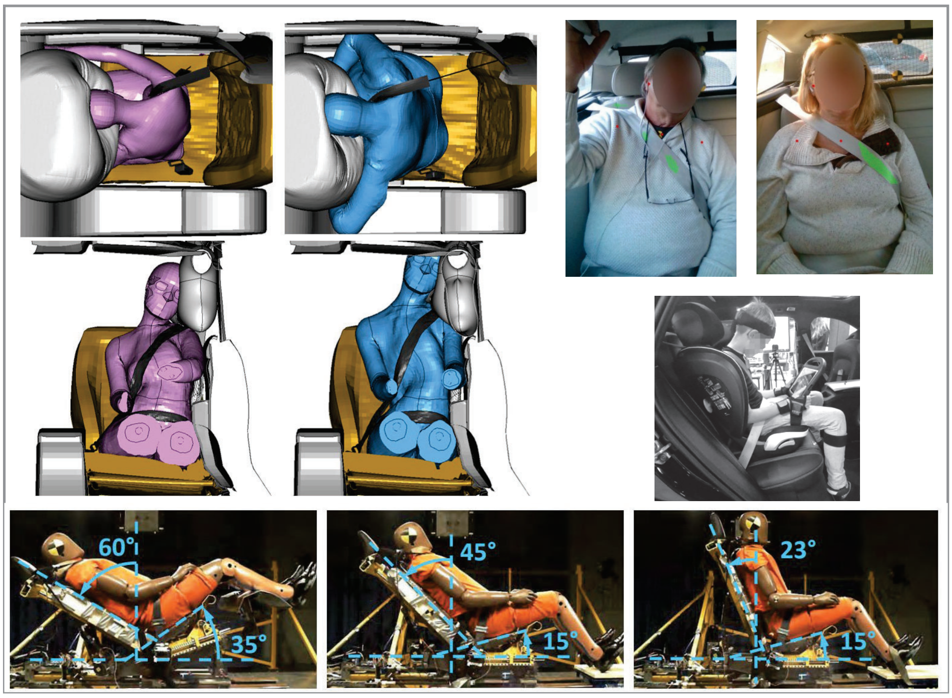
Car Passenger Safety – to the Next Level

Passagerarsäkerhet i bil – till nästa nivå

FFI 2020–02943



Authors: Lotta Jakobsson, Katarina Bohman, *Volvo Cars*
Karl-Johan Larsson, *Autoliv*
Anna-Lisa Osvalder, Melina Makris,
Johan Iraeus, Mats Svensson, *Chalmers*

Date: 2024-07-04

Project within: Trafiksäkerhet och automatiserade fordon

FFI Fordonsstrategisk Forskning och Innovation

Content

1 Summary

Protecting passengers in cars requires the use of seatbelts. Although most passengers are restrained today, some are not, and some are not optimally restrained. Those individuals are thereby exposed to higher injury risks in case of a crash. In line with the future mobility services, the challenges are even more pronounced, exemplified by availability of boosters for children in shared mobility, and automated driving cars with a larger spread in seat positions and self-selected postures, such as reclined. Hence there is a need to enhance knowledge on passengers' variations in size, perceptions, sitting postures and beltfit, as input to restraint developments, in addition to assessment tools and evaluation methods beyond the current standardized crash test methods. This research project, ongoing from November 2020 to June 2024, has taken knowledge and tools needed for car passenger safety assessment to the next level, focusing on restraint interaction.

This was achieved by combining expertise from industry and academia with multiple competencies, involving senior researchers as well as doctoral and master students, besides international collaboration. Several diverse studies have been packaged together to address the challenges of car passenger heterogeneity. These include user studies to study car passengers while traveling or just seated in the car; assessment studies on novel crash test dummies (Anthropomorphic Test Devices, ATDs), development of a morphing method for a Human Body Model (HBM), and crash tests and simulations to investigate different protection principles.

The learnings from the user studies include a greater understanding of passengers' sitting postures, beltfit, movements, comfort experiences and attitudes, to be used as input to restraint developments. It is clear that not just differences in sizes, but also body shapes influence beltfit and that perceptions, behavior and activities influence sitting posture. Specifically, the focus on comfort aspects and what drives different behaviours are essential learnings to be used for seat design, in addition to seatbelt positions and adjustment possibilities. By understanding discomfort, adaptions can be made to improve comfort, in addition to being used as means for guiding towards preferred protective positions. In a booster-seated child study, the understanding of postures driven by behavior was evident, such as forward leaning due to engagement in electronic devices. This is an aspect not included in crash protection assessment today.

Moving from a limited part of the population being included in standardized crash assessments today, the project has provided a method to morph the SAFER HBM to represent women and men of a wide range of size, shape and age. Simulation series have given learnings on important occupant factors that need to be included in a safety assessment for the protection of the adult population. A method on how to include this into crash assessment was developed and demonstrated in a study with individuals representing a 90% envelop of height and weight for both women and men.

The results from the project have provided input to safety system development, ATD/HBM design, upgraded assessment methods and several identified research challenges for future work. Specifically, there is a need to further explore the passenger interaction with the restraint system in terms of seat positions and variations in body sizes, shapes and postures. In addition, comfort aspects were included as a way to enhance usability and thereby also safety. Reflecting this in crash assessment, the inclusion of the heterogeneous population into more advanced tools such as HBMs is crucial. Although the current project has taken knowledge and tools for passenger safety assessment to the next level, several challenges remain to cover the entire scope of passenger safety in future cars. This is further emphasized when moving closer to "zero injuries" and the situations to address are more unique and specific.

2 Background

Although most passengers use seatbelts today, not all of them do. It is undisputed that unrestrained passengers are exposed to a relatively higher risk of being injured in a crash. Likewise it is a fact that how the belt is positioned may affect the injury risk. Protecting passengers in cars is essential when targeting “zero injuries” in traffic. This becomes even more challenging with the transition towards automated driving (AD) and a higher degree of car sharing and ride sharing (Jakobsson et al., 2019). In addition, in unsupervised AD the driver becomes a passenger too. Car sharing and increased use of taxis and other ride sharing call for attractive, effective, comfortable, and safe protection systems, customized for a wide range of ages, sizes, seat positions and seating configurations. In addition, automatic collision mitigation systems, such as automatic braking and / or steering will influence the pre-impact kinematics and the crash configurations, adding demands to the restraint interaction.

In the future, car passengers are expected to choose their seat position and sitting posture with even more freedom than today, resulting in a larger spread in self-selected 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) are not validated and therefore may not be biofidelic. Besides this, the influence from sitting postures and beltfit on the occupant protection is not yet fully understood.

The initial position of the shoulder and lap belt over the body (beltfit) is highly related to the seat position and the passenger’s posture, shape, and anthropometry. The aging part of the population is increasing, and besides the greater fragility and frailty in this group, there are challenges with respect to the lap belt position (Fong et al., 2016). Similar challenges are also seen for obese passengers, for whom the abdomen influences the lap belt to a high position relative to the pelvis (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. The smallest children are optimally protected using rearward facing child seats, while children from approximately 4 years of age can use the car’s seatbelt (Jakobsson et al., 2005). However, these children need to use belt-positioning boosters to adapt to the seatbelt (Reed et al., 2008). With increased usage of car sharing and ride sharing, it will require flexible and easy-to-use solutions for children in order to maintain a high usage rate and best possible protection.

Tools for car passenger protection assessment are mainly ATDs and virtual HBMs. ATDs are available as physical tools, and they have virtual counterparts. They are available in a limited number of sizes and do not reflect the great variety in body shapes that we see in the human population. HBMs, being more anatomically similar to humans, have greater potential to represent human kinematics in all impact directions. In addition, they can represent a much wider range of anthropometries of both sexes and of varying age groups. They also have the potential to predict injury risk at the organ or tissue level and to recreate more humanlike interactions with the car interior, 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.

The current project followed on the prior project “Assessment of passenger safety in future cars” (FFI 2017-01945), utilizing various methodologies and protection principles of applied research to address this wide topic (Jakobsson et al., 2017 and 2023a). In the current project, the inclusion of the comfort perspective has been more pronounced as a tool in the toolbox to identify the synergy between safe and comfortable seating in cars.

3 Purpose, Research Questions and Methods

With the purpose to enhance protection of the heterogeneous population in a variety of sitting postures, seat positions and seat configurations, in case of a crash, the overall goal was to create new knowledge and develop assessment tools and methods for real-world shoulder and lap belt interaction for car passengers (aged 4 and older). The overall goal is large and diverse. This is motivated by the fact that it is essential to have a holistic view; covering the variety of influencing factors, due to the complex interaction between user characteristics and behavior and vehicle safety systems.

To narrow the scope of the project, the following Research Topics and combinations of them, were focused:

A. The self-selected sitting postures and effects from car travelling dynamics; focus on beltfit and investigation of influencing factors, including comfort aspects as means to help guide the beltfit.

B. Beltfit in the context of the challenges in the mobility trends and increased variety of postures and seat positions, including need of adaptations for specific groups of passengers, e.g. children.

C. Development of a family of adult HBMs and investigation of their capability to represent a range of the heterogeneous population, and the identified crash context for use.

D. State-of-the-art HBMs and ATDs to evaluate protection principles for the heterogeneous population in the different restraint interactions, focusing on the most advanced versions of HBMs.

The project was a collaborative project involving two PhD students and more than 18 senior researchers from the academy and industry. Several diverse studies have been packaged together to address the challenges of car passenger heterogeneity. These include user studies in cars to study sitting posture, beltfit, kinematics, comfort, experiences and attitudes; assessment studies on novel ATDs, development of a morphing method for the SAFER HBM (Pipkorn et al., 2023), and crash tests and simulations to investigate different protection principles.

3.1 User Studies

With the overall purpose to provide input to protection strategies for passenger-to-restraint interaction, user studies were executed to explore car passengers' preferences in sitting postures, their movements and beltfit. Subjective and objective data was combined, and methods were developed to enhance efficiency in data collection and analyses. This research not only may improve current types of passenger cars, but also explores future transportation modes considering both adults and children. A variety of individual differences (such as sex, age and body constitution) and differences in types of set-ups (stationary and driven) were included with the aim to identify how passenger characteristics and context can influence sitting posture and beltfit.

One method development study addressed automatic quantification of sitting posture and shoulder beltfit of film data, as shown in Figure 1a (Hartleitner et al., 2022). Another study explored the influence of time and study-scenario for sitting posture, beltfit and comfort, by exposing 19 participants (ten females, nine males, average age 45 years) to two test scenarios (Makris et al., 2023 and 2024c, and Makris, 2023). Additionally, the study sought to investigate whether comfort perceptions could be predicted through the analysis of video recordings. The participants were seated in the rear seat and experienced one stationary scenario in which the car remained stationary in an indoor garage, and one driven scenario in which the car was driven in a predefined route in regular traffic. Both scenarios lasted for 45 minutes each. A mixed methods approach was used, collecting both video recordings, questionnaires, and interview data. The video data was collected to enable describing the various postures and beltfit that participants adopted. The subjective data was collected to identify when discomfort occurs and where in terms of body region. The subjective data aimed to explain the reasons why discomfort was perceived, in terms of what it was associated with. Combining these methods resulted in a deeper understanding of participants' behaviours and factors influencing the sitting postures, beltfit and comfort experiences.

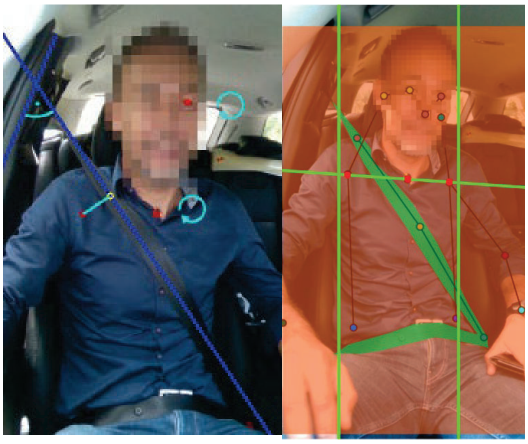


Fig. 1a. Test person in study by Hartleitner et al., (2022), showing the automatic quantification of posture and shoulder beltfit analysis.

Fig. 1b. Test person in study by Baker et al. (2023a), showing posture when using an eletronic device.

With the purpose to provide a holistic model of overall ride comfort aspects in cars, Makris et al. (2024b) analyzed two empirical studies involving in total 48 participants. Various factors that influence the comfort experience were gathered and analyzed, including the categories of physical, psychological, and functional comfort. Another user study was conducted to explore methods for measuring posture and subjective comfort, as well as to examine the influence of seat cushion length and seat back angle on comfort, sitting posture, and beltfit for rear-seated passengers. In total 39 adults of varied sizes and 20 children were involved in this study, providing insights based on a large span of individual differences.

Parameters influencing slouching were identified and explored in a limited user study, revealing that the choice of upholstery material influenced the slouched posture, while reclined backrest had limited effect (Andreasson Persson and Larson, 2021). This was further investigated through a simulation series using the SAFER HBM to explore the consequences of slouched postures during frontal impacts (Bohman et al., 2023).

In a user study involving 25 children, detailed measurements of posture and beltfit were taken for children ranging from 103 to 146 cm in stature. The study investigated various booster design features in combination with different postures, including self-selected postures, nominal posture and postures when engaged in electronic devices (Baker et al., 2023b). An example of the posture when engaged in electronic devices is shown in Figure 1b. In addition to the children, ATDs representing 6-year-old and 10-year-old children were exposed to the same measurements. Additionally, comparisons on child posture and beltfit were made for the 25 children seated on booster cushions from the

Swedish market with available data on 26 children on booster cushions from the US market (Baker et al., 2022).

Another user study involved teenage passengers (Parenteau et al., 2021). It was conducted in two steps. The first step identified teenagers´ postures and activities during ride in one passenger car. A set of characteristic ‘non-nominal’ postures were identified. In step 2, these postures were quantified and studied in more detail while the same passenger car was stationary.

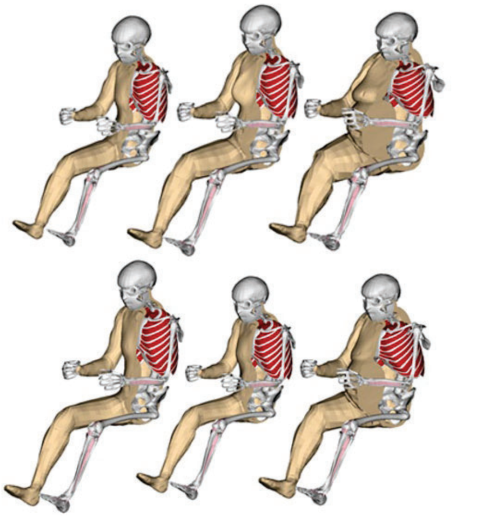
With the objective to explore drivers’ overall comfort in self-selected reclined seat positions during AD, and whether the chosen seat back angle was affected by stature, 29 participants were engaged in a user study on a test track at 30 km/h (Makris et al., 2024a). After they had experienced AD, the participants could adjust their reclined position settings according to their preference. The data collection included seat settings of upright, reclined and adjusted reclined positions, along with questionnaires and interviews regarding their comfort experience. Statistical tests of questionnaire data and seat settings, as well as thematic analysis of the interview data were performed.

3.2 Tools

Tools, including ATDs and HBMs, were assessed to explore their abilities to serve as substitutes for car passengers in a crash. Studies included assessing variations in versions of specific ATDs and their capabilities to assess novel applications, in addition to further development of morphed HBMs to represent the heterogeneous population of occupants.

Targeting a family of HBMs capable of representing the future adult population for evaluation of restraints, a morphing method was implemented for SAFER HBM v10 (Pipkorn et al., 2023), enabling representation of males and females of a wide range of heights and weights (Figure 2a). A validation database was created consisting of publicly available experiments with 19 post-mortem human subjects (PMHS), together representing a wide range of female and male sizes and ages. Using this database, a validation study was executed (Larsson et al., 2022b). The morphed HBMs predicted the in-crash kinematics of the PMHS with corresponding age and anthropometry with good accuracy. While the HBM rib fracture predictions on average were aligned with PMHS rib fractures, there were individual outcomes not predicted by the HBMs (Larsson, 2023), even when using a newly developed fracture risk function (Larsson et al., 2021), (Figure 2b). A study computing rib fracture risk for a population of passengers in both front and side crashes was performed, and it was identified that a family consisting of 25 females and 25 male HBM sizes distributed over population height and weight ranges can capture population rib fracture risk trends with good accuracy (Larsson et al., 2023b).

As rib fractures remain a prevalent injury outcome in car crashes and the morphed HBMs could not predict individual rib fracture risk in all validation cases, further studies focused on understanding population variability important for rib fracture risk beyond the sex and body size trends represented by the morphing method. Individual variability in ribcage shape (Larsson et al., 2022a), rib size, bone thickness and various material parameters were investigated. It was concluded that the population variability in rib material properties, bone thickness and cross-sectional dimensions are highly influential for risk predictions and needs to be considered for population risk assessments (Larsson et al., 2023a). These factors should also be personalized when targeting to predict the outcome of a particular individual PMHS. The aforementioned studies and publications around morphed HBMs and population rib fracture risk predictions are summarized in a PhD thesis (Larsson, 2023).



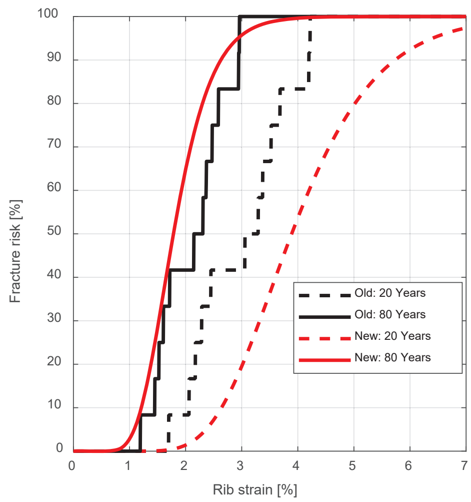


Fig. 2a. Examples of morphed versions of SAFER HBM. Three female anthropometries (top row) and three male anthropometries (bottom row).

Fig. 2b. 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 3 (Östling et al., 2021). In a following step, the mid-sized male HBM and a morphed large-sized male version were evaluated in similar conditions in a simulation study, Figure 4 (Östling et al., 2022a).

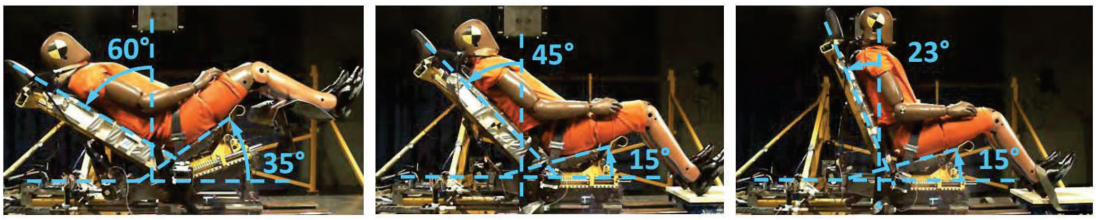


Fig. 3. THOR-50M positioned on a generic seat in the relaxed, reclined and upright seating conditions (left to right), (Östling et al., 2021).

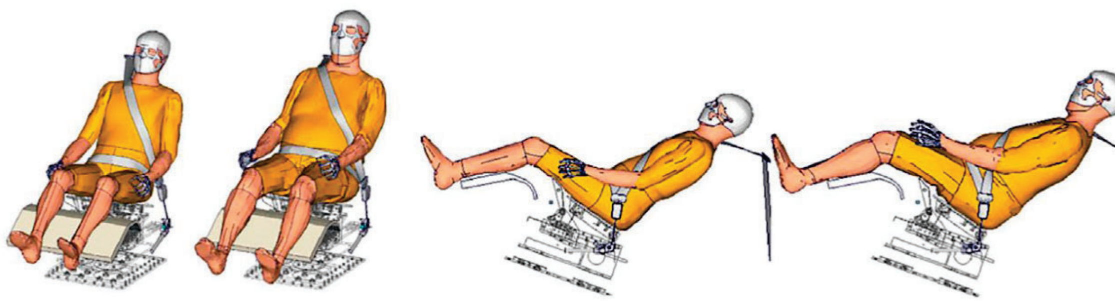
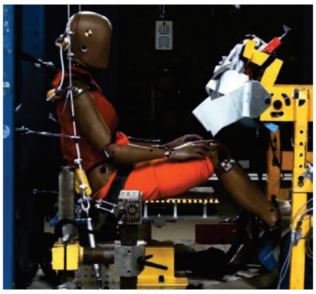
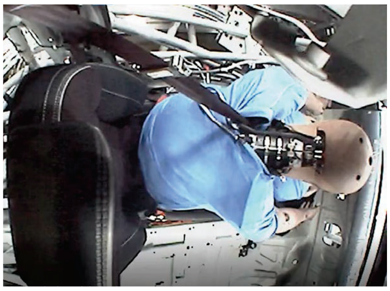


Fig. 4. SAFER HBM positioned on the generic seat. Left: front views of the mid-sized male and the large-sized male. Right: side views of the mid-sized male and the large-sized male (Östling et al., 2022a).

Frontal impact sled tests were run with the novel small-sized female THOR-5F ATD (Figure 5a), with comparative tests with the small-sized female Hybrid III-5F ATD (Carroll et al., 2021).





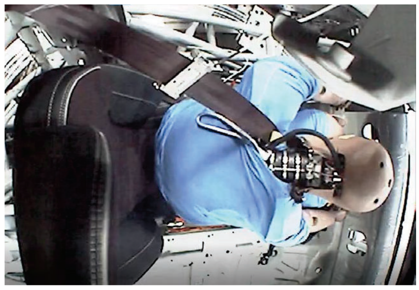


Fig. 5a. The novel small-sized female ATD, THOR-5F (Carroll et al., 2021).

Fig. 5b. Top view of shoulder belt interaction with the original THOR-50M shoulder pad, during frontal impact.

Fig. 5c. 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 frontal impact crash. The original shoulder pad (Figure 5b) was compared to updated 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), although one of them only managed to do so (Figure 5c). This study is an example of the importance of understanding the influence of the dummy's design on shoulder belt interaction during a crash, improving the assessment methods towards more human and real-world like.

3.3 Assessment of Protection Principles

Physical sled tests and virtual simulations were performed to investigate principles of car passenger protection using different ATDs and HBMs in non-nominal conditions. The studies included variations in seat position, sitting postures, seatbelt routing and features, in addition to booster design for the children. In addition some volunteers were used to assess repositioning av the seatbelt. Some examples, illustrating the spread in applications, are provided.

Adult Passenger Protection

Several series of sled tests and simulations were performed with the purpose to study adult occupant retention in novel seat positions (e.g., reclined) exposed to frontal impacts. They investigated 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., 2021, Östling et al. 2022a, Östling and Lubbe, 2022, Östling and Eriksson, 2022). Figure 6 shows the influence of a seatbelt system including double lap belt load limiter to the occupant kinematics in a frontal sled series using the mid-sized male Hybrid III 50M ATD (Östling and Lubbe, 2022)

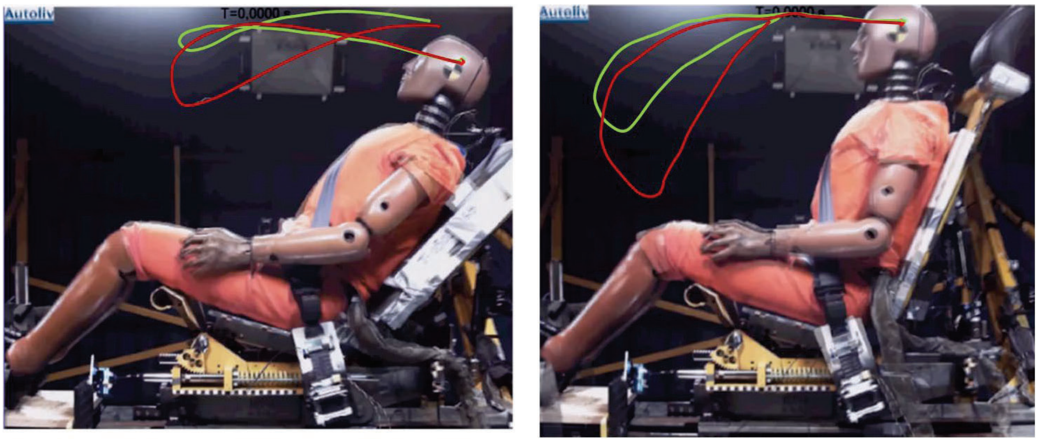


Fig. 6. Hybrid III 50M with (green line) and without (red line) double lap belt load limiter, in reclined position (left) and upright position (right). The lines show the head trajectories tracked during the test. (Östling and Lubbe, 2022).

Another study explored the influence of sitting posture on rear-end impact protection, comparing variation of forward leaning posture (pre impact positioning, Figure 7) and a whole-sequence simulation of braking followed by a rear-end impact (Jakobsson et al., 2021). Activation of seatbelt pretensioner during the pre-impact braking helped to reduce the responses during the following rear-end impact, which could be assessed in the whole-sequence simulations.

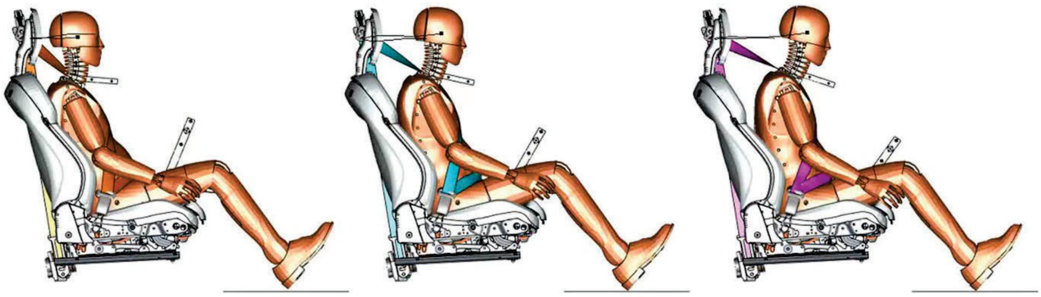


Fig. 7. Pre impact positioning, influence of backset 35, 130 and 200mm, during a rear-end impact.

A study involving 35 volunteers sitting in a stationary car seat was done with the purpose to investigate whether off-shoulder seatbelt positions could be repositioned to an on-shoulder position by triggering of a pre-pretensioner. The influence of location of belt attachments points as well as differences in body shape was in focus (Eliasson and Bohl, 2023).

Child Passenger Protection

With the purpose to explore the challenges for booster-seated children in reclined seat positions, a simulation study was run using the PIPER HBM, representing a 6-year-old sized child (Bohman et al., 2021 and 2022a). Three different booster types were used, varying pretensioner activation, attachment to the ISOFIX anchorages and shoulder belt outlet positions.

A simulation study using both the PIPER HBM and Q6 (a 6-year-old sized ATD) explored the impact of a support leg on the protection of booster-seated children in a passenger car rear-seat environment (Figure 8a) (Bohman et al., 2022b).

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). Booster cushion concepts were explored in order to fulfill UN Reg. No 129 specifications, resulting in increased height of the booster cushion and at the same time offering a portable solution suitable for car-sharing and ride-sharing, while still fulfilling protection principles. The foldable booster cushion reduced the volume by 37% in compressed state, compared to user state (Figure 8b). Folding the belt guides as well could reduce size even further.

Fig. 8a. Q6 (left) and PIPER6y (right) in booster seat with support leg (Bohman et al. 2022b).

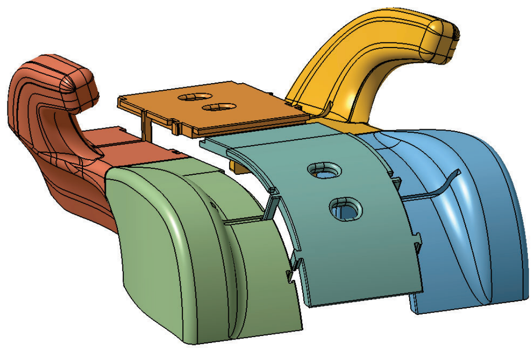


Fig. 8b. A foldable booster cushion for shared mobility (Jakobsson et al. 2020).

To emphasize and discuss the protection principles of boosters, a publication at the international conference ESV was presented with the main purpose to serve as a reflection on the developments of boosters today, and the mismatch with the needs in future mobility, such as car sharing and ride sharing (Jakobsson et al., 2023b). The target was to exemplify concerns on what the regulation and consumer information tests are pushing, and to raise a voice in trying to turn it back to more simplified design, but still adhering to the protection principles. This was also in line with the conclusions from the project's international workshop in 2022, raising the fact that the booster serves as an adapter for the child to fit into and benefit the vehicle restraints (Arbogast et al., 2022).

3.4 Dissemination

Hosted by the project team, two international multidisciplinary workshops on Child Occupant Protection were held in Sweden in September 2022 and May 2024 (Arbogast et al., 2022 and 2024). The workshops were the 7th and 8th biannual workshops on this topic. Starting in 2009, the prior workshops were hosted within prior research projects over the years and summarized by Arbogast et al. (2011, 2013, 2015 and 2017) and Bolte et al. (2019). The participants of the workshops included worldwide leaders in the fields of child passenger protection, biomechanics, and automotive safety. The overall structure for the two-day workshop included presentation on relevant topics with the focus on 'pressing issues in child and adolescent occupant protection', followed by a one-day discussion on high priority areas, as defined based on the first day's discussions. Adjacent to the workshops, and hosted by the project team and SAFER, a one-day open seminar was held in Gothenburg, Sweden, with presentations by the international researchers on current child occupant protection topics.

The two-day workshop in 2022 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 (Arbogast et al., 2022). 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. Hence the booster's main purpose is to complement with the child specific needs, i.e., to elevate the child in position for the seatbelt. 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. In 2024, the workshop focused on the role of regulations and consumer information ratings and communication to improve protection for children and adolescents in cars. Additionally, the discussions aimed to identify unbalance in current type-approval and rating methods in relation to real-world needs. More specifically, the workshop highlighted barriers to restraint use and correct use. This underscored the need for simplified, affordable child restraint designs with focus on usability to ensure increased usage. Furthermore, the use of child HBMs for evaluating occupant kinematics were identified as an essential complement to child ATDs. The discussions are summarized and are planned to be disseminated at the annual international child occupant protection conference in Munich in December 2024 (Arbogast et al., 2024), to engage further experts into the mindset of the whole context of the car, the child restraint and the user to adhere to real-world child protection.

Serving the purpose to assure optimal relevance for project execution as well as to contribute to dissemination, continuous interaction with international researchers in the field have taken place, such as contacts with UMTRI regarding the enhancement of the morphing tool, and the visiting researcher Gretchen Baker from Ohio State University, for the child user study in 2021. Dedicated workshops were held with both universities, two per each, for exchange of research results and discussions. In addition, the project partners participated and interacted in several parallel relevant projects, such as the EU projects VIRTUAL and SAFE-UP, and the FFI projects on SAFER HBM developments.

Project members are active in the ISO working group on Child Restraint Systems, the Swedish national mirror group at Swedish Institute of Standards (SIS), as well as connected to the UN work on child seat type-approval and UN IWG EqOP on Equitable Occupant Protection. Especially in the area of child seats, there has been a close interaction and several actions providing input to influence. The project results have also been discussed with consumer information programs, such as Euro NCAP and IIHS, as well as the US National Highway Traffic Safety Administration (NHTSA).

4 Objective

The objective was to create new knowledge and develop assessment tools and methods for shoulder and lap belt interaction for car passengers aged 4 and older. The purpose was to enhance protection of the heterogeneous population in a variation of sitting postures, seat positions and seating configurations in case of a crash, reflecting the real-world context.

A combination of studies were included to enable this, such as empirical behavioral studies on a variety of passengers travelling in cars, development and use of HBMs of different sizes, ages and sex in virtual crash simulations, in addition to active collaboration with ongoing novel international research within this area.

5 Results and Deliverables

The project has delivered one PhD thesis, one Licentiate thesis, three Master theses, and eighteen peer-reviewed articles and thirteen conference papers. Their content ranges from how people sit in cars and their postures, comfort perception and beltfit, to assessment and development of tools and methods, in addition to outreaching summaries on research needs and protection principles.

Addressing the four Research Questions, the following is highlighted:

Several studies contributed to the understanding of self-selected sitting postures and the effects on belt position, including influencing factors (Research Question A). Especially, steps have been taken in the area of understanding comfort aspects as means to help guide the beltfit, as well as methods and models for measuring and explaining these effects. Makris et al. (2023) found that shorter, stationary studies of three minutes effectively captured average sitting postures and beltfit, while longer studies are needed to capture posture variations. Particularly for individuals with certain body shapes, longer driving studies were found crucial for assessing variations in shoulder belt positions. Makris (2023) and Makris et al. (2024b) found that discomfort changes became noticeable after 15 minutes, irrespective of stationary or driving study design. Particularly, discomfort increased over time. Increased back discomfort was associated with slumped postures.

The user study comprising 39 adults and 20 children showed that taller adults rated higher comfort with an extended seat cushion, while shorter adults reported limited changes in overall comfort with increased seat cushion length. Additionally, taller adults were also more affected by changes in seat back angle compared to the shorter adults. For children, the study revealed that an increased seat back angle had minor impact on lap belt position, whereas increased seat cushion length resulted in the lap belt being positioned higher up on the pelvis.

In the user study involving 25 booster-seated children, it was seen that the variation between self-selected and nominal posture was minimal, while the children displayed a more forward and flexed head posture when using electronic devices (Baker et al., 2023a). The comparisons between the booster cushion from US and Swedish markets showed that in general the boosters from these two markets provided beltfit and postural outcomes within similar ranges, with exceptions of some low back booster from US providing more slouched postures due to long seat cushions lengths or lack of boost (Baker et al., 2022).

With respect to beltfit in the context of the challenges in the mobility trends and increased variety of postures and seat positions (Research Question B), the learnings from the previous sections are even more pronounced. In addition, the adaptations required for specific groups, such as boosters for children, add to the contributing factors. This was summarized in a paper on booster-seated children (Jakobsson et al., 2023b).

Through implementing the morphing method, a capability to represent a heterogeneous population of occupants with SAFER HBM has been developed (Research Question C). The biofidelity of the morphed HBMs was evaluated against a validation database including tests with 19 male and female subjects of various sizes. Population-wide evaluations of passengers in front and side crashes showed that a family of 25 male and 25 female HBMs can represent population trends in rib fracture injury outcomes. Beyond sex and body size trends, population variability in rib properties was found to be important to consider for population rib fracture risk evaluations. A new research project has been initiated, which includes improved representation of this aspect of population heterogeneity as a deliverable.

The assessment of state-of-the-art HBMs and ATDs to evaluate protection principles for the heterogeneous population in the different restraint interactions (Research Question D) included crash simulations and testing as well as static comparison of posture capabilities of child ATDs in relation to child passenger postures.

The HBM simulation series exploring the consequences of slouched postures during frontal impacts showed that a slouched posture influenced the overall kinematics leading to higher loading to the lumbar spine compared to nominal posture (Bohman et al., 2023). Hence the findings on the effect of upholstery material on sitting posture (Andreasson Persson and Larson, 2021) may have consequences in a crash, although further studies are needed to understand to what extent.

Adult-sized tools were evaluated to provide insight into their capabilities of addressing future car safety assessment needs, such as more reclined seats. Östling et al. (2021) 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 was preferred (Shin et al., 2022) and further understanding of the measurements are needed. Östling et al. (2022a) found that, similar to the sled tests with the THOR-50M, the lumbar spine compression forces of both the mid-sized and the large male HBMs increased in the relaxed seat position, while unlike THOR-50M, a lower risk for rib fractures was predicted. The seatbelt system with two lap belt load limiters effectively reduced the forces induced in the pelvis wings. However, longer pelvis forward displacement obtained with the two lap belt load limiters may increase the risk of submarining or sliding off the seat. The results obtained in this preliminary study will guide the development of a mechanical 3-point belt system prototype to be used in reclined PMHS tests for the EU-project Enable New Occupant Position (ENOP).

The child sized PIPER6y HBM was used in the pioneering study on challenges for booster-seated children in reclined seat position (Bohman et al., 2021 and 2022a). Although greater pelvis displacement in reclined as compared to upright, the lap belt stayed on the pelvis when the pretensioner was activated, hence providing the booster-seated child good protection in a reclined seat position.

The novel THOR-5F ATD was found to interact with the restraint system differently as compared to the Hybrid III-5F, showing larger chest deflection and more forward pelvis excursion (Carroll et al., 2021). This ATD is still being modified but is soon expected to be included in standardized tests, whereby it is essential to follow and understand the capabilities of this tool to assist in understanding protection principles.

Based on the user study involving 25 children, it was seen that the child ATDs generally represented the nominal child posture well, but failed to accurately represent postures when children are engaged in electronic devices (Baker et al., 2023b). Although this might seem obvious due to the non-flexible ATD design, this study made a structural quantified comparison framing the capabilities of the tools beyond what has been done before. When addressing protection of the heterogeneous population, including sitting postures, this knowledge is an essential part.

5.1 Contribution to the Objective of the FFI Program

The results of this project contribute to the reduction of injuries sustained by car occupants and support the work towards the Vision Zero ambition of reducing fatalities and injuries in traffic. The project also contributes to increase the Swedish vehicle industry's competitiveness and to strengthen the Swedish traffic safety research edge.

By focusing on car passengers of today, complemented with a study on drivers in an automated driving configuration making them passengers of future vehicles, the results derived are set to contribute both today as well in the long run to injury reduction. The inclusion of the heterogeneous population and the implementation into advanced tools such as HBMs are essential, acknowledging that when moving closer to "zero", the situations to address will be more unique.

With a special focus on beltfit and seating comfort, this new knowledge will help in designing vehicle protection system ensuring both good beltfit and good comfort, enhancing usage and contributing to improved occupant protection as aiming for Vision Zero.

Future Cars and Mobility Trends

As cars are getting more automated, there is both a higher need as well as a greater opportunity for advancements in occupant protection. With increased degree of pre-impact vehicle kinematics due to automated braking and / or steering, in addition to the driver-initiated maneuvers, the need of potential pre-impact measures (e.g. occupant retention) is increasing. Another challenge is a larger variety of seat positions and sitting postures. Among the opportunities is the availability of interior and exterior sensors in automated cars which could assist in providing protection adaptation to seat positions and sitting postures, in addition to crash situations and occupant parameters. However, this is only possible if knowledge on how to adapt the restraints for the specific configurations is available. Although more knowledge is to be gained, the learnings made in this project provide important input to this area. Examples of the contribution are data on how people sit as passengers in cars and methods to further collect such data, the exploration of protection principles for reclined seating and the heterogeneous population, in addition to the toolbox of morphed HBM models for crash assessment.

The user study exploring drivers' overall comfort experiences in selected reclined position during AD reflects that the driver will become a passenger in future cars when in unsupervised mode (Makris et al., 2024a). The study showed that drivers do not want to recline as much as reported from previous research done in static environments. The results also showed that the drivers' willingness to sit in a reclined position while travelling was influenced by the overall comfort experience in terms of physical, psychological, and functional aspects. Drivers may prefer reclined positions during AD if they can observe the traffic and intervene easily with the AD system. The results also showed that the chosen seat back angle was influenced by stature. There was a moderate correlation between the stature and chosen seat back angle in both upright and reclined positions. However, the stature played a lesser role in reclined in AD, than in upright. This might be due to reduced involvement in the driving task when reclined. This study provided insights into how to design to make drivers feel comfortable and safe during AD.

The wider range of seat positions and postures for the driver in cars with AD capacity as compared to current passenger cars may have implication on protection strategies, the capabilities of the tools and the assessment methods. However, this already applies for front seat passengers in current passenger cars, and much can be learnt from studying them. This has been one foundation of the current project. Other studies confirm this, showing that front passengers' seats are in the most rearward position more than 20% of the travelling time and rearward of the mid-track position more than 90% of the time (Reed et al., 2020). This more rearward seat position is likely to influence the sitting posture, such as by providing more legroom allowing the passengers to adjust the postures easier, such as crossing the legs (Stanglmeier et al., 2021). Leledakis et al. (2021) studied the influence of crossed leg postures during crash and showed an influence on kinematics and kinetics using the SAFER HBM of varied sizes. They also emphasized the challenges with assessing such posture variation. Furthermore, a reclined seat back is often considered more comfortable for longer trips (Östling and Larsson, 2019). To satisfy the demand for comfort, it is expected that seats in passenger cars with AD capacity will have a longer longitudinal adjustment range and a seat-back designed to recline. Several studies on reclined seating using both ATDs and HBMs were run in the project. Both tool types were shown useful and can deliver meaningful results. However, for reclined seating, recreation of specific and complex interactions which are essential for the occupant retention becomes more important, and is still a challenge to address. Development of protection systems capable for high degree of adjustments calls for upgraded methods and tools, such as advanced HBMs. However, to be able to implement safe reclined seating in future cars there is a need for both ATDs and HBMs.

As one of the first in the field, the study on child HBMs in reclined positions provided insights into that generally booster-seated children were better off than the adults thanks to the booster. However, they still required seatbelt pretensioner, and the sensitivity to the shoulder position was to be handled to provide equal protection as when upright (Bohman et al. 2021).

The Heterogeneous Population

Designing protective systems for the heterogeneous population is challenging due to the fact that people are different in size, shape and age and their beltfit vary due to this. The development of morphed HBMs and improved tissue-based injury prediction (in this project mainly rib fractures) have contributed to the possibilities for a higher precision and flexibility of scenarios and individual differences. This is especially of importance when the cars are becoming more automated, with interior and exterior sensors which then also can be used for adapting the restraint characteristics based on the individual. In addition to addressing specific individuals, there is a need to identify a representative family enabling prediction of population injury outcomes. The pioneering study by Larsson et al. (2023b) took a first step toward this.

There are many factors influencing comfort and beltfit for different sizes of car passengers. Makris et al. (2023) showed that pronounced abdominal fat and large breasts positioned the shoulder belt close to the armpit and thereby also uncomfortably close to the neck (Figure 9). The rear seat cushion length and seat back angle study with 39 adults and 20 children showed that a deeper seat cushion was perceived more comfortable by the taller adults. For the children the deeper cushion resulted in a lap belt position higher up on the pelvis and a diagonal belt position closer to the neck. The on-road user study with teenagers identified some non-standardized postures as results of activities and comfort (Parenteau et al., 2021). The postures included bending forward when using an electronic device and crossing legs and/or slouching for comfort. These three studies all showed a large variation of postures which are influenced by individual differences, comfort preferences or activities. The single 'nominal' posture used in standardized crash assessment today cannot represent this large variety. The crash test dummies may never be capable of the flexibility needed for several of the postures, in addition to meet the large variation in sizes and shapes, while the HBM has potential to be used as a complement to better incorporate the heterogeneous population.

Fig. 9. Example of how test persons' body shape influence beltfit and chosen strategies (right) to reposition the shoulder belt during the ride (Makris et al., 2023)

The study investigating whether a pre-pretensioner would be capable of repositioning an off-shoulder belt position to an on-shoulder position showed that belt repositioning was mainly affected by the location of the belt attachment points and upper body shape (Eliasson and Bohl, 2023). Protective measures activated prior to the impact provides opportunities for enhancing the potential protective capabilities of the seatbelt, especially for the heterogeneous population in the real-world context. Repositioning of occupants prior to a rear-end impact was explored in the study by Jakobsson et al. (2021), focusing on strategies to include sitting postures in assessment tests.

The Booster as an Adapter

For optimal protection of booster-seated children it is essential that the car, the booster and the users are regarded as one entity. However, the development of boosters, including their type-approval, is contradictory. This was elaborated at the ESV conference (Jakobsson et al., 2023b), by the international workshop presentation (Arbogast et al., 2022) as well as shown in a publication on boosters in shared mobility (Jakobsson et al., 2020). In the latter, a small user study with three children was included, illustrating the limited possibility in offering good beltfit for various sizes of children due to a regulatory limitation of allowing multiple routing of the shoulder belt portion of the belt. Figure 10a 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 beltfit 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. Unfortunately, different shoulder belt routings are not allowed in the most recent type-approval (UN R129).

Figure 10b illustrates the bulkiness of boosters, which is driven by type-approval as well as child restraint rating by test institutes (Jakobsson et al., 2023b). Due to the introduction of side impact test methods, using a sled which doesn't reflect a real car, the sides of the booster backrest are made too wide, having consequences on space as well as comfort.

Fig. 10a. 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 for the 11-year-old (right).

Fig. 10b. Rear seat with two mid-size males and one booster seat (Jakobsson et al., 2023b)

For real-world protection, the booster serves the main purpose of raising the child into a good position of the restraints, proving a good beltfit and enabling the child to be protected by the vehicle safety systems. The project team is driving these questions internationally while also supporting the Swedish communication, which is challenged by the recent change by EU to ban sales of R44 seats and thereby only allowing sales of the R129 approved seats in Sweden, which means that booster cushions for children shorter than 125cm cannot be purchased anymore. This is problematic from a shared mobility perspective, in which booster cushions serve a very important contribution to provide easy to access high level protection together with the seatbelt, for children from 4 years of age.

Swedish Research Edge and International Outreach

The knowledge gained in this project contributes to increase the competitiveness of the Swedish vehicle industry and provide proof-points to help strengthen the Swedish capacity for research and innovation. It contributes to maintain and strengthen the world-leading position within traffic safety that Swedish industry and universities have today. This was summarized and concretized in a publication at the international conference ESV 2023 (Jakobsson et al., 2023a). Important knowledge on passenger protection has been generated and shared, helping to provide impact globally.

The project has also provided inspiration for other researchers, by identifying new topics/areas. The child HBM study in reclined positions was one of the first in its field and has inspired other research groups to further explore the effect of reclined seating on booster-seated children (e.g., Graci et al., 2022 and 2023). Another example is the seatbelt system with two lap belt load limiters, which was studied in this project. It was used as inspiration for the development of a mechanical three-point belt system prototype, which was further investigated in the EU project ENOP (Östling et al., 2022b, Eggers et al., 2024).

The current project has been a part of the SAFERs' HBM competence cluster, which is based on a continuous path of research projects, working in sequence or parallel toward creation of the SAFER HBMs; being morphable, capable of recreating potential pre-crash kinematics and with omni-directional capability to predict injury risks in crashes (Pipkorn et al., 2023). This project contributed with the morphing part, in addition to the research on understanding the diversity of the heterogeneous population, including sitting postures and beltfit. The project partners are actively working towards making the SAFER HBM available for the wide community. The enhancement done by this project will help position it as a state-of-the-art HBM and as a preferred tool for virtual testing in consumer information protocols globally.

6 Dissemination and Publications

The project results are utilized in product development and advanced engineering projects within the industrial partners of the project. The SAFER HBM is used as complement to the standardized ATDs, providing further insights into occupant protection needs. The child sized HBM (PIPER) has been integrated into industrial usage and contributes to real-world assessment of child passenger protection. Furthermore, the knowledge and assessment tools created in the project are used in educational activities within Chalmers Master Programs, Theses at Master and Bachelor levels, as well as assignments in different university courses.

6.1 Knowledge and Result Dissemination

How are the project results planned to be used and disseminated?		Comment
Increase knowledge in the field	X	Significant contribution, exemplified by the amount, variety and novelty of studies, and their publications and outreach by presentations.
Forwarded to other advanced technological development projects	X	Project results are used as input to vehicle and restraint developments by the industrial partners.
Forwarded to product development projects	X	The results on the ATD and HBM evaluation and developments have been used in in-house testing and development of restraints and vehicles for production. The morphed models are used as part of the product development process.
Introduced on the market		The project results are used in vehicle and restraint system development by the industrial partners.
Used in investigations / regulatory / licensing / political decisions	X	The project results have influenced regulations, ISO-standards and consumer information tests (e.g. EuroNCAP and IIHS) specifically with respect to child safety and rear seat safety for adults.

<u>Examples of dissemination</u> in addition to the publications and conference presentations listed in Chapter 6.2:

Poster at **Injury Biomechanics Student Symposium**, The Ohio State University, online, May 24-25, 2021 online, by Karl-Johan Larsson, Bengt Pipkorn and Johan Iraeus, entitled *HBM morphing for biofidelic predictions of kinematics and rib fracture risk for a diverse population of occupants*. https://ibrc.osu.edu/2020-posters-and-manuscripts/

Presentation at **RCCADS** (Research Consortium for Crashworthiness in Automated Driving Systems) **Public Workshop**, May 26, 2021online, by Martin Östling, entitled *Will new seating positions require new occupant restraints?* https://www.trcpg.com/media/in4bcg0x/ostling_will-new-seating-positions-require-new-occupant-restraints.pdf

Presentation at CChiPS' seminar **Virtual Advances in Child Injury Prevention Conference (APIC),** June 15-16, 2021 online, by Katarina Bohman, entitled *Evaluation of booster cushion design effects on child occupant kinematics and loading in frontal impacts*,

Arranging the SAFER seminar **Child Occupant Protection: Latest knowledge and Future Opportunities**", Sept 21, 2022, Gothenburg, including project presentations by Katarina

Bohman and Lotta Jakobsson; https://www.saferresearch.com/events/child-occupant-protection-latest-knowledge-and-future-opportunities-1

Presentation at **Nordic LS-Dyna Users Conference**, October 18-19, 2022, Gothenburg, by Karl-Johan Larsson, Johan Iraeus and Bengt Pipkorn, entitled *Human Body Modelling of Vehicle Occupant Diversity*

Presentation at NTF Väst's event **Barn Liv och Trafik 2024**, March 6, 2024, Gothenburg, by Isabelle Stockman, entitled *Barnsäkerhetsutmaningar med nya former av bilägande.* https://vast.ntf.se/pagaende-projekt-och-uppdrag/barn-liv-och-trafik/

Showing morphed HBMs in virtual reality showroom at **SAFER Stage 5 final event**, March 8, 2024 Gothenburg

Arranging the SAFER seminar **Child Occupant Protection: Latest knowledge and Future Opportunities**, May 31, 2024, Gothenburg, incl. a project presentation by Lotta Jakobsson; https://www.saferresearch.com/events/child-occupant-protection-latest-knowledge-and-future-opportunities-2

6.2 Publications

Theses

Karl-Johan M Larsson, **Human Body Model Morphing for Assessment of Crash Rib Fracture Risk for the Population of Car Occupants**. *Thesis for the degree of Doctor of Philosophy*, Dept of Mechanics and Maritime Sciences, Chalmers University of Technology, Sweden. 2023 ISSN 0346-718X https://research.chalmers.se/en/publication/535578

Melina Makris, **How does it feel and how is it measured? Assessing sitting comfort and postures of rear-seated car passengers in stationary and driven scenarios over time**. *Licentiate Thesis*, Dept of Industrial and Materials Science, Division of Design and Human Factors, Chalmers University of Technology, Gothenburg, Sweden, 2023, IMS-2023-10 https://research.chalmers.se/publication/538284

Rasmus Andreasson Persson and Johan Larson. **Evaluation of slouched sitting postures of rear seated car passengers**, *Master thesis in Product Development*, Dept of Industrial and Materials Science, Chalmers University of Technology, 2021, https://odr.chalmers.se/items/eec6ffed-dc30-4a43-9e1e-748f20376b60

Julia Solhed. **Applicability of Graph Neural Networks to predict Human variability in Human Body Model Rib Strain Predictions**, *Master thesis*, Teknisk-naturvetenskapliga fakulteten, Uppsala universitet, Sweden, June 2022, http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-477806

Klara Eliasson and Louise Bohl. **Car occupant seat belt fit; the effect of belt pre-pretensioning**, *Master thesis in Biomedical Engineering*, Department of Mechanics and Maritime Sciences, Division of Vehicle Safety, Chalmers University of Technology, Gothenburg, Sweden, 2023. https://odr.chalmers.se/server/api/core/bitstreams/8331c811-b549-4317-a125-178e27a75d3c/content

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7 Conclusions and Future Research

The project has delivered novel data, tools and methods to assess the protection of the heterogeneous population of passengers in future cars, and thereby taken the research area to the next level. The cross-competence collaboration and the large number of diverse studies have enabled creation of new knowledge and developments on assessment tools and methods on lap and shoulder belt interactions, including influencing factors such as variation in occupant characteristics and sitting postures. In total, the project has resulted in one PhD thesis on using morphed HBMs for crash safety assessment, one Licentiate thesis on sitting comfort and postures, three Master theses and at least 31 publications, whereof 18 are peer-reviewed articles.

Passenger protection needs were studied through observation studies on passengers, in combination with simulation series and crash testing, to be used for restraint development and improving the methods used today. New learnings and methods on assessing comfort were made. By understanding discomfort, adaptations can be made to improve comfort, in addition to be used as means for guiding towards preferred protection positions. The importance of body shape was highlighted as was the challenges for comfortable beltfit for some body shapes. Activities and behaviours during ride also influence sitting posture, in addition to the beltfit. In two of the studies, a forward leaning posture was seen when the children/teenagers were using electronic devices. This is a posture not included in crash protection assessment today, but frequently seen in traffic.

Methodology for selection of representative individuals for crashworthiness assessment was developed, addressing the heterogeneous population. Morphing techniques developed in a prior project were refined and established and are now used by the industrial partners to develop restraints and vehicle safety systems. This functionality of the SAFER HBM is combined with the parallel developments of the HBM's biofidelity, injury prediction and muscle activation within other research projects, making it a state-of-the-art HBM.

With validated morphed HBMs, the effects of population height and weight variations for both male and female passengers were computed in front and side crashes. It was found that a family consisting of 25 female and 25 male sizes was sufficient to represent the effects of population height and weight variations on crash outcomes. For rib fracture risk, however, other factors such as properties of the ribs also had a strong influence on the outcome. Future research should target to include additional rib property variations in HBM evaluations for an improved population rib fracture risk assessment.

Furthermore, the project arranged the 7th and 8th biannual International Child Occupant Protection 2-days workshop, in addition to international workshops, two open seminars, and other exchanges with Swedish and international researchers and other stakeholders. The international multi-disciplinary interaction serves the purpose to assure optimal relevance for project execution as well as dissemination.

This project has contributed to developing knowledge and assessment methods to be used for vehicle safety system development. Adaptable protection using interior and exterior sensing capabilities in cars with high degree of automation requires such knowledge, tools and methods to optimally tune the restraints and leverage the automation capabilities. Future research includes ongoing projects partly initiated by the current project, such as further development of the pelvis and thorax for improved restraint interaction prediction. In addition, a continuation project is planned to further strengthen the area of human factors/ergonomics design with the purpose of understanding passengers' behavior, experiences and attitudes and how to further take this into account in crash protection.

8 Project Partners and Contact Persons

The project partners are Chalmers University of Technology, Autoliv Research and Volvo Cars, with the main participants throughout the project:

Chalmers:

Mats Svensson and *Johan Iraeus*, Vehicle Safety Division, Mechanics and Maritime Sciences

AnnaLisa Osvalder and *Melina Makris*, Human Factors Design, Industrial and Materials Science

Autoliv:

Martin Östling, *Karl-Johan Larsson* and *Bengt Pipkorn*

Volvo Cars:

Katarina Bohman, *Isabelle Stockman*, *Pernilla Nurbo* and *Lotta Jakobsson* (Project leader, contact details: lotta.jakobsson@volvocars.com)

In addition, the following researchers have contributed in selected parts of the project:

Ekant Mishra, *Amanda Hederskog*, *Nils Lubbe* and *Arun Muthumani* at Autoliv

Fredrik Heurlin, *Jonas Östh*, *Sara Alpsten*, *Sarah El-Mobader* and *Emil Gröndahl* at Volvo Cars

Gretchen Baker, PhD student and Guest researcher from Ohio State University, USA

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