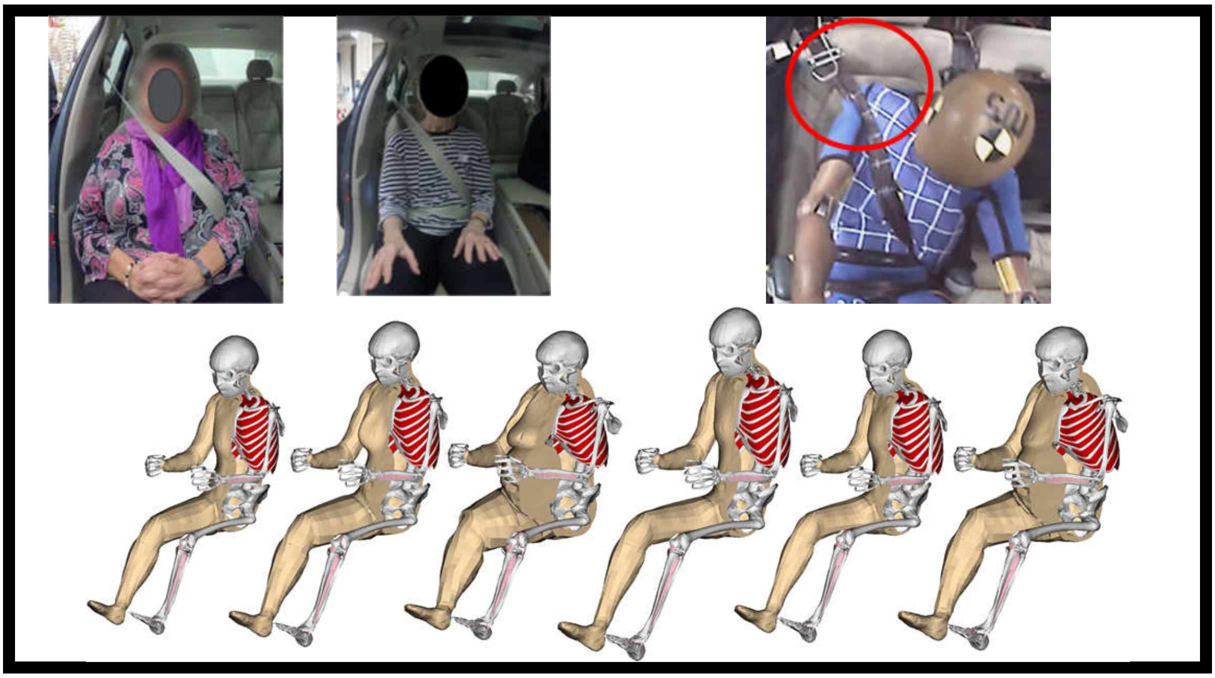
Assessment of Passenger Safety in Future Cars

Passagerarsäkerhetsutvärdering i framtida bilar

Public Report



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FFI Fordonsstrategisk Forskning och Innovation

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FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

Currently there are five collaboration programs: **Electronics, Software and Communication, Energy and Environment, Traffic Safety and Automated Vehicles, Sustainable Production, Efficient and Connected Transport systems.**

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1 Summary

The population is becoming older and the diversity in car passenger sizes is growing. Future cars will likely include a higher degree of collision mitigation systems, and a larger range of seat positions and seating configurations, in addition to increased degree of car sharing, such as car-pools and taxis. These aspects call for assessment tools and evaluation methods beyond the standardized crash test methods of today. This project addresses the research question on how to assess the protection of the heterogeneous population of passengers in future car crashes. Specifically, the project aims to achieve method developments based on enhancement of tools (physical and numerical human substitutes) and to create knowledge on passenger protection needs, focusing restraint interaction.

The project combines multiple competences, a range of studies using different methods and international collaboration. The methods include real-world crash data analyses to identify scenarios and situations, human-product interaction user studies on attitudes, expectations, comfort and usability, in addition to crash testing and simulation. Furthermore, the project includes evaluation of novel adult crash test dummies (ATDs) and a child-sized Human Body Model (HBM), in addition to the development of adult morphed HBMs of various sizes and applying these for investigating protection principles.

The project has delivered one Licentiate thesis, thirteen Master theses and more than eighteen international publications, in addition to a family of diverse HBMs representing an adult population for further studies. Novel studies on prediction of future crash configurations and seating preferences contribute to new studies and insights, as well as high international visibility. Influence of body shape on beltfit and quantified lateral movements during turns in everyday traffic situations are examples of findings from the user studies. This knowledge provides input to understand passenger protection design needs and for development of assessment methods. The crash test and simulation series helped to evaluate novel ATDs and to explore protection principles for adults, in upright as well as reclined seat positions. Through several child safety publications, presentations and by arranging an international workshop; the project group has raised child passenger protection challenges, having impact on international standard development as well as rating and regulatory discussions.

The project results are utilized in product development and advanced engineering projects within the industrial partners of the project. The adult morphed SAFER HBMs are used as complements to the three standardized ATD sizes available. HBMs of a variety of occupant sizes, ages and sex; used together with the knowledge on how they sit as passengers in cars, enhances the relevance of passenger protection assessment. The child HBM (PIPER) has been integrated into industrial usage and contributes (with its more humanlike capabilities) to real-world assessment of child passenger protection, emphasizing the importance of whole system interaction (the vehicle, the child restraint and the user). Furthermore, the knowledge and assessment tools created in the project are used in educational activities and research within Chalmers.

The results of this project contribute to the reduction of injuries sustained by vehicle occupants and support the work towards the Vision Zero of reducing fatalities and injuries in traffic. By studying passengers of today, complemented with prediction studies on future situations of crashes and vehicle interior designs, the results derived are set to contribute to long-term injury reduction. The inclusions 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 and specific.

2 Sammanfattning på svenska

Världens befolkning blir äldre och mångfalden i storlek ökar. Framtida bilar tros innebära mer aktiva säkerhetssystem, nya säteskonfigurationer och -inställningar, samt en högre andel bildelning, såsom bilpooler och taxi. Utmaningarna kräver utvärderingsmetoder utöver de standardiserade krockprovmetoder som används idag. Målet med projektet är att svara på frågan hur man kan utvärdera skyddet för den heterogena populationen av passagerare i framtida bilars krocksituationer. Projektet syftar till att utveckla metoder baserat på verktyg (fysiska och virtuella humansubstitut) samt öka förståelse kring passagerarskyddsbehoven, med fokus på bältesinteraktion.

I projektet kombineras olika kompetenser och ett flertal studier i en mångfald av olika metoder med ett internationellt samarbete. Metoderna inkluderar olycksanalyser om scenarier och situationer, användarstudier om attityder, förväntningar, komfort och användning, samt fysisk och virtuell krockprovning. Dessutom inkluderar projektet utvärdering av nya vuxna krockdockor och en barn-humanmodell, samt utveckling av vuxna 'morphade' humanmodeller av olika storlekar och dess tillämpning för att undersöka principer av skyddssystem.

Projektet har levererat en licentiatavhandling, tretton examensarbeten av magisternivå och mer än arton internationella publikationer, samt en familj av humanmodeller som är representativa vuxna för vidare studier. Prediktionsstudier om framtida krockkonfigurationer och bilinteriörer har bidragit med banbrytande studier och insikter samt att synliggöra vår svenska forskning. Kroppsformens påverkan av bältesplacering på kroppen och data om passagerares rörelse vid svängar i rondeller är exempel på nya kunskaper från användarstudierna. Dessa är exempel på kunskap som bidrar till att förstå behov av utformning av passagerarskydd, samt för utveckling av utvärderingsmetoder. De fysiska och virtuella krockproven bidrog till att utvärdera nya krockdockor, samt att undersöka skyddsprinciper för vuxna, i upprätt liksom bakåtlutad sittställning. Genom ett flertal barnsäkerhetspublikationer och -presentationer, samt arrangerande av en internationell workshop, har projektgruppen lyft många aktuella utmaningar avseende skydd av barn i bil och genom detta påverkat utveckling av standarder, såväl som bidragit i diskussioner kring konsumentupplysningsprov och barstolscertifiering.

Projektresultaten används i produktutveckling och förberedande utvecklingsprojekt hos industriparterna. De vuxna 'morphade' humanmodellerna används som komplement till de tre storlekarna av standardiserade krockdockor. Humanmodeller, som är av olika storlek, åldrar och kön, i kombination med den generade kunskap om hur passagerare sitter i bilen, lyfter relevansen av passagerarsäkerhetsutvärdering. Barnhumanmodellen (PIPER) har industrialiserats, varvid dess mer människolika egenskaper bidrar till mer verklighetsnära barnsäkerhetsutvärdering, vilket har ytterligare påvisat betydelsen av att bil, barnskydd och användare samverkar. Utöver detta har kunskapen och utvärderingsverktygen framtagna inom projektet använts av akademin för undervisning och forskning.

Projektresultaten bidrar till skadereduktion av bilpassagerare och stödjer arbetet mot nollvisionen. Genom att studera passagerare idag, kompletterat med prediktionsstudier för framtida situationer och bilinteriörer, är resultaten riggade för att bidra en lång tid framöver. Inkludering av den heterogena populationen och implementering i de avancerade humanmodellerna är viktig, i och med utmaningarna av unika situationer som blir realitet när man rör sig närmre ”noll”.

3 Background

Safety for passengers in cars is of increased importance moving towards automated vehicles (AV) and a higher degree of car sharing and taxi transportations. In unsupervised AV mode, the driver becomes a passenger. Car sharing and increased use of taxis, call for effective, comfortable and safe protection systems, customized for a wide range of ages and sizes as well as a likely wider range of seat positions and seating configurations. In addition, the advanced driver-assistance systems (ADAS) will influence the crash configurations, when activated but not avoiding the crash completely.

It is expected that future passengers will choose their seat position and sitting posture with even more freedom than today, presenting a large spread in real-world postures in crashes. For example, choosing reclined seat positions beyond conventional test configurations. This poses the challenge of assessing safety for novel postures and positions where current tools (physical and numerical human substitutes) may not be biofidelic.

The ageing population is growing, and beside their fragility and frailty, there are challenges with respect to lap belt positioning (Fong et al., 2016). Similar mechanisms are also seen for overweight passengers, for whom their abdomen size influences lap belt position, with increasing body mass index (BMI) placing the lap belt further from the optimum (Reed et al., 2012, Park et al., 2016), with an increased risk for submarining due to too high positioned lap belt (Howes et al., 2015). The belt fit, and especially the lap belt positioning, is highly related to occupant position, posture and anthropometry.

Many passengers are children. Children have specific needs due to their body shape and development, which will not change in future cars. The smallest children are optimally protected using rearward facing child seats, while children from approximately age 4 years can use the vehicle seat belt. However, these older children need to use boosters to adapt to the seat belt designed for the adult population (Reed et al., 2008). Specifically, for children, the increased usage of transportation modes, such as taxis and car sharing, will require flexible and easy-to-use solutions in order to maintain high protection.

To enable future mobility services (such as fully AV and car sharing) and to ensure protection of a heterogeneous passenger population, safety assessment methods and tools need to be evaluated, updated and developed. Tools for car passenger protection assessment are mainly crash test dummies (ATDs) and virtual human body models (HBM). 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. In addition, they also have limitations in their design and validation to be used in other sitting postures than upright sitting. HBMs, being more anatomically similar to humans, have greater potential to be omni-directional, representing human kinematics and injury risk in all impact directions, in addition to representing a wider range of body sizes for both sexes. They also have the potential for evaluating injury risk at the organ or tissue level, in addition to recreate more humanlike interaction, e.g. shoulder to shoulder belt interaction.

4 Purpose, Research Questions and Methods

The project addresses the research question on how to assess the protection of the heterogeneous population of passengers in future car crashes. Future car crash challenges include the influence of ADAS and the increased flexibility that will be offered in future AV, in addition to the change of transportation modes. With the overall purpose to develop personalized restraints for enhanced protection, the specific aims of the project are to achieve method developments based on enhancement of tools (physical and numerical human substitutes) and to create knowledge on passenger protection needs, focusing restraint interaction.

The project considers passengers of age 4 and older in passenger cars. Younger children, not using the vehicle seat belt as part of their protection, are excluded. Drivers are excluded, since the passengers provide more interesting learnings, being more free to choose a greater variation of seat adjustments and sitting postures. Passengers are also more relevant for future car safety challenges.

Improving safety for car passengers requires enhanced knowledge in several areas involving multiple disciplines. This joint research project aims at gathering a variety of competences and combining different types of methods as a way to leverage the research, providing new insights and learnings. The variety of methods are described in subchapters to follow, also reflecting the Work Package structure of the project.

The project is based on two “pillars”, feeding into the overall research question, as illustrated in Figure 1. The left “pillar” comprises a combination of human factor related user studies (attitudes, comfort and usability studies of human-product interaction) and real-world crash data to identify scenarios and situations defining the ‘Use-cases’. The ‘Use-cases’ serve the purpose to define the context for future passenger protection, by investigating passengers’ expectations and attributes towards future travels (including phenomena occurring today which are still relevant in the future), in addition to understand how future vehicles will crash. Within the right “pillar”, opportunities and limitations with existing tools for injury assessment and potential development of these are investigated.

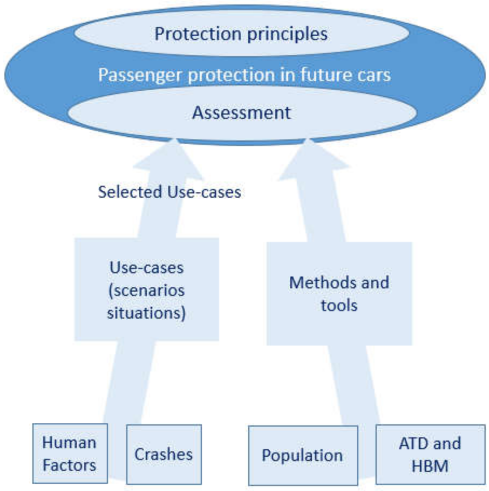

Figure 1. Project content overview

Half-way into the project, the studies performed within the left “pillar” at that stage were summarized. Four ‘Use-cases’ were selected for further actions and addressed within the remaining project. In parallel, additional relevant areas, being current and in the frontline, were included as well. The four ‘Use-cases’ are:

A. The family of HBMs (stature, BMI, age, sex) representing the future adult population for evaluation of restraints.
B. The challenge of assessing adult pelvis rotation and lap belt interaction, irrespectively of self-selected/comfort or due to seat position/reclination.
C. The child HBMs’ sensitivity of assessing diagonal belt interaction, taking comfort and retention into account.
D. Addressing child occupant protection when taking activities and use of devices into account.

Some of the different types of studies performed within the project are summarized below.

4.1 Real world data

Real-world crash data analyses to identify scenarios and situations, in addition to human factor design interaction user studies, including attitudes, expectations, comfort and usability were performed.

Crash databases were used as input to determine future safety-critical scenarios. Lubbe et al. (2018) and Östling et al. (2019a and 2019b) used GIDAS and NASS-CDS data, respectively, to identify future unavoidable crash scenarios for advanced driver-assistance systems (ADAS) equipped vehicles and what crashes fully AVs will be exposed for in mixed traffic analysis. The unavoidable crashes identified in the NASS-CDS data was further analysed to identify what injuries that remain (Östling et al., 2018). Analyses of crash data bases also served the purpose to summarize passenger car occupants with respect to seat occupancy, age, sex, height and weight. A comparison between Sweden, Germany and USA was performed using crash databases in each of the country.

User studies of varied kind were performed to map real world sitting postures as well as investigating preferences of seating configurations, seat position and sitting postures in future travel modes. Eight Master theses and five publications were produced within this area. Several of them were pioneering studies in their field. In addition, project internal workshops were performed serving the purpose to establish definitions and to gather and discuss available studies within the area. Specifically, workshops were held to summarize findings regarding the 'Use-case' B on pelvis rotation assessment and influencing factors.

Four of the Master theses investigated methods for quantifying adults' sitting postures and beltfit in cars and collecting data of passengers while driving or stationary. Ankartoft and Alfredsson (2018) focused on older adults and their beltfit and comfort. Their work was included in two peer-review papers (Osvalder et al., 2019 and Bohman et al., 2019b). Janson and Wedmark (2018) investigated methods for quantifying sitting postures in cars with focus on pelvis orientation, including instrumentation such as XSENSE and digital measurements of body landmarks. Their work served as inspiration for a second Master thesis within the topic, but with more focus on data collection and analysis of sitting postures during drive (Hansson and Lysén, 2019). Olander and Andersson (2019) studied beltfit, lateral postures and movement in everyday vehicle rides exposing front seat passenger volunteers for turns such as in round-abouts. Their work was included in a peer-review publication by Bohman et al. (2020a).

Studies investigating preferences in future autonomous vehicles were performed using different methods. One Master thesis investigated preferred reclined seat positions in fully autonomous cars, with a comfort and safety approach, using volunteers in a test-rig equipped with a production vehicle seat (Hagberg and Jodlovsky, 2017). Two studies, in Vårgårda, Sweden, and Shanghai, China, respectively, were performed using the method "setting the stage" (Petterson and Karlsson, 2015) to predict adults' and children's perception on seating configurations in some trip scenarios of fully autonomous cars (Jorlöv et al., 2017, Östling, 2018 and Östling and Larsson, 2019). This method uses a minimalistic design to encourage reflection and to explore user expectations of future products. It was never used in this application of vehicle safety before. The method is a qualitative experimental approach to interview users about future artefact use, allowing the participants a more dynamic role than purely being an informant. The participants explored vehicle seating configuration in a stationary test-set up, guided through different test scenarios by the test leader.

Makris (2020) addressed the research question: How should a valid user study be conducted to assess the end user requirements and preferences on the reclined seating position and its HMI for transitions between upright and reclined mode?

Addressing 'Use-case' D, Gereben and Swenson (2020) investigated older (10 to 17 years old) children's behaviour in cars and what activities they do. The methods included interviews, Instagram diaries, and family home sessions. The aim was to understand how the activities affects their experience, comfort and safety.

Focusing shared mobility, Simmons and Johansson (2020) and Elinder and Hultman (2020) investigated the users' needs, as part of their Master theses on child restraints for car sharing services. Interviews and online questionnaire surveys were used, focusing children in the ages of booster and rearward facing seats, respectively. A publication on boosters for shared mobility by Jakobsson et al. (2020) included parts of the work by Simmons and Johansson (2020).

4.2 Methods and Tools

Addressing ‘Use-case’ A on the family of HBMs representing the future adult population for evaluation of restraints, Larsson (2020) summarized literature on the occupants with increased injury risk in vehicle crashes to identify the future population of car passengers posing challenges to contemporary safety systems and evaluation methods. Identifying women, the older adults and the obese, 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 to enable creation of the individuals in the diverse population was selected and implemented for the SAFER HBM. A family of diverse HBMs was created representing an adult population for further studies, some of the individuals are shown in Figure 2. A validation database was created consisting of publicly available post-mortem human experiments performed with 19 individual subjects, together representing a wide range of male and female sizes and ages. Using this database, a morphed HBM validation study was executed (Larsson et al., 2021a, in press). Strengths and limitations of the morphed HBMs were identified through this validation.

Using recently created experimental data, Blennow (2020) created new rib fracture risk functions and rib material property regression models. The influence of sex and age was investigated. Sex did not influence rib material properties, but age was identified to have a stronger contribution to rib fracture risk than previously existing rib fracture risk functions represent. The findings contribute to the SAFER HBM model injury prediction developments (Larsson et al., 2021b, under submission).

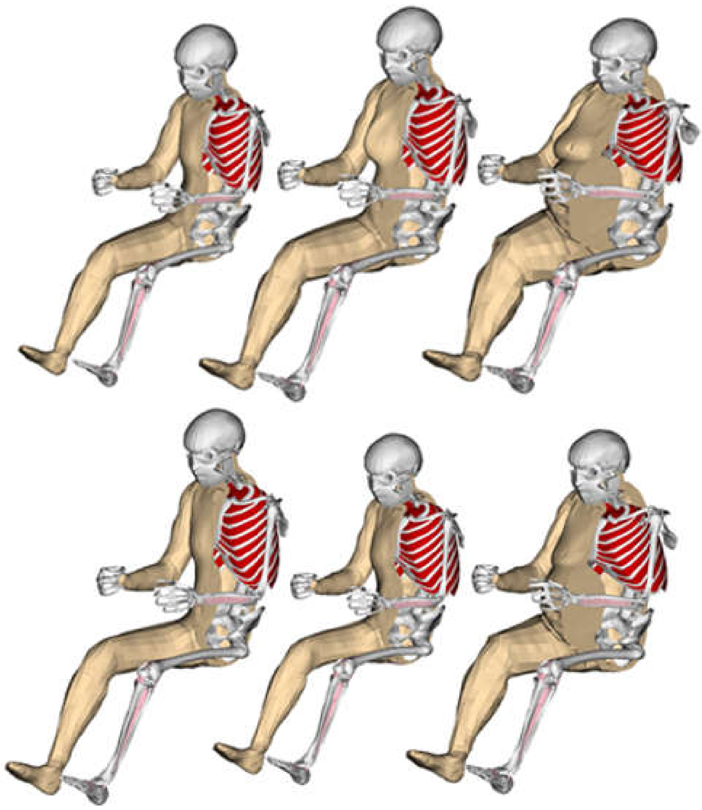

Figure 2. Examples of morphed versions of SAFER HBM. Top row: three female anthropometries; bottom row: three male anthropometries.

Addressing parts of ‘Use-case’ C, the open-source child HBM model, PIPER (Figure 3a, Beillas et al., 2016), was evaluated in three Master theses (Berntsson, 2018, El-Mobader, 2018, Daouacher, 2020). The primary task was to investigate its readiness and usefulness for child passenger protection evaluations in a vehicle environment. The 6-year-old PIPER model was used in a vehicle rear seat, restrained with seat belt and boosters. With the purpose to investigate the sensitivity to different shoulder and lap belt geometries, studies included variations of seat belt geometries and booster designs.

With the purpose to provide input to consumer information testing on the 10-year-old sized ATD Q10, crash tests were performed to compare two different versions (Bohman et al., 2018 and 2019a). The original Q10 (Figure 3b) was compared to the modified Q10 (Figure 3c). The modified Q10 included the upgrade kit with 5 modifications, including 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 two different versions were compared in both frontal and side impact tests, to provide insights into the influence of trajectories and responses.

Figure 3a. The open-source child HBM, PIPER

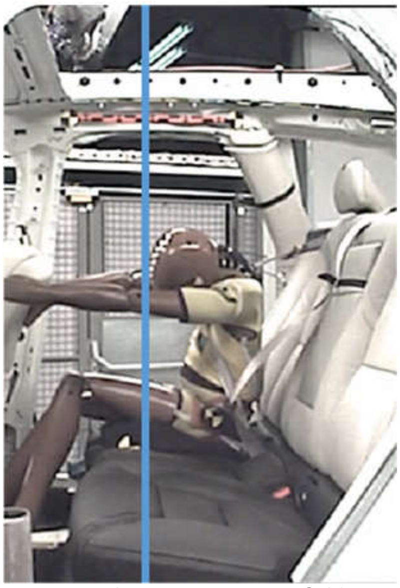

Figure 3b. The original Q10 in Bohman et al. (2019a)

Figure 3c. The modified Q10 in Bohman et al. (2019a)

Novel adult ATDs were evaluated to provide insight into their capabilities of addressing future car safety assessment needs, such as more reclined seats and the diversity in size and sex. The virtual mid-sized male THOR -50M AV ATD model (Humanetics, 2020a) was evaluated by simulations of upright and reclined seat position and compared to the mid-sized males Hybrid-III and THOR ATDs and the SAFER HBM. This novel ATD prototype is based on the most advanced mid-size male ATD, THOR, however substantially modified, targeting more reclined sitting postures.

Physical crash tests were run with the novel small-female sized THOR-5F ATD (Humanetics, 2020b), with comparative tests with Hybrid-III ATD of same size (Carroll, 2021). Three different configurations; belt only at 35 km/h, belt and airbag at 35 km/h and belt and airbag in 56 km/h were included.

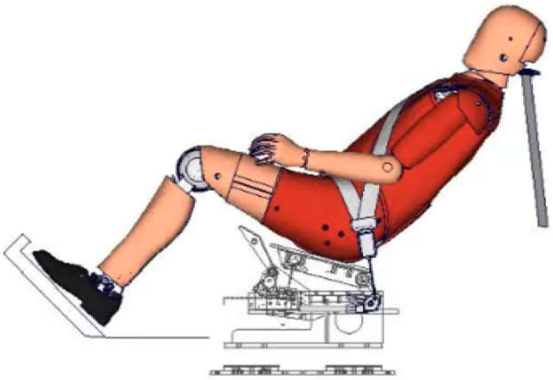

Figure 4a. Mid-sized male THOR – 50M AV model (Humanetics, 2020a)

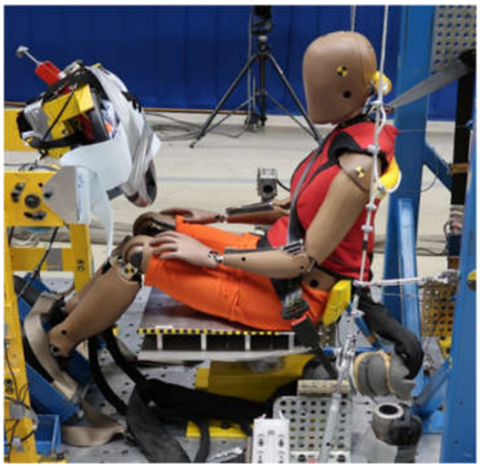

Figure 4b. Small female-sized crash test dummy, THOR-5F (Humanetics, 2020b)

4.3 Implement assessment methods to develop protection principles

Throughout the project, simulation series and crash testing were performed to investigate the capabilities of the different ATDs and HBMs to help assess different protection principles. The aim of the project was not to develop protection systems, but to develop knowledge on how the different human substitute tools could be used to assess the interaction with the lap and shoulder belt in the variety of configurations. Variations in seat position, sitting postures, seat belt routing and design, in addition to booster design when applicable, were included in the studies. Some examples, illustrating the spread in applications, are provided.

Test series and simulation series were performed to study occupant protection in novel seat positions (e.g. reclined), investigating different restraint principles, such as lap belt pretentioners and lap belt geometries (Östling et al., 2017).

Sled tests with the mid-sized THOR ATD were performed, using an inflatable belt as a protection principle. The aim was to investigate its responses (kinematics, neck and spine load) in a frontal impact, comparing the traditional upright seat position and a reclined seat position when exposed to an inflatable belt.

With the purpose of investigating the influence of booster cushion design on child occupant kinematics and loading; simulations using the PIPER and crash tests using the ten-year-old sized ATD, Q10, were performed (Bohman et al., 2019c and 2020b).

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 trend and the users' needs in shared mobility (Jakobsson et al., 2020), one of them as a part of the Master thesis by Simmons and Johansson (2020).

Addressing the 'Use-case' (B) on influence of activities and use of devices. Gereben and Swenson (2020) developed design concepts addressing activities of children aged 10-17 years old, targeting safety and comfort. 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.

4.4 Dissemination

An international multidisciplinary workshop was held in September 2019, to identify high-priority research topics and strategize toward their implementation. The workshop was the 6th biannual workshop starting in 2009 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 were worldwide leaders in the fields of child occupant protection, biomechanics and automotive safety. The overall structure for the two-day workshop included presentation of relevant topics with the focus on 'pressing issues in child and adolescent occupant protection' in addition to reviewing progress of research priorities identified during previous workshops the first day, followed by a one-day discussions on high priority areas as defined based on the first day discussions. An important part was to summarize and present the workshop discussions 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). Following the workshop, a one-day open seminar was held at SAFER, with presentations by the international researchers on current child occupant protection topics (details in Chapter 7.1).

Serving the purpose to assure optimal relevance for project execution as well as contribute to dissemination, continuous interaction with international researchers in the field is an important part of the project. The project partners participate in three ongoing relevant EU project; VIRTUAL, OSCCAR and SAFE-UP. Similar studies are performed within those projects. As an example, the 'Use-case' methodology initiated and used in the present project, was carried over and refined within the OSCCAR project. After published, the SAFE-UP project has implemented it, serving the purpose to structure the combination of the human, the sitting aspects and the crash configurations. In addition, project members have been active sharing research results and presenting the project at workshops and seminars, when possible, see examples in Chapter 7.1).

Twice during the project, one of the project members has spent time at UMTRI in Ann Arbor, Michigan, USA, interacting with Professor Reed and his team, mainly to enhance the morphing methodology. Throughout the project, six workshops with visiting researchers from UMTRI (Matt Read), Ohio State University (John Bolte), Children's hospital of Philadelphia (Kristy Arbogast) and UVA (Jason Forman) have been arranged, significantly contributing to help the project to focus important and current topics.

Project members are active in the ISO working group of Child Restraint Systems, the Swedish national mirror group at Swedish Institute of Standards (SIS), as well as connected to the UN ECE work on child seat standards. Especially in the area of booster regulations, there has been a close interaction and possibilities to influence. The project results have also been discussed with consumer information programs, such as EuroNCAP and IIHS, as well as the US National Highway Traffic Safety Administration (NHTSA).

5 Objective

The objective was to answer the research question on how to assess the protection of the heterogeneous population of passengers in future vehicle crashes. Specifically, the project aimed to achieve method developments based on enhancement of tools (physical and numerical human substitutes) and implement and apply these methods to deliver novel protection principles. In order to do that, the overall research question was broken down to the following sub-questions, also illustrating the “spread” of methods needed to achieve this:

- Which are the passengers’ seating preferences in future car usage?
- Which are the challenging occupant protection needs in future vehicles?
- How can existing tools be used to represent the population heterogeneity?
- How can existing tools be used to represent different sitting postures and positions?
- Can morphed versions of existing numerical human body model tools represent a larger portion of the population and how do we choose the target population?

This objective and all the research questions have been addressed throughout the project, delivering results in line with them.

The project set-up enabled flexibility in approach, contributing to creation of current studies and quick activation/contribution to the international agendas.

6 Results and Deliverables

The project has delivered one Licentiate thesis, thirteen Master theses and more than eighteen publications on e.g. sitting postures in cars, prediction of future critical crash configurations, HBM model validations, futuristic seating in cars and current child safety topics; in addition to creation of morphing methods for adult passenger tools (HBMs).

When assessing the protection of the heterogeneous passenger population in future vehicle crashes, the tools’ capability of high-quality prediction of the lap- and shoulder belt interaction is essential, as well as the need of a multitude of occupant sizes. An HBM serves as the preferred tool in both these aspects, with more detailed anatomical structure and possibilities to create more sizes of occupants. The pelvis is central in the occupant restraint interaction. After initial studies, the project team saw the need to create a separate research project taking on the challenge to develop a morphable and parameterized model of the pelvis, to be integrated into the common platform of SAFER HBMs. That project was granted funding and is ongoing 2019 to 2022 (FFI 2018–04998). That project is also connected to international resources for validation data needed for reclined seat positions. The advances of the morphing methods and the studies with the family of adult HBMs are significant and the morphed HBMs can be used for industrial application today. More refinements and validation research activities are needed. This work is included in the succeeding project (FFI 2020-02943), ongoing since November 2020.

Through several child safety publications, presentations and by gathering the international workshop, the project group has raised child passenger protection challenges, having impact on international standard development as well as rating and regulatory discussions. In addition, the project has contributed to an enhanced toolbox for inhouse child safety testing for the partners; by the introduction of a child HBM (PIPER, see Figure 3a) and evaluations on up-date kits on existing child ATDs (Figure 3c). These studies are also examples of provided direct input to rating protocols, and potentially, eventually regulation. As an example of influencing the global child safety agenda, several studies on child protection in the context of shared mobility was performed and shared with different involved stakeholders, raising criticism to several stakeholders, including lawmakers, test institutes and child restraint manufactures (Jakobsson et al. 2020).

Through the project's agile and knowledge-sharing way of working - adapting parts of the research to current topics and inviting researchers in dialogues - it has inspired to new research by other research groups (e.g. at University of Virginia (UVA), UMTRI and the CChIPS partners in the USA, as well as researchers in Australia). As an example, the world first reclined human subject tests to generate validation data to HBM by UVA (Richardson et al., 2020) was built on the knowledge from the crash test in reclined occupant position done within this project (Östling et al., 2017). The project has also contributed to the successful applications of the EU-projects OSCCAR and VIRTUAL. Although benefits of a larger funding and more involved partners, the EU projects cannot replace the profits of the FFI projects' ability to be agile and more flexible in execution, adapt to the current situation, and easier to take joint decisions on what to do, how and when. As an example, during this project we have executed thirteen Master theses involving 21 students. The topics of the majority of these Master theses were not decided when starting this 3-year project. They were all selected based on current areas of interest at that time. Up to date, six scientific papers have been the result of the Master theses, contribution to driving novel research areas.

The project results are utilized in product development and advanced engineering projects within the industrial partners of the project. The adult morphed SAFER HBMs are used as complements to the standardized ATD sizes available, providing further insights into passenger protection needs. The child 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 Contribution to the objectives 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 passengers of today, complemented with prediction studies on future crash situations and vehicle interior designs; the results derived are set to contribute to long-term injury reduction. The inclusions 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.

Future cars

Automated vehicles are important contributions to Vision Zero ambitions by likely reducing the frequency of crashes. However, in a foreseeable future, even unsupervised AVs will be exposed to crashes e.g. other by manual driven vehicles. In order to address the expectations of the occupants to engage in other sitting postures, positions and activities, new protection principles must be developed. The project has contributed with new insights and assessment methods addressing this; including studies ranging from prediction of types of crashes to investigate expectations regarding vehicle interior design.

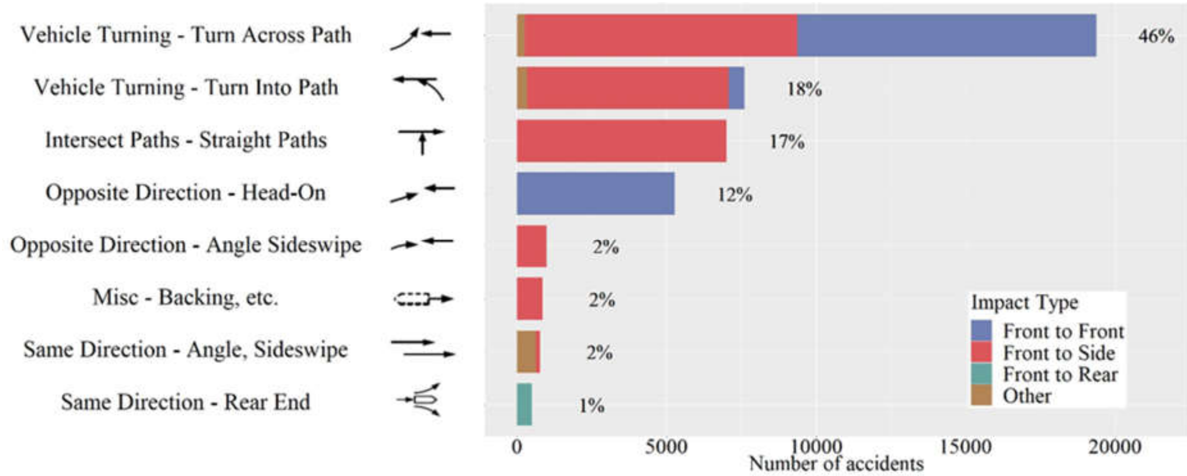

Figure 5. Prediction of unavoidable crash scenarios, based on ADAS functions, example from the NASS CDS database in USA (Östling et al., 2019a)

An example of results from one of the crash scenarios prediction studies is shown in Figure 5. Using current real-world data and a method of applying prediction of influence of ADAS functions, a priority of crash scenarios can be made. Using the "Setting the stage" method (Figure 6a), vehicle interior design preferences in unsupervised AVs were evaluated in Sweden (Jorlöv et al. 2017) and in China (Östling and Larsson, 2019). Although two different countries, the user expectations were similar. In both studies the volunteers expected fully automated vehicles to allow reclined seat positions, versions of a living room setup, and more comfortable seats with screens and tables for various activities. In the Master thesis by Hagberg and Jodlovsky (2017), Figure 6b, it was found that the tendency to sit reclined increased when the seat was of highly AV design and the reclined positions often led to a lap belt that was placed above the pelvis. Another interesting finding was that a majority of the respondents (64%) did not think about crash safety when selecting their seat positions.

Figure 6a. Investigating future expectations of future automated vehicle interiors (Östling and Larsson, 2019)

Figure 6b. Reclined seat in the study by Hagberg and Jodlovsky (2017)

The heterogenous population

The development of assessment methods for protection of the heterogeneous population has contributed to the possibilities for a higher precision and flexibility of scenarios and individual differences. 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 in Figure 2). Validation studies were performed. HBMs of a variety of occupant sizes, ages and sex; used together with the knowledge on how they sit as passengers in cars, enhances the relevance of occupant protection assessment.

As described in the FFI goals, a substantial amount of fatal and injurious crashes is likely avoided by active safety systems. However, it is also of importance to ensure good protection of the car occupants in the cases where the crash is not avoided completely. For this purpose, the capabilities of the morphed SAFER HBMs, including active muscles, are superior to any other assessment tool of today; providing the variations of occupant sizes in combination with the seamless manoeuvre followed by impact ability. The results in this project have taken the morphed SAFER HBMs into a first step of industrialization. Although, still ongoing refinements and validations, there is now a family of different sizes to be used. Today, they are used by the industrial partners within the product development process.

Figure 7a. Example of passengers in the older adult study (Ankartoft and Alfredsson, 2018)

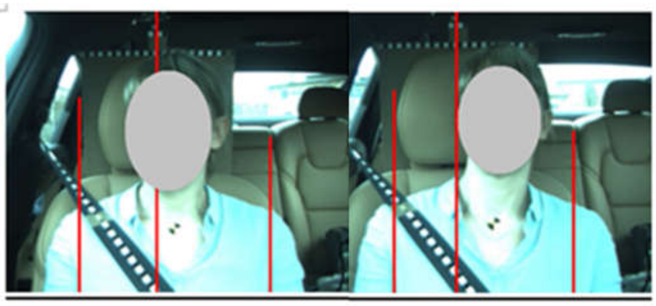

Figure 7b. Example of a front passenger prior to turn (left) and at max lateral position with head off the head restraint (right) (Bohman et al., 2020a)

The project has explored a variety of individual differences in seating, including women and men, of different age groups and during different types of travel. The research contributes to address protection strategies; by understanding how the protection systems interact with the car passenger. These studies are essential for understanding exposure of varieties of sitting postures and how to adapt to assessment methods. Some examples for adults are shown in Figure 7. The studies on the older adults in a stationary car (Figure 7a) provided insights into seat beltfit from a body shape as well as comfort perspective. The study on lateral movements during driving in every-day situations (Figure 7b), provided quantified data that can be used as input to simulation studies for assessing protection principles in relevant sitting postures.

Figure 8 provides some examples of studies on children in cars. The study on older child passengers resulted in strategies on how to address the behaviour of those children and their protection (Figure 8a). Children that have graduated from child restraints, but are yet not adults, deserve to be more addressed in vehicle safety research; which this study is an example of. For optimal protection of children using child restraints, it is essential that the car, the child restraint and the users are regarded as one entity. The research group has worked over a long period of time to encourage the child safety stakeholders, globally, to work together towards this mind-set. Figure 8b is from the most recent presentation and publication on this topic, identifying the mismatch between booster developments and the users' needs, specifically in the increasing trend of shared mobility (Jakobsson et al., 2020).

Figure 8a. Concept of rear seat entertainment system for older child passenger (Gereben and Swenson 2020)

Figure 8b. Example of a 6-year-old child trying out the booster prototype in Jakobsson et al. (2020)

Swedish research edge

The knowledge gained in this project contributes to increase the competitiveness of the Swedish vehicle industry and provides 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. Important knowledge was generated regarding passenger protection in future vehicles, providing impact globally. One of our studies is the most frequently cited article in publications on seating challenges in future vehicles (Jorlöv et al., 2017). Inviting to the sixth bi-annual international child occupant protection workshop with world-leading researchers and everyone prioritized the event and participated (partly on their own budget) is a true example of our international position and way of working. Our way of working includes performing limited studies within unexplored areas, and to share with peer-researchers. Several of our publications on quantifying passenger sitting postures and restraint interactions have inspired other research groups to follow, usually with larger studies providing more data. An example is the large-scale study by UMTRI (Reed et al., 2020), which was inspired by our pioneering studies.

The project's studies on the novel adult ATD evaluation provide insights into their capabilities of representing challenges in future transportation, but also raised concerns on their biofidelity. This has triggered recent studies at UVA and a dialogue with the researchers at the National Highway Traffic Safety Administration (NHTSA) in USA. Our studies showed that the novel THOR-AV ATD (Figure 4a) was capable of submarining more easily than the current THOR ATD in reclined seat position. However, Richardson et al. (2020) showed that four out of five human subjects exposed to similar condition did not submarine. In another test series within the project, the novel small female sized THOR 5F ATD (Figure 4b) was shown to replicate the kinematics of the mid-size male counterpart THOR 50M ATD in upright seat position, which differed from the Hybrid III ATD counterparts. It is still to be determined whether the kinematics of the THOR ATD family replicates a human better than the older family of Hybrid III ATDs, in upright seat position as well as reclined seat position, when subjected to frontal crash without knee bolsters, as would be the situation in more futuristic vehicle interior like the living room seat configuration. Recent studies at UVA have shown that, in reclined seat position, the mid-sized male Hybrid III ATD better replicates humanlike pelvis kinematics (Kerrigan et al. 2020).

Further studies within this topic are ongoing, partly in collaboration between project partners and universities in USA. This research is essential to ensure that the ATDs used for reclined seat positions in future cars are biofidelic.

The project is a part of the SAFER's HBM competence cluster, which is based on a continuous path of research projects working in sequence or parallel towards 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. This project contributes with the morphing part, in addition to the research on understanding future needs in car traveling, including sitting postures. The HBM modelling results from this project was integrated, together with the parallel projects' recent research, into an update of the SAFER HBM during 2020 (version 10.0). The other projects contribute with muscle activation and control strategies for pre-crash kinematics and refinement of different body regions, such as pelvis, lumbar spine and shoulders including omni-directional injury prediction (2017-05516 and 2018-04998). The interaction with the ongoing EU-projects (OSCCAR, VIRTUAL and SAFE-UP) as well as the recently finalized Vinnova funded project ViVA II (2016-03353) are examples of other interactions within the SAFER's HBM competence cluster.

7 Dissemination and Publications

7.1 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.
Be passed on to other advanced technological development projects	x	Project results are used as input to future seat and restraint developments by the industrial partners.
Be passed on 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.
Introduced on the market		The project results are used in vehicle and restraint system development within the industrial partners.
Used in investigations / regulatory / licensing / political decisions	x	The project results have influenced regulations, ISO-standards and rating tests (e.g. EuroNCAP), specifically with respect to child safety.

Examples of dissemination in addition to the publications and conference presentations listed in Chapter 7.2:

- Arranging the SAFER seminar "Child Occupant Protection: Latest knowledge and Future opportunities" September 2019; https://www.saferresearch.com/events/child-occupant-protection-seminar-latest-knowledge-and-challenges-future-mobility
- Presentation at FFI's Resultatkonferens 27 September 2017, Göteborg: Lotta Jakobsson (and Trent Victor); "*Säkerhet och självkörande personbilar*" https://www.vinnova.se/kalenderhandelser/2017/09/trafiksakerhet-och-automatiserade-fordon/
- Presentation at SAFER lunch seminar, 5 April 2018: by Martin Östling, entitled "*Crash Configuration Definition for Assessment of Passenger Safety in Future Cars*"
- Poster presentation at FFI's Resultatkonferens, 27 September 2018, Göteborg https://www.vinnova.se/kalenderhandelser/20182/09/resultatkonferens-for-ffi-trafiksakerhet--automatiserade-fordon/
- Project presentation at FFI TSAF Program, 12 November 2018: by Lotta Jakobsson
- Presentations at SAFER lunch seminar, 10 October 2019: by Lotta Jakobsson, entitled "*Child occupant protection workshops; an example of successful project dissemination and international interaction*", and by Katarina Bohman, entitled "*Child protection challenges in future cars - increased automation and shared mobility*"
- SAFER Research Area Human Body Protection workshop on "New seating and ways to use future cars", 14 January 2020: presentations by Katarina Bohman and Martin Östling on *Prediction future seating preferences* and *Investigating seating configurations*
- SAFER's pre-event to UN 3rd Global Ministerial Conference on Road Safety, Stockholm 18 February 2020: *Poster presentation* as part of the Human Body Protection exhibition, by Mats Svensson and Lotta Jakobsson.
- RCCADS Public Workshop webinar,19 May, 2020: Martin Östling part in Panel Q&A discussion together with Rini Sherony (CSRC), Ann Mallory (TRC Inc.) and Carol Flannagan(UMTRI), and presentation entitled "*Predicting Future Intersection Crashes: Two Methods of Different Complexity on Automated Driving and ADAS Coming to Similar Conclusions*".
- Licentiate Thesis presentation and discussion, 10 June 2020: Karl-Johan Larsson and Opponent Philippe Beillas, IFSTTAR, France.
- Lindholmen Open Day, celebrating LSP 20 years, 15 September 2020: part of SAFER's presentation, by Lotta Jakobsson
- 48th NHTSA Workshop on Human Subjects for Biomechanical Research, Webinar, 27-28 October 2020: Martin Östling part of study presented "*Comparison of Hybrid III and THOR in Recline Frontal Sled Tests without a Knee Bolster*", by Richardson R, Kerrigan J, Forman J, Gepner B, Ostling M.
- Presentation at SAE Government Industry Digital Summit, SAE International, USA (online) 2 February 2021: by Jolyon Carroll, Autoliv, entitled "*Comparison of THOR-5F with Hybrid III 5th percentile*"

7.2 Publications and Conference Presentations

Licentiate Thesis:

Karl-Johan Larsson. *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, Chalmers University of Technology, Göteborg, Sweden, 2020.

Master Theses:

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

Robin Ankartoft and Svante Alfredsson. *Elderly passengers in cars – Study of belt fit and comfort, Master Thesis in Industrial Design Engineering, Chalmers University of Technology*, 2018

Mathilda Janson and Jessica Wedmark. *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*, 2018

Josefine Berntsson. *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, 2018

Sarah El-Mobader. *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, 2018

Anna Olander and Agnes Andersson. *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, 2019

Annika Hansson and Emma Lysén. *A study of sitting posture and belt fit in a travelling car- How do passengers sit in a travelling car? Master Thesis in Automotive and Biomedical Engineering, Chalmers University of Technology*, 2019

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

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

Eric Elinder and Jaquline Hultman. *Child restraint system for shared mobility – Development of a mobile, rear-facing and safe car seat for the car travels of the future,* Master Thesis in Industrial Design Engineering, Chalmers University of Technology, 2020

Mio Gereben and Maia Swenson. *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, 2020

Amanda Blennow, *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, 2020

Melina Makris. *Seating and driver interaction sin automated vehicles*, Master Thesis in Biomedical Engineering, Chalmers University of Technology, 2020

Peer-review papers:

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

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 Conference*, IRC-18-11, Aten, Greece, 2018

Larsson K-J, Pipkorn B, Iraeus J, Bolte IV JH, Agnew AM, Hu J, Reed MP, Sunnevång C. Evaluation of the Benefits of Parametric Human Body Model Morphing for Prediction of Injury to Elderly Occupants in Side Impact, *IRCOBI Conference*, IRC-19-22, Florence, Italy, 2019

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

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

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

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*, 2020

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Conference Publications

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, 29 Nov 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

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Östling M, Lubbe N, Jeppsson H, Puthan P. Passenger car safety beyond ADAS: Defining remaining accident configuration as future priorities. *Proc of 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV),* Paper Number 19-0091, Eindhoven, the Netherlands, 2019

Östling M, Larsson A. Occupant activities and sitting positions in automated vehicles in China and Sweden, *Proc of 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV),* Paper Number ref 19-0083, Eindhoven, the Netherlands, 2019

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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

In preparation:

Jakobsson et al. “Assessment of passenger protection in future cars – a project overview”, targeting next ESV conference, 2022?

8 Conclusions and Future Research

The importance and complexity of passenger protection in cars increase with 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 and car usage and ownership, require assessment tools and evaluation methods beyond the standardized crash test methods of today. The project has contributed to advancements of assessing protection of the heterogeneous population of passengers in future car crashes, by gathering a variety of competences, combining different types of methods and international collaboration.

Novel studies on prediction of future crash configurations and seating preferences were performed, contributing to new insights as well as high international visibility. One of our studies from 2017 is frequently cited in publications on “future vehicles”.

Passenger protection needs were studied through observation studies on passenger sitting postures and beltfit, in combination with simulation series and crash testing. The importance of body shape was highlighted in a study including older adults, while the influence of booster design was raised for children. Restraint principles for adults in reclined seat position was investigated, along with evaluation of the capabilities of the assessment tools (e.g. novel crash test dummies). Studies were performed with good timing and have inspired research initiatives globally.

Methodology for selection of representative individuals for crashworthiness assessment was developed, addressing the heterogeneous population. Morphing techniques were established, and a family of morphed Human Body Models was created and prepared for use in vehicle and safety system developments.

The project has delivered novel data, tools and methods to assess the protection of the heterogeneous population of passengers in future vehicle crashes. In total, the project has resulted in one Licentiate thesis, thirteen Master theses and at least eighteen publications, whereof half are peer-review papers.

Furthermore, the project arranged the 6th International Child Car Passenger Protection 2-days workshop in Sept 2019, in addition to more than six workshops and other exchanges with international researchers. The international interaction serves the purpose to assure optimal relevance for project execution as well as dissemination.

Future research includes ongoing projects initiated by the present project results, such as pelvis model development including scalability and validation for reclined seat position. Further research challenges will be addressed in the succeeding project ‘Car Passenger Safety – to the next level’. In that project, the PhD student in the present project, will continue the development of the family of morphed Human Body Models. In addition, a second PhD student is added to the team to further strengthen the area of human factors/ergonomics design and the understanding on passengers’ behaviour, experiences and attitudes, and how to take that into account in crash protection. Furthermore, international dialogues and interactions will be further emphasized.

9 Project Partners and Contact Persons

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

Chalmers:

Mats Svensson, Anna-Lisa Osvalder

Autoliv:

Martin Östling, Karl-Johan Larsson, Bengt Pipkorn

Volvo Cars:

Katarina Bohman, Isabelle Stockman, Pernilla Nurbo, Lotta Jakobsson (project leader)

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

Hanna Jeppsson and Nils Lubbe at Autoliv

Maria Wimmerstedt, Magdalena Lindman, Jacob Wass, Jonas Östh, Fredrik Heurlin, Catherine Lef and Henrik Nilsson at Volvo Cars

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