-world data involving modern passenger cars virtually equipped with 15 different ADAS (Östling et al., 2019a). As a result, about 90% of the remaining crashes involving moderate to fatal injuries were assigned to four of the crash scenarios (Figure 1). Three of them are intersection related, representing together three quarters of all remaining crash scenarios, while the fourth is the 'Opposite Direction - Head-On crash scenario'.

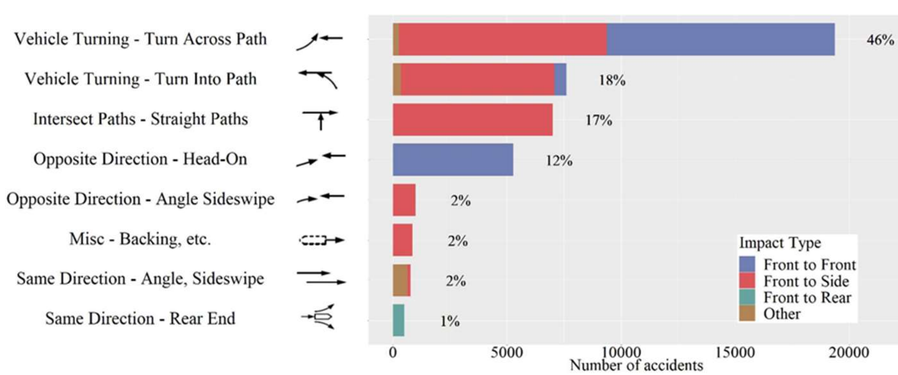


Figure 1. Prediction of unavoidable crash scenarios, after applying 15 ADAS, example from the NASS CDS database in USA (Östling et al., 2019a).

Exploring users' preferences in future transportation

Studies investigating preferences in future transportation were executed using different methods, addressing either AD or passenger cars in shared mobility services.

Hagberg and Jodlovsky (2017) investigated preferred reclined seat positions in potential unsupervised AD, with a comfort and safety approach using volunteers in a test-rig equipped with a production passenger car seat including a leg support (Figure 2a). It was found that the preference to sit reclined increased when the seat was equipped with the leg support compared to without. In addition to that, the reclined positions often led to a lap-belt position above the pelvis. Another important finding was that most of the respondents did not consider crash safety when selecting their seat positions.

An experimental setup was developed to assess drivers' experiences of the reclined sitting posture and the human machine interfaces (HMI) for transitions between upright and reclined modes and between manual and automated driving modes (Makris, 2020, Makris and Osvalder, 2022). The experimental setup consisted of four steps: practicalities, preparations, execution, and data collection methods. Six aspects were identified as important when assessing user experiences in a dynamic test: (1) recruiting appropriate participants, (2) providing consistent tasks, (3) providing adequate time constraints, (4) avoiding social influences, (5) utilizing appropriate data collections methods, and (6) carrying out a pilot study.

Figure 2a. Reclined seat with a leg support in the study by Hagberg and Jodlovsky (2017).

Figure 2b. Investigating future expectations of future automated passenger car interiors (Östling and Larsson, 2019).

Two studies, one in Vårgårda Sweden, and one in Shanghai China, were executed using the method "setting the stage" (Pettersson and Karlsson, 2015) to predict adults' and children's perception on seating configurations in different trip scenarios unsupervised AD (Jorlöv et al., 2017, Östling, 2018, Östling and Larsson, 2019). The participants explored seating configurations in a stationary test setup (Figure 2b), guided through different trip scenarios by the test leader. This qualitative experimental approach was used to explore users' expectations of future products using a minimalistic test setup design and interviews, allowing the participants to take on a more dynamic role than purely being an informant. Although in different continents, the user expectations in Sweden (Jorlöv et al., 2017) and in China (Östling and Larsson, 2019) were similar. In both studies the volunteers expected unsupervised AD to offer reclined seat positions, versions of a living room setup especially when several passengers would be travelling together, and more comfortable seats with screens and tables for various activities. Children showed a more positive attitude than adults, when asked if they would accept extra restraints if that would allow them to use new seating configurations (Jorlöv et al., 2017).

Focusing on booster-seated children in shared mobility, the users' needs on child restraints for car sharing services were studied by interviews and online questionnaire surveys in Sweden (Simmons and Johansson, 2020, Jakobsson et al., 2020). It was found that the majority of respondents had no experience with car sharing services, and they stated that one of the reasons not to use such services was the difficulties with child restraints. Portability, size, and weight were stated as important design features for boosters to be used in shared mobility services. 72% of the participant would use a booster if available in the car, instead of bringing their own.

Sitting postures and beltfit

User-studies were executed to explore and document real-world sitting postures, passenger movements and beltfit of passengers in current cars. A variety of individual differences (such as gender, age and body constitution) and differences in types of travels were explored with the purpose of learning from current car passenger seating. The aim was to identify how passenger characteristics and driving situations can influence sitting posture and beltfit, as input for further work on how occupant to restraint interaction can be addressed in future protection strategies. Some studies also included the development of methods for collection and analyses.

A number of the user-studies focused on older adults and their beltfit and comfort as front seat passengers in stationary cars, also including a comparison to younger adults (Ankartoft and Alfredsson, 2018, Osvalder et al., 2019, Bohman et al., 2019b). In addition to comfort perspectives, insights were gained on beltfit depending on body shape; as illustrated in Figure 3a. Twenty six of the 55 participants had non-optimal beltfit, including poor lap or shoulder-beltfit (Osvalder et al., 2019). Belt close to the neck increased the reporting of shoulder-belt discomfort. Overall, the safety awareness was low among the older adults compared to younger adults. Although not evaluated, it was estimated that most of the non-optimal beltfit could have been avoided, if the participant had used the adjustments possibilities offered in the car (Bohman et al. 2019b). In both studies, it was found that participants with high BMI were more likely to have the shoulder-belt higher up on the abdomen, resulting in that the shoulder-belt was routed closer to the neck. This beltfit occurred regardless of sex or age but was related to the body shape. Women with high BMI tended to have poorer lap-beltfit compared to men with high BMI, potentially due to the fat distribution differences. (Osvalder et al., 2019, Bohman et al., 2019b).

Figure 3a. Examples of passengers with different body constitutions and their beltfit (Osvalder et al., 2019).

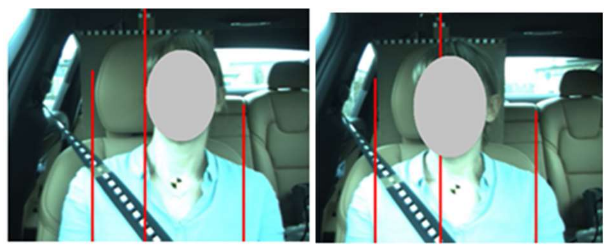


Figure 3b. Example of a front passenger prior to turn (left) and at maximum lateral position with head off the head restraint (right) (Bohman et al., 2020a).

Another user-study investigated 26 front seat passenger volunteers exposed to turns representing everyday driving. The study provided quantified data of beltfit, laterally leaning postures and lateral movement that can be used as input to simulation studies for assessing protection principles in relevant sitting postures (Olander and Andersson, 2019, Bohman et al., 2020a). An example of a passenger sitting upright and at max lateral position due to a turn is shown in Figure 3b. In the turn with highest lateral acceleration (0.3 g), the torso moved on average 45 mm from the centerline of the seat. The shoulder-belt stayed on the shoulder in all turns for all participants, but in some cases the head was positioned laterally off the head restraint (Figure 3b). The shorter participants showed a trend of greater lateral movement than the taller.

Addressing the challenging area of methods for quantifying sitting postures in cars with focus on pelvis orientation, instrumentation such as XSENS and digital measurements of body landmarks were explored using 27 volunteers in six setups (Janson and Wedmark, 2018). Both methods provided similar results, although the pelvis angle was more easily captured by XSENS. The pelvis angle changed on average 15˚ when the seatback was changed from upright (22˚) to reclined (45˚). This study served as inspiration for a follow-up driving study with the focus on pelvis rotation, in addition to slouching of front seat passengers, changes during the ride (Hansson and Lysén, 2019). It was found that pelvis rearward rotation and slouching forward increased over time with an average rearward pelvis rotation of 10° and 30 mm forward for the 20 participants.

User-studies were conducted with child volunteers who have advanced from child restraints but are yet not adults. With the aim of to understanding how the children's activities affect their experience, comfort and safety as car passengers, Gereben and Swenson (2020) investigated the behaviours of children aged 10 to 17 years old. The methods included interviews, a UX diary study and focus group sessions with the families at their home. Figure 4a shows a concept of a rear seat entertainment system with adjustable touch screen and a safe wireless phone charging place enabling the smart phone to be used as a control, developed as an example of how to nudge safe sitting posture and beltfit (Gereben and Swenson, 2020).

Figure 4a. Concept of rear seat entertainment system for study on child passenger aged 10 to 17 years old (Gereben and Swenson, 2020).

Figure 4b. Two children trying out the booster prototype in Jakobsson et al. (2020). The shoulder-belt is routed under the belt guide for the 6-year-old (left), while over the belt guide for the 11-year-old (right).

A user-study, limited to three children, was included in a study on belt-positioning boosters for children in which the mismatch between booster developments and the users' needs for shared mobility was in focus (Jakobsson et al., 2020). Figure 4b shows the role of the booster's belt guides as means to help guide the shoulder-belt, having an impact on comfort as well as protection in a potential crash. The 6-year-old child achieved a more optimal shoulder-belt fit when the shoulder-belt was routed below the belt guide, while the 11-year-old child benefited from a shoulder-belt routing above the belt guide. For optimal protection of booster-seated children it is essential that the car, the booster and the users are regarded as one entity.

TOOLS

Tools, including ATDs and HBMs, were assessed to explore their abilities to serve as substitutes for car passengers in a crash. This included examples of studies evaluating varieties in versions of specific ATDs, their capabilities to adapt to different sitting postures and comparison of two generations of dummies. A special task on the development of morphed HBMs is included as well.

Adult occupant tools

Targeting a family of HBMs representing the future adult population for evaluation of restraints, Larsson (2020) summarized the literature on the occupants with increased injury risk in car crashes, to identify the future population of car passengers posing challenges to contemporary safety systems and evaluation methods. Identifying women, older adults, and obese occupants, the boundary case method, as described by Brolin et al. (2012), was used to define 27 individuals to represent a diverse population. A morphing method for the SAFER HBM was selected and implemented to enable the creation of the individuals in the diverse population. Adult passenger HBMs, representative of both women and men of a wide range of statures, weights and ages were developed using the morphing method, examples shown in Figure 5a. A validation database was created consisting of publicly available experiments with 19 post-mortem human subjects (PMHS), together representing a wide range of male and female sizes and ages. Using this database, an extensive validation study was executed, identifying strengths and limitations of the morphed HBMs (Larsson et al., 2021a). It was found that the morphed HBMs predicted the in-crash kinematics of the PMHS with corresponding age and anthropometry with good accuracy in several crash scenarios.

In addition, a new rib fracture risk function based on recently created experimental data, that can be used to estimate HBM rib fracture risk was developed (Blennow, 2020) and implemented (Larsson et al., 2021b). The new HBM rib fracture risk function was not influenced by sex, but age was identified to have a stronger contribution to rib fracture risk than represented by previous rib fracture risk functions, enabling more accurate risk estimations over the span of adult passenger ages (17-99 years), see Figure 5b. The findings contribute to the SAFER HBM injury prediction developments (Larsson et al., 2021b).

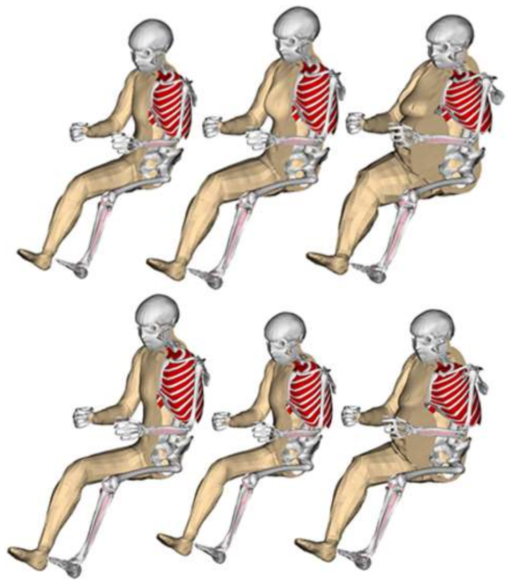


Figure 5a. Examples of morphed versions of SAFER HBM. Three female anthropometries (top row) and three male anthropometries (bottom row).

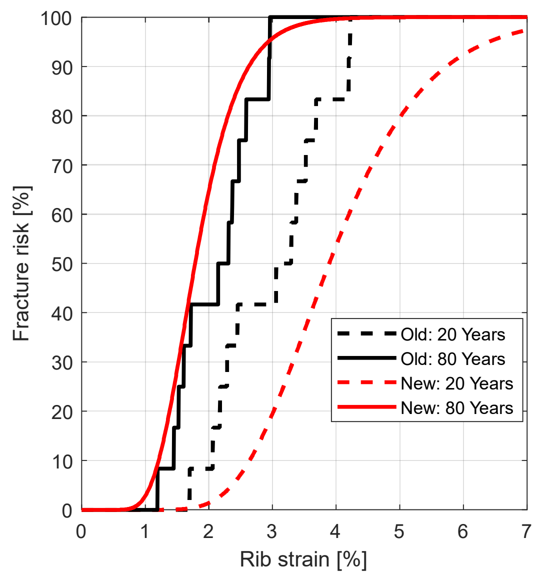


Figure 5b. New age-adjusted rib fracture risk function (red) compared to a previously existing fracture risk function (black) for 20- and 80-year-olds.

Adult-sized tools were evaluated to provide insight into their capabilities of addressing future car safety assessment needs, such as more reclined seats. The THOR-50M, a mid-sized male ATD, was evaluated in terms of kinematics and its interaction with the restraint system, exposed to frontal impacts using a generic test-rig in three different seating conditions: relaxed, reclined and upright, see Figure 6 (Östling et al., 2021). It was found that it was possible to position THOR-50M in the two reclined seat positions and the measured accelerations and forces appeared meaningful in relative comparisons even if a kinematic validation is preferred (Shin et al., 2022). As an example, the thoracic spine compression increased from 4 kN in the upright seat position to 6 kN in the two other positions. However, chest compression Rmax, measured as the maximum of the resultant value from the four IR-TRACCs, might not be meaningful in the two reclined seat positions. It was found that instead of a longitudinal compression, an angular change in vertical direction dominated the Rmax value. This might be explained by initial non-horizontal IR-TRACCs position in reclined and relaxed seat positions; the IR-TRACCs appeared to work as intended only when initially oriented horizontally as they are in the upright position (Östling et al., 2021). As a result, the Rmax indicated a higher risk of rib fractures in the two reclined seat positions despite that a lower shoulder-belt force was measured. In a following step, the mid-sized male SAFER HBM and a morphed large-sized male version were evaluated in similar conditions in a simulation study, Figure 7 (Östling et al., 2022). Similar to the sled tests with the THOR-50M, the lumbar spine compression forces of both HBMs increased in the relaxed seat position, while unlike THOR-50M, a lower risk for chest injury was predicted. However, it should be pointed out that chest injury risk is predicted by rib strain using the HBMs and chest deflection using the THOR-50.

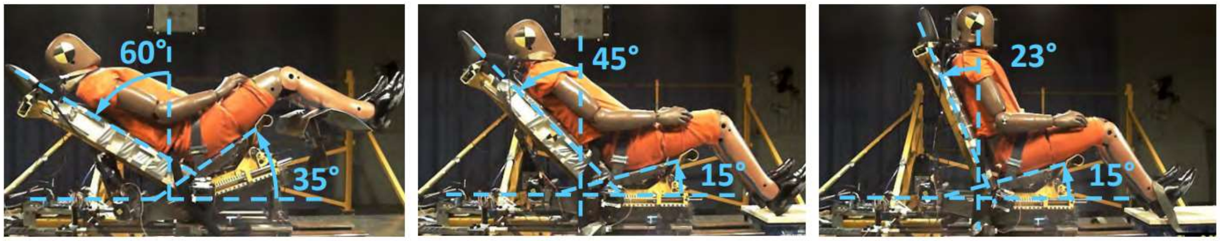


Figure 6. THOR-50M positioned on a generic seat in the relaxed, reclined and upright seating conditions (left to right), (Östling et al., 2021).

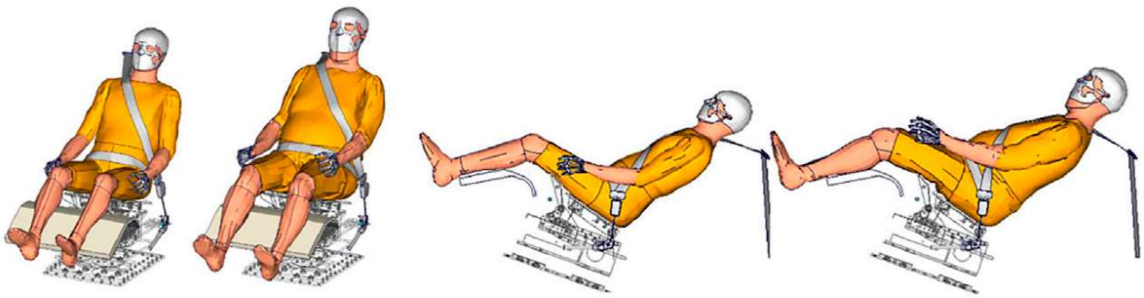


Figure 7. SAFER HBM positioned on the generic seat. Left: front views of the mid-sized male and the large-sized male. Right: side views of the mid-sized male and the large-sized male (Östling et al., 2022).

Frontal impact sled tests were run with the novel small-sized female THOR-5F ATD (Figure 8a), with comparative tests with the small-sized female HybridIII-5F (HIII-5F) ATD (Carroll et al., 2021). The SENIOR test buck (Eggers et al., 2017) was used with three different configurations: belt only at 35 km/h, belt and airbag at 35 km/h and belt and airbag at56 km/h. It was found that the two ATDs interact with the restraint system differently. The THOR-5F showed larger chest deflection and more forward pelvis excursion as compared to the HIII-5F.

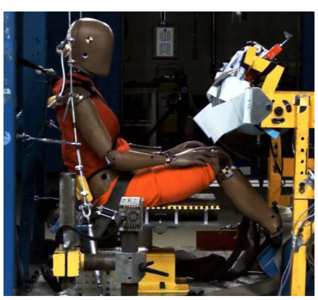


Figure 8a. The novel small-sized female ATD, THOR-5F (Carroll et al., 2021).

Figure 8b. Top view of shoulder-belt interaction with the original THOR-50M shoulder pad, during frontal impact.

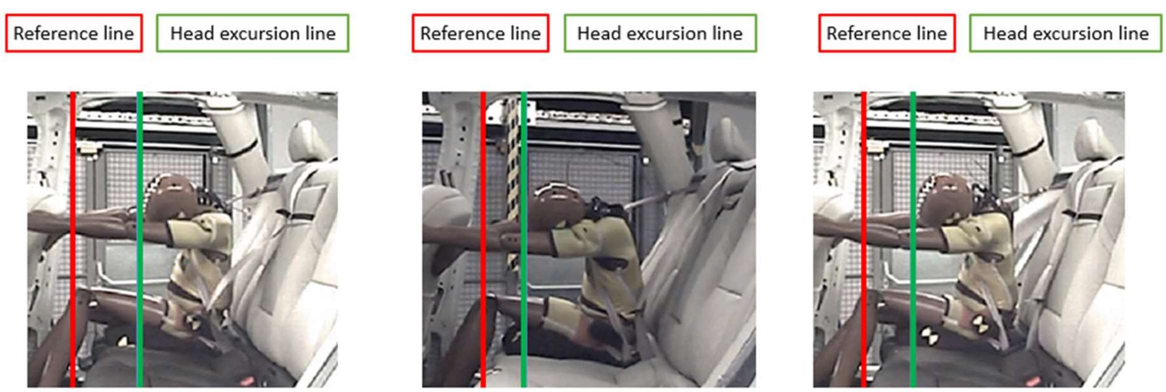
Figure 8c. Top view of shoulder-belt interaction with Humanetics updated THOR-50M shoulder pad, during frontal impact.

A sled test series was performed investigating THOR-50M's shoulder to shoulder-belt interaction, when exposed to a Euro NCAP Mobile Progressive Deformable Barrier (MPDB) frontal impact crash. The original shoulder pad was compared to update versions from two different suppliers, Kistler and Humanetics, respectively. Tylko et al. (2018) observed that with the original shoulder pad design, the shoulder-belt may slip over the shoulder pad collar into a gap between the neck and the shoulder pad. This gap is a dummy artifact and is not representative of humans. The updated versions were developed to prevent this shoulder-belt entrapment (Wang et al., 2019). In the sled test series, the shoulder-belt slipped off the shoulder pad collar into the gap in the tests with the original shoulder pad (Figure 8b), as well as with the updated shoulder pad by Kistler. While the shoulder-belt stayed on the shoulder in the tests with the updated shoulder pad by Humanetics (Figure 8c). The differences in shoulder-belt interaction influenced the dummy responses. The chest criterion Rmax was 33% higher, and the neck shear force was 27%, higher, when the shoulder-belt stayed on the shoulder. This study is an example of the importance of understanding the dummy design's influence on shoulder-belt interaction during a crash, improving the assessment methods towards more human and real-world like.

Child occupant tools

The open-source 6-year-old sized child HBM, PIPER6y (Beillas et al., 2016), was evaluated in studies to investigate its readiness and usefulness for child passenger protection assessment in a passenger car environment (Berntsson, 2018, El-Mobader, 2018, Daouacher, 2019). It was found capable of providing relevant information regarding sensitivity for lap-belt variations from the kinematic perspective in terms of capturing kinematic offset, submarining and pelvis interaction with the lap-belt (El-Mobader, 2018). PIPER6y also showed sensitivity to variations in shoulder-belt geometry, resulting in both inboard and outboard shoulder-belt movements (Berntsson, 2018, Daouacher, 2019). At the time of these studies, PIPER6y had some issues with early termination. Over time, the robustness has improved, and PIPER6y has become a valuable tool for studies on restraint interaction and booster design properties (Bohman et al., 2020b, Bohman et al., 2022).

Frontal and side impact sled tests were performed comparing three different versions of the Q10, an ATD with the size of a 10-year-old child (Bohman et al., 2018 and 2019a). Q10 is used in certification rig tests (UN ECE R129) and as a rear seat passenger in consumer information testing by Euro NCAP, wherefore it is essential to understand any consequences of variation between versions. The original Q10 was compared to two modified versions, here called 'Q10update', and 'Q10light'. The 'Q10update' comprises an upgrade kit with 5 modifications, which includes changes to the shoulder joint, shoulder liner, mass redistributions, soft tissue representation at nipples and head and neck shift resulting in nose more upward rotated. The 'Q10light' includes three of those changes: the head and neck shift, shoulder liner and mass redistributions. The three versions, when exposed to the frontal impact, are shown in Figure 9. The two modified Q10 showed greater head excursion and more upper torso tilt, than the original Q10, due to the mass distribution differences. This kinematics was anticipated to be more biofidelic. The 'Q10upgrade' showed limited sensitivity to shoulder-belt position, while 'Q10light' showed sensitivity to shoulder-belt position but still had a more stable behavior than the original Q10. Following these studies, the 'Q10light' version was selected by Euro NCAP to be used in their rating program starting 2020, now called Q10 2020.



The original Q10 | The modified 'Q10update' | The modified 'Q10light'

Figure 9. Three Q10 versions evaluated in Bohman et al. (2019a), at time of maximum head excursion in a frontal impact.

A follow-up study was conducted to compare supplier setups of the Q10 2020, including one complete Cellbond manufactured Q10 ('Q10_Cellbond'), one complete Humanetics manufactured Q10 ('Q10_Humanetics') and one version with Humanetics Q10 base and upgrade kit by Cellbond (Q10_HU_CB). The ATDs were restrained with the seat belt and a booster cushion, positioned in the right rear seat position and exposed to a frontal impact Euro NCAP MPDB crash pulse. Upper chest deflection was 62% larger for 'Q10_Humanetics' as compared to 'Q10_HU_CB' and 'Q10_Cellbond'. The difference could not be explained by shoulder-belt interaction nor difference in kinematics, since all three versions showed similar behavior (Figure 10). The neck tension was 27% higher for 'Q10_Cellbond' compared to 'Q10_Humanetics'. Additional tests were made by shifting the suits between 'Q10_Humanetics' and 'Q10_Cellbond'. However, no differences in dummy response or kinematics were seen between those tests.

'Q10_Humanetics' 'Q10_HU_CB' 'Q10_Cellbond'

Figure 10. The shoulder-belt to shoulder interaction of the three different versions of Q10 at the time of max forward excursion in a frontal impact.

ASSESSMENT OF PROTECTION PRINCIPLES

Physical sled tests and virtual simulations were performed to investigate principles of car passenger protection using different ATDs and HBMs. The aim was not to develop protection systems, but to develop knowledge on how the different tools could be used to assess the interaction with the lap- and shoulder-belt in the variety of configurations. The studies included variations in seat position, sitting postures, seat belt routing and features, in addition to booster design when applicable. Some examples, illustrating the spread in applications, are provided.

Adult occupant protection principles

Östling et al. (2017) proposed a seat belt system that incorporated a triple belt pretensioner to avoid submarining in reclined seat position testing using a THOR-50M. When this system was evaluated in reclined PMHS tests, it was found that submarining could be avoided in four out of five tests (Richardson et al., 2020b). However, iliac wing fractures were induced by the lap-belt in two out of five tests, and lumbar spine vertebra fractures were induced by the reclined upper body (Boyle et al., 2019, Richardson et al., 2020a) in three out of five tests. Based on these findings, several sled test and simulation series were performed with the purpose to study occupant retention in novel seat positions (e.g., reclined), investigating the assessment of different restraint principles, such as lap-belt pretensioners and load limiters, lap-belt geometries, and a seat track load limiter (Östling et al., 2017, Östling et al., 2021, Östling et al. 2022, Östling and Lubbe, 2022, Östling and Eriksson, 2022).

When evaluating the effect of a seat track load limiter (i.e., reducing the crash severity by adding an energy absorbing element in the seat track) using the THOR-50M and the SAFER HBM, both tools indicated a reduced risk of lumbar spine vertebra fracture (Östling et al., 2021, Östling et al., 2022). However, whereas the SAFER HBM showed a substantial reduction in rib fracture risk, the THOR-50M indicated an increased risk of thorax injury when evaluated by the Rmax criterion. This was despite a lower shoulder-belt force. This difference supported the statement in Östling et al. (2021): "We believe HBMs with human-like design and use of rib strain as an indicator of risk of rib fractures, are likely to be more biofidelic than chest deflection to evaluate a potential increase or decrease in risk of rib fractures in reclined and relaxed positions".

The occupant mass effect on the seat track load limiter was studied in different frontal impact crash severities utilizing the mid-sized male and large-sized male versions of the SAFER HBM (shown in Figure 7). Östling et al. (2022) showed that by adding a release mechanism in combination with an adaptable activation logic in terms of crash severity and occupant mass, the seat track load limiter protection capacity was enhanced.

Sled tests and simulations were run using the mid-sized male Hybrid III 50M (HIII-50M) ATD (Östling and Lubbe, 2022) and the SAFER HBM (Östling and Eriksson, 2022) to evaluate the influence of lap-belt load to limit the kinematics and measured injury assessment values. It was seen that the lap-belt load limiter did not only reduce the lap-belt force and thereby the risk for iliac wing fracture, but also limited forward-downwards head excursion and thereby a reduced likelihood for head-to-thigh contact, see Figure 11 for HIII-50M. Interestingly, despite fundamental different designs, both tools (ATD vs HBM) indicated similar effect on the occupant kinematics (Östling and Lubbe, 2022, Östling and Eriksson, 2022).

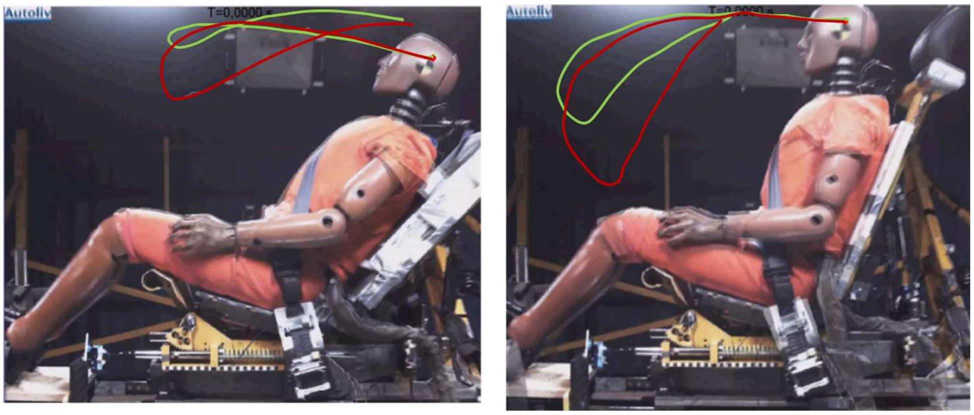


Figure 11. HIII-50M with and without double lap-belt load limiter, in reclined position (left) and upright position (right). The head trajectory was tracked during the test; red line is from test with no lap-belt load limiter and the green line is from the test with double lap-belt load limiter (Östling and Lubbe, 2022).

Another protection principle which was explored using two different tools, was conceptual air belts (Figure 12a). Frontal impact simulations with SAFER HBM were performed with two versions of conceptual air belts, a 10 liter and 18 liter airbag, respectively. Mainly focusing on kinematics, and neck and spine loads, the effect of air belt was assessed for upright seat position, and a reclined seat position. The simulations were followed-up with sled tests using THOR-50M (Figure 12b). In neither of the studies, a significant effect of the air belt was seen.

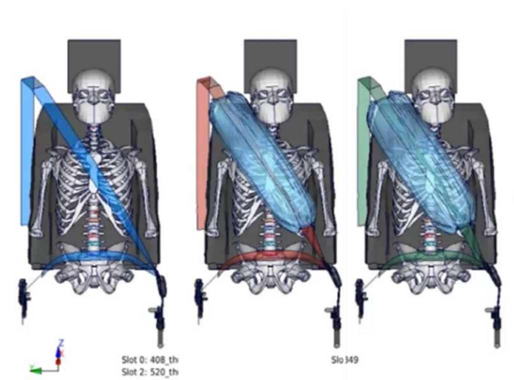


Figure 12a. SAFER HBM in the three setups; no air belt (left), air belt of 10 liters (mid) and 18 liters air belt (right).

Figure 12b. THOR-50M with a 10 liters air belt, in the sled test setup of upright (left) and reclined (right) seat position.

Child occupant protection principles

With the purpose to investigate the influence of booster cushion design on child occupant kinematics and loading; simulations using PIPER6y and sled tests using Q10 were performed, Figure 13 (Bohman et al., 2019c and 2020b). It was found that both Q10 and PIPER6y showed that though the boosters providing similar initial beltfit, the occupant responses were different during the crash. Compression of the booster cushion resulted in a delayed pelvis restraint, influencing the upper body kinematics. Furthermore, the belt guide design as well as the belt routing above or under the guide also influenced the upper body kinematics and shoulder-belt interaction (Bohman et al., 2020b).

Figure 13. PIPER6y (left) and Q10 (right) at the time of maximum head excursion restrained on three different booster cushions (Bohman et al., 2020b).

Another study used PIPER6y to explore the challenges for booster-seated children in reclined seat position and different restraint parameters (Bohman et al., 2022). Three different booster types were used in a front passenger seat with two different seatback angles. The study included variation of pretensioner activation (yes/no), attachment to the ISOFIX anchorages (yes/no) and two different shoulder-belt outlet positions. Activating the pretensioner resulted in shorter body displacement and lower head and neck responses in both seat positions compared to pretensioner non-activation. Submarining occurred only for one of the boosters, when in reclined position without pretensioner. Overall, greater pelvis displacement was observed when in reclined position as compared to upright position'. In both seat positions, greatest pelvis displacement was observed on the booster allowing a relatively more forward initial lap-belt position. Among the three included boosters, the booster providing most favorable initial lap-belt to pelvis contact and controlled vertical movement of the pelvis offered the most efficient lap-belt interaction. Furthermore, this study highlighted the importance of including the whole context of child occupant protection when investigating reclined seating, such as the interaction and compatibility of the booster, the car seat and the seat belt (Bohman et al., 2022).

Two booster cushion concepts were developed to demonstrate the needs and challenges in shared mobility, serving the purpose to illustrate and communicate the mismatch between the booster design trend and the users' needs in shared mobility (Jakobsson et al., 2020, Simmons and Johansson 2020). Booster cushion concepts were explored in order to fulfill UN ECE R129 requirements, resulting in increased height of the booster cushion and at the same time offering a portable solution suitable for ride-share and car share mobility, while still fulfilling protection principles. The foldable booster cushion, shown in Figure 14, reduced the volume by 37% in compressed state, compared to user state. Folding the belt guides as well could reduce size even further.

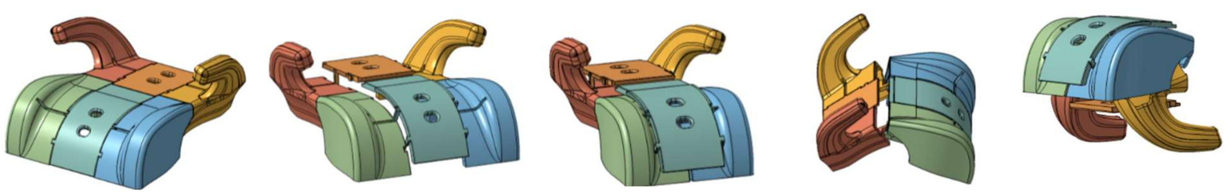


Figure 14. A sequence of pictures from user-state (left) to compressed/folded state (right) (Jakobsson et al. 2020).

INTERNATIONAL OUTREACH

Two international multidisciplinary workshops on Child Occupant Protection were held in Sweden in September 2019 and September 2022 with the purpose to identify high-priority research topics and strategize toward their implementation. The workshops were the 6th and 7th biannual workshops on this topic, and hosted by the project team and SAFER, within prior research projects over the years (Arbogast et al., 2011, 2013, 2015 and 2017). The participants of the workshops included worldwide leaders in the fields of child occupant protection, biomechanics, and automotive safety. Adjacent to the workshops, a one-day open seminar was held at SAFER in Gothenburg, Sweden, with presentations by the international researchers on current child occupant protection topics. The discussions at the workshops were summarized and presented at the International Conference Protection of Children in Cars in Munich, enabling a wider dissemination and contributing to setting the agenda of future research and development (Bolte et al., 2019; Arbogast et al., 2022).

The workshops of 2019 and 2022 followed the methodology of prior workshops with focused interaction and discussions during two-days. The first day included reflections on relevant topics on ‘pressing issues in child and adolescent occupant protection’, in addition to reviewing progress of research priorities identified during previous workshops. The second day included discussions on high priority areas, as defined based on the first day’s discussions.

The workshop in 2019 focused on the topics of what automated driving systems mean to children and youths, how new mobility may alter their behavior, and how to ensure protection of all ages of passengers when moving from a driver-centric mobility to a passenger centric mobility. Critical safety points were defined as a unified voice for all stakeholders in child safety to ensure safety for all road users as we move into a world of autonomous driving systems. The critical points highlighted that every trip is important, and special focus was put on ensuring safe trips when using shared mobility services. Furthermore, the design of the seat and restraints should promote occupant behavior allowing the individual to be both comfortable as well as safe in all types of trips. In addition, a continuous need was emphasized to improve the child-specific occupant tools (ATDs and HBMs) to address challenges in variations in sitting posture, seating configurations and pre-crash maneuvers.

In 2022, the workshop focused on what strategies are necessary to further reduce the burden of motor vehicles crash deaths and injuries for children and adolescents; and how to guide future restraint development to help protect them in shared mobility, while still ensuring protection in more traditional riding scenarios. Focusing on booster-seated children, the key safety concept that emerged from the discussions was the need to message that a booster is an adapter, not a restraint! And second, the importance to reorient the consumer to how a booster works, driving simple solutions that positively impact safety as well as the other key characteristics of accessibility and affordability. To acknowledge the real-world evidence and experience, and adhere to demonstrated protection principles, in addition to acknowledge that the car’s protection will help protect the booster-seated child as well. Hence the booster’s main purpose is to complement with the child specific needs, i.e., to elevate the child in position for the seat belt. The protective performance of a well-designed booster cushion is well established, and there is evidence that booster cushions as well as integrated boosters are relatively more used among the older child age group. Adapting these to the protection needs of booster-seated children and making them portable, focusing on size and weight while still adhering to the protection principles, will help keep children safe. It was emphasized that the journey towards increased safe shared mobility, being an enabler for a more sustainable and accessible transport system, is a collaborative task by all involved stakeholders. Vehicle manufacturers, as well as the booster manufacturers and the users, in addition to rulemaking and organizations influencing the design, such as consumer information testing, need to work together and be aligned towards the common goal of sustainable and safe transportation.

DISCUSSIONS

Assessment of passenger safety in future cars involves evaluation of protection beyond current standardized crash testing and ATDs. Real-world car passenger protection needs require knowledge on aspects important for the diverse population and tools that can reflect these aspects. It also requires abilities to assess the arise of potential injury mechanisms when introducing new seating possibilities. With increased automation and shared mobility services, capabilities are needed to consider pre-crash events as part of the occupant protection assessment, as well as understanding the context of restraint usage, passengers’ activities in the car, and the influence of potential add-on features such as boosters. The challenges are many, and the research area is wide. The foundation of this research project was to combine multiple competencies, international collaboration and a range of studies using different methods and tools. The project’s agile and knowledge-sharing way of working – by adapting parts of the research to current topics and inviting researchers in dialogues - has inspired additional research initiatives by other research groups. Although some of the research project’s studies were small in size, though pioneering within the area, they have helped to raise awareness, and to provide inspiration for, e.g., the large-scale car passenger observation study by UMTRI (Reed et al., 2020) and the world first reclined PMHS tests performed with the purpose to generate validation data to HBMs (Richardson et al., 2020b).

Challenging passenger protection needs in current and future cars include protection of the heterogenous population in new seat positions and sitting postures. This requires tools that can address the kinematics, the interaction with the restraint system, and potentially new injury mechanisms arising. In addition, the tools need to be capable of including the pre-crash event as part of the occupant protection assessment. Restraint principles for adults in reclined seat position were investigated, along with an evaluation of the capabilities of the assessment tools. The adult HBMs of varied sizes, ages and sex provided enhanced insights into passenger protection assessment compared to the limited sizes of ATDs. Novel studies predicted representative crash configurations when future crash interventions were applied, suggesting that there will likely be a large share of intersection related crash configurations whereby emphasizing the need of tools capable of omnidirectional kinematics and injury predicion. Studies with PIPER6y, with its more humanlike capabilities for real-world assessment as compared to the child ATDs, emphasized the car/booster/user entity for the protection of booster-seated children. Unfortunately, this is not how boosters are developed and assessed today. In some parts of the world, booster cushions are banned as a consequence of the regulatory test setups. In addition, booster seats are growing in size and complexity, driven by simplified test methods without taking into account the protective contribution by the car in a real-world crash. This leads to a problematic situation for children in future crashes, especially considering the users' need for easy access in shared mobility services (Jakobsson et al., 2023).

In order to gain knowledge on car passengers' sitting postures and beltfit, a number of studies were conducted using different methods. They included observation studies on car passengers in current cars, and novel methods to predict seating preferences in future cars with new seating configurations. Studying car passengers in current cars, it was obvious that passengers' self-selected postures deviated from standardized ATD positions. Several observation studies highlighted the influence of body shape on initial beltfit. There are many dimensions of body shape influence, which all should be explored further. The influence of comfort experience should also be further explored, gaining insights on favorable beltfit and sitting postures, which thereby can be used to help guide or nudge the passengers into safely designed contexts. A driving study provided insights into how shoulder-belt positions for some front seat passengers varied in everyday traffic. During turns, the passengers moved laterally, in some cases resulting in head off the head restraints. Prior studies have shown that during evasive braking events, front seat passengers (Ólafsdóttir et al., 2013) moved further forward as compared to drivers (Östh et al., 2013). The larger movements of passengers as compared to drivers is one reason to focus on car passengers. Another reason is that future car usage will include a larger share of ride sharing and eventually unsupervised AD, resulting in a larger share of non-drivers. Passenger protection also includes addressing a larger span of ages, as well as a rear seat environment. Compared to younger adults (aged 25-30), a lower safety awareness among older adult front seat passengers (aged 72-81) was observed in one of the studies. This had implications on using available adaptivity in the seat and seat belt to explore the possibilities of improved beltfit. In a rear seat study on children aged 10-17 years old, different design concepts were explored, targeting to encourage comfortable and safe sitting postures, while being engaged in various activities.

Adding to the understanding on how existing tools can help address the real-world needs for passenger safety assessment, testing and simulations studies on both adult and child ATDs and HBMs were executed. The studies on novel adult ATDs provided insights into their capabilities of representing challenges in future transportation, but also raised concerns on their biofidelity. This has triggered recent studies at University of Virginia (Shin et al., 2022) in which the HIII-50M and THOR-50M ATDs were compared to identical test conditions as the reclined PMHS test by Richardson et al. (2020b). It was concluded that both the HIII-50M and THOR-50M exhibited overall comparable responses to the PMHS. However, magnitudes and even directions of the pelvis kinematic varied between the ATDs and the PMHS. These findings have initiated new research to improve the biofidelity of THOR-50M when in reclined posture within the newly formed Research Consortium for Crashworthiness in Automated Driving Systems (RCCADS). In another test series, the novel small-sized female THOR-5F (Figure 8a) was shown to replicate the kinematics of the mid-size male counterpart THOR-50M in an upright seat position, which differed from the HIII counterparts (Carroll et al., 2021). In future passenger car interiors, such as face-to-face seating configuration, knee restraints are less likely to be included. Further studies on this topic are ongoing, partly in collaboration between project partners and universities in the USA. Such research is essential to ensure that the ATDs used for reclined seat positions are biofidelic. The study on the Q10 supplier variants provided insights in large spread in responses depending on supplier, showing the urgent need for improved and more detailed specifications of ATDs to ensure repeatability, no matter supplier.

The family of morphed HBMs that represents the population variability in body shape due to sex, height, weight, and age variations is useful in the design of future cars and safety systems targeting increased safety for all passengers. The validation of morphed SAFER HBMs showed that the morphed HBMs provided good predictions of in-crash kinematics (Larsson et al., 2021a). Crash database analyses indicated that females, elderly, and obese car occupants were at increased injury risk (Larsson, 2020). These subpopulations need further consideration in the design of crash safety features. Using morphed HBMs may have the potential to reveal injury mechanisms in a way that is not possible by only considering the standardized ATD sizes. Continued developments of morphed SAFER HBMs, as well as methods to incorporate passenger variability through morphed HBMs are ongoing. The choice of the target population to be represented by morphed HBMs was based on the height and weight variability existing for males and females in the general population. Acknowledging the extent of population variability, and also enabling representation of this variability in crash safety evaluations through morphed HBMs are important steps to enable improved crash safety for all passengers.

This comprehensive research project provided input to safety system development, ATD and HBM designs, assessment methods development, and future research challenges. Addressing the challenges of protection assessment of the heterogeneous passenger population in future car crashes requires multidisciplinary and collaborative research and a multitude of methods, such as an iterative work of user-studies and crash testing/simulations. By studying current passengers, complemented with prediction studies on future situations of crashes and passenger car interior designs, the derived results may also contribute to safety developments addressing future cars. The inclusions of the heterogeneous population into more advanced tools such as HBMs are essential, acknowledging that when moving closer to "zero injuries", the situations to address are more unique and specific. Although a range of studies using different methods were included in this research project, many challenges still remain to cover the scope of passenger safety in future cars.

CONCLUSIONS

The importance and complexity of passenger protection in cars increase with a higher degree of automation and shared mobility. The population is becoming older, and the diversity in passenger sizes is growing. This, in addition to new seat positions, seating configurations, as well as car usage and ownership, requires assessment tools and evaluation methods beyond the current standardized crash test methods. The presented research project has contributed to advancements of assessing the protection of the heterogeneous population of passengers in future car crashes, by gathering a variety of competencies, combining different types of methods and performing international collaboration.

As examples, passenger protection needs were studied through observation studies on passenger sitting postures and beltfit in combination with simulation and sled test series. The importance of body shape was highlighted for older adults, while the influence of booster design was raised for children. Restraint principles for adults in reclined seat positions were investigated as well as evaluation of the capabilities of the assessment tools (i.e., ATDs and HBMs). Applying the protection principles to new seating configurations and seat positions is challenging and will require more advanced tools. Novel studies predicted future crash configurations and seating preferences, contributing to new insights on challenging passenger protection needs in current and future car crashes. In addition, a methodology was developed for the selection of representative individuals for crashworthiness assessment, addressing the heterogeneous population. Morphing techniques were established, and a family of morphed HBMs was created and prepared for use in car and safety system developments. HBMs of a variety of occupant sizes, ages and both sexes, used together with the knowledge on how they sit as passengers in cars, enhance the relevance of occupant protection assessment.

The way forward addressing the challenges of assessing protection of the heterogeneous passenger population in future car crashes is a collaborative work. There is a need to further explore car passenger positions and variations of sizes, shapes and postures as well as to develop means to assess real-world occupant to restraint interactions in a multitude of scenarios. A variety of methods and competencies, as well as iterative cooperation of user-studies and crash testing/simulations are required. Population heterogeneity needs to be reflected by more advanced tools, such as HBMs, to accurately assess restraint interaction – a pressing passenger protection need.

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REFERENCES

Blue text indicates that the publication is part of the project.

Ankartoft R, Alfredsson S. Elderly passengers in cars – Study of beltfit and comfort, *Master Thesis in Industrial Design Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2018

Arbogast K, Boström O, Jakobsson L, Fildes B. Setting the Future Agenda for Child Occupant Protection: Results from a Workshop in Prato, Italy. *9th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2011

Arbogast KB, Bohman K, Stockman I, Jakobsson L. Child occupant protection: Latest knowledge and future opportunities – Results of a workshop in Gothenburg, Sweden. *11th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2013

Arbogast K, Bohman K, Brolin K, Jakobsson L. Child occupant protection: latest knowledge and future opportunities. *13th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2015

Arbogast KB, Bohman K, Jakobsson L. Protecting children and youth in cars: highlighting non-nominal cases and the user experience, *15th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2017

Arbogast K, Jermakian J, Bolte J, Jakobsson L, Bohman K. A safety framework for evolution of booster seats; current and future mobility, *20th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2022

Beillas P, Giordano C, Alvarez V, Li X, Ying X, Chevalier M-C, Kirscht S, Kleiven S. Development and performance of the PIPER scalable child human body models. *14th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2016

Berntsson J. A Parametric Study of Shoulder belt Interactions with the PIPER Scalable Child Human Body Model in Frontal and Frontal Offset Impacts, *Master Thesis in Biomedical Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2018

Bohman K, Stockman I, Jakobsson L, Wimmerstedt M, Kruse D, Sundmark H. A comparison of Q10 update and current Q10 dummies in frontal and side impact sled test. *16th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2018

Bohman K, Stockman I, Jakobsson L, Wimmerstedt M, Kruse D, Sundmark H. Q10 Euro NCAP 2020 update dummies compared to current Q10 in frontal and side impact sled tests, *Proc. of 26th Int. ESV Conf.,* Paper Number 19-0295, Eindhoven, the Netherlands, 2019a

Bohman K, Osvalder AL, Ankartoft R, Alfredsson S. A comparison of seat beltfit and comfort experience between older adults and younger front seat passengers in cars, Presented at *AAAM Conference*, Madrid, Spain; *Traffic Inj Prev*. 15, Aug 2019b:1-6

Bohman K, Östh J, Jakobsson L, Wimmerstedt M, Wallin H, Wass J. The influence of booster cushion design on child kinematics and loading, using the PIPER model and the Q10 in frontal impacts, *17th Int. Conf. Protection of Children in Cars,* Munchen, Germany, 2019c

Bohman K, Jakobsson L, Nurbo P, Olander A, Andersson A. Lateral movement of front seat passengers in everyday traffic, *IRCOBI Conf.*, IRC-20-53, 2020a

Bohman K, Östh J, Jakobsson L, Stockman I, Wimmerstedt M, Wallin H. Booster cushion design effects on child occupant kinematics and loading assessed using the PIPER 6y HBM and the Q10 ATD in frontal impacts, Presented at *AAAM Conference*, *Traffic Inj Prev*. 2020b, DOI: 10.1080/15389588.2020.1795148

Bohman K, El-Mobader S, Jakobsson L. Effects of restraint parameters using PIPER 6y in reclined seating during frontal impact, *Traffic Inj Prev*. 2022 Oct 10;1-7

Bolte IV J, Arbogast KB, Bohman K, Jakobsson L. Child occupant protection: Autonomous driving systems, *17th Int. Conf. Protection of Children in Cars*, Munchen, Germany, 2019

Boyle KJ, Reed MP, Zaseck LW, Hu J. A human modelling study on occupant kinematics in highly reclined seats during frontal crashes. *IRCOBI Conference*, IRC-19-43, Florence, Italy, 2019

Blennow A, Improvement of Human Body Model Rib Fracture Risk Prediction - Creation of injury risk curves and rib cortical bone regression models for age adjusted risk prediction. *Master thesis in Biomedical Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2020

Brolin E, Högberg D, Hanson L. Description of boundary case methodology for anthropometric diversity consideration. *Int. J. of Human. Factors Modelling and Simulations* 3, 2012:204–223, https://doi.org/10.1504/IJHFMS.2012.051097

Carroll J, Kruse D, Mishra E, Mroz K, Lubbe N. Comparison of Hybrid III and THOR 5th percentile female dummies in frontal crash tests, *IRCOBI Conf.*, IRC-21-26, online, 2021

Daouacher M. Evaluation of occupant kinematics in crash using the PIPER model, in frontal and oblique crash simulations, *Master Thesis in Mechanical Engineering*, Karlstad University, Karlstad, Sweden, 2019

Eggers A, Ott J, Pipkorn B, Bråse D, Mroz K, Lopez Valdes F, Hynd D, Peldschus S. A new generic frontal occupant sled test set-up developed within the EU-project SENIORS. *Proc. of 25th Int. ESV Conf.,* Paper No. 17-0261, Detroit, USA, 2017

El-Mobader, S. Effect of Lap Belt Position on Kinematics & Injuries by using 6YO PIPER child HBM - in Frontal Crash Simulations, *Master Thesis in Science in Mechanical and Material Engineering*, Karlstad University, Karlstad, Sweden, 2018

Fong CK, Keay L, Coxon K, Clarke E, Brown J. Seat belt use and fit among drivers aged 75 years and older in their own vehicles. *Traffic Inj Prev.* 17:2*, 2016*

Gereben M, Swenson M. Youths as passengers in cars - A behavioural study on user experience and safety, *Master Thesis in Industrial Design Engineering and Product Development*, Chalmers University of Technology, Göteborg, Sweden, 2020

Hagberg A, Jodlovsky S. Reclined seating positions for level 4 HAD vehicles - a comfort and safety approach, *Master Thesis in Industrial Design Engineering,* Luleå University of Technology, Luleå, Sweden, 2017

Hansson A, Lysén E. A study of sitting posture and beltfit in a travelling car- How do passengers sit in a travelling car? *Master Thesis in Automotive and Biomedical Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2019

Howes M K, Hardy WH, Agnew MM, Hallman JJ. Evaluation of the kinematic response and potential injury mechanisms of the jejunum during seatbelt loading. *Stapp Car Crash J.* 59, 2015:225–67

Jakobsson L, Isaksson-Hellman I, Lundell B. Safety for the growing child – Experiences from Swedish accident data. *Proc of 19th Int. ESV Conf.*, Paper No. 05-0330, Washington DC, USA, 2005

Jakobsson L, Bohman K, Andersson M, Stockman I, Boström O, Svensson M, Svanberg H, Wimmerstedt M, Arbogast KB. Rear Seat Safety in Frontal to Side Impacts – Focusing on Occupants from 3yrs to Small Adults. *Proc. of 22nd Int. ESV Conf.*, Paper No. 11-0257, Washington DC, USA, 2011

Jakobsson L, Bohman K, Svensson M, Wimmerstedt M. Rear seat safety for children aged 4-12: Identifying the real-world needs towards development of countermeasures, *Proc. of 25th Int. ESV Conf.,* Paper No. 17-0088, Detroit, USA, 2017

Jakobsson L, Bohman K, Svanberg B, Victor T, Occupant protection for AD cars – The paradigm shift in crash safety? *Proc. of 26th Int. ESV Conf*., Paper No. 19-0281, Eindhoven, The Netherlands, 2019

Jakobsson L, Bohman K, Stockman I, Simmons S, Johansson C. Booster cushions for shared mobility, *18th Int. Conf. Protection of Children in Cars*, online, Dec 2020

Jakobsson L. Bohman K. Stockman I. Real-world protection of booster-seated children – needs and challenges in future transportation, *Proc. of 27th Int. ESV Conf.,* Paper No.23-0187, Yokohama, Japan, 2023

Janson M, Wedmark J. Investigation of methods for quantifying sitting postures in cars – a study focused on pelvic orientation for improved safety assessment, *Master Thesis in Ergonomics for Engineers and Product Development*, Lund University, Lund, Sweden, 2018

Jorlöv S, Bohman K, Larsson A. Seating positions and activities in highly automated cars – A Qualitative study on future automated driving scenarios, *IRCOBI Conf.*, IRC-17-11, Antwerp, Belgium, 2017

Larsson K-J. Evaluation of Morphed Human Body Models for Diverse Occupant Safety Analysis, *Thesis for the degree of Licentiate of Engineering in machine and vehicle systems*, Dept of Mechanics and Maritime Sciences, Division of Vehicle Safety, Chalmers University of Technology, Göteborg, Sweden, 2020

Larsson K-J, Pipkorn B, Iraeus J, Forman J, Hu J. Evaluation of a Diverse Population of Morphed Human Body Models for Prediction of Vehicle Occupant Crash Kinematics, *Computer Methods in Biomechanics and Biomedical Engineering,* 25(10), 2021a https://doi.org/10.1080/10255842.2021.2003790

Larsson K-J, Blennow A, Iraeus J, Pipkorn B, Lubbe N. Rib cortical bone fracture risk as a function of age and rib strain: Updated injury predictions using Finite Element Human Body Models. *Front. Bioeng. Biotechnol. Biomechanics,* 2021b https://doi.org/10.3389/fbioe.2021.677768

Lubbe N, Jeppsson H, Ranjbar A, Fredriksson J, Bärgman J, Östling M. Predicted road traffic fatalities in Germany: the potential and limitations of vehicle safety technologies from passive safety to highly automated driving, *IRCOBI Conf.*, IRC-18-11, Athens, Greece, 2018

Makris M. Seating and Driver Interactions in Automated Vehicles: Development of a User Study Investigating Seating Positions and HMIs. *Master Thesis in Biomedical Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2020 https://hdl.handle.net/20.500.12380/301045

Makris M, Osvalder A-L. Experimental Setup for Assessing Drivers' Experiences of Reclined Sitting Posture in Automated Vehicles. *Proc.: AHFE 2022 Int. Conf. on Applied Human Factors and Ergonomics, New York. Advances in Transportation,* Vol. 60, 2022:1–10. doi: 10.54941

Ólafsdóttir JM, Östh JKH, Davidsson J, Brolin K. Passenger Kinematics and Muscle Responses in Autonomous Braking Events with Standard and Reversible Pre-tensioned Restraints. *IRCOBI Conf.*, Gothenburg, Sweden, 2013

Olander A, Andersson A. How lateral movement affects front seat passengers – a user study during normal drive in three phases identifying improvement areas, *Master Thesis in Industrial Design Engineering*, Chalmers University of Technology, Göteborg, Sweden, 2019

Osvalder Al, Bohman K, Lindman M, Ankartoft R, Alfredsson S. Seat Beltfit and Comfort for Older Adult Front Seat Passengers in Cars, *IRCOBI Conf.*, IRC-19-12, Florence, Italy, 2019

Park J, Ebert SM, Reed MP, Hallman JJ. Effects of Occupant and Vehicle Factors on Three-Point Beltfit in Rear Seats. *IRCOBI conference*, IRC 16-92, Malaga, Spain, 2016

Pettersson I, Karlsson M (2015). Setting the stage for autonomous cars: a pilot study of future autonomous driving experiences. *IET Intell Transp Syst*. 9(7), 2015:694-701

Reed MP, Ebert-Hamilton S, Klinich KD, Manary MA, Rupp JD, Assessing Child Beltfit, Volume I: Effects of Vehicle Seat and Belt Geometry on Beltfit for Children with and without Belt Positioning Booster Seats, *UMTRI-2008-49-1, NHTSA*, 2008

Reed MP, Ebert SM, Rupp J D. Effects of obesity on seat beltfit. *Traffic Inj Prev.* 13, 2012:364–372

Reed M, Ebert S, Jones M, Hallman J. Prevalence of non-nominal seat positions and postures among front-seat passengers, *Traffic Inj Prev.*, 2020, DOI: 10.1080/15389588.2020.1793971

Richardson R, Jayathirtha M, Chastain K, Donlon J-P, Forman J, Gepner B, Östling M, Mroz K, Shaw G, Pipkorn B, Kerrigan J. Thoracolumbar spine kinematics and injuries in frontal impacts with reclined occupants, *Traffic Inj. Prev.*, 21:sup1, 2020a:S66-S71, DOI: 10.1080/15389588.2020.1837365

Richardson R, Donlon JP, Jayathirtha M, Forman J, Shaw G, Gepner B, Kerrigan J, Östling M, Mroz K, Pipkorn B. Kinematic and Injury Response of Reclined PMHS in Frontal Impacts, *Stapp Car Crash Journal*, 64, 2020b

Simmons S, Johansson C, Booster cushion for shared mobility; The development of two new portable booster cushions. *Master Thesis in Product Development*, Chalmers University of Technology, Göteborg, Sweden, 2020

Shin J, Donlon JP, Richardson R, Gepner B, Forman J, Östling M, Kerrigan J. Biofidelity Evaluation of the Hybrid-III 50th Male and the THOR-50M in Reclined Frontal Impact Sled Tests. *IRCOBI Conf.*, IRC-22-48, Porto, Portugal, 2022

Tylko S, Tang K, Giguère F, Bussières A. Effects of shoulder-belt slip on the kinetics and kinematics of the THOR. *IRCOBI Conf.*, Athens, Greece, 2018

Wang ZJ, Fu S, MCinnis J, Arthur J. Evaluation of novel design to address the shoulder-belt entrapment for THOR-50M ATD, *IRCOBI Conf.*, IRC-19-93, Florence, Italy, 2019

Östh J, Ólafsdóttir JM, Davidsson J, Brolin K. Driver Kinematic and Muscle Responses in Braking Events with Standard and Reversible Pre-tensioned Restraints: Validation Data for Human Models. *Stapp Car Crash Journal*, 2013, 57:1–41

Östling M, Kock H-O, Sunnevång C; Potential future seating positions and the impact on injury risks in a Learning Intelligent Vehicle (LIV), *VDI-Tagung Fahrzeugsicherheit*, Berlin, Germany, Nov 29, 2017

Östling M, Driver behaviour in automated vehicles and effects on safety. *3rd International VDI Conference, Safety Systems - The Impact of Automated Driving on Occupant Protection*, Dusseldorf, Germany, May 16–17, 2018

Östling M, Puthan P, Jeppsson H, Lubbe N, Sunnevång C. Future passive safety needs: Predicted injury patterns and possible countermeasures. *Airbag 2000*, Nov 2018

Östling M, Larsson A. Occupant activities and sitting positions in automated vehicles in China and Sweden, *Proc. of 26th Int. ESV Conf.,* Paper No. 19-0083, Eindhoven, the Netherlands, 2019

Östling M, Lubbe N, Jeppsson H, Puthan P. Passenger car safety beyond ADAS: Defining remaining accident configuration as future priorities. *Proc. of 26th Int. ESV Conf.,* Paper No. 19-0091, Eindhoven, the Netherlands, 2019a

Östling M, Jeppsson H, Lubbe N. Predicting crash configurations in passenger car to passenger car crashes to guide the development of future passenger car safety, *IRCOBI Conf.*, IRC-19-92, Florence, Italy, 2019b

Östling M, Lundgren C, Lubbe N, Huf A, Wernicke P, Pipkorn B. The influence of a seat track load limiter on lumbar spine compression forces in relaxed, reclined, and upright seating positions: a sled test study using THOR-50M, *IRCOBI Conf.,* IRC-21-46, On-line, 2021

Östling M, Lubbe N. Load-limiting in the lap belt reduces injury risks associated with new seating positions, *International Journal of Crashworthiness*, 2022, DOI: 10.1080/13588265.2022.2109882

Östling M, Eriksson L. Simulating the Influence of Lap-belt Load Limiting on Injury Risks for Upright and Reclined Occupants with the SAFER Human Body Model, *IRCOBI Conf.,* IRC-22-117, Porto, Portugal, 2022

Östling M, Lundgren C, Lubbe N, Pipkorn B. Reducing Lumbar Spine Vertebra Fracture Risk with an Adaptive Seat Track Load Limiter. *Front. Future Transp.* 3:890117. 2022, doi: 10.3389/ffutr.2022.890117