OCCUPANT PROTECTION FOR AD CARS – THE PARADIGM SHIFT IN CRASH SAFETY?

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ABSTRACT

When moving towards unsupervised autonomous driving (AD) and the customer expectations of those vehicles, the approach, tools and methods used today in occupant protection assessment are likely not sufficient. Single sitting postures, limited sizes of occupants and crash test set-ups used today will not cover the situations arising. Fundamental changes in evaluation approach and underlying assumptions are foreseen, similar to a paradigm shift.

The objective of this paper is to elaborate on and concretize the research needed, specifically targeting the question: How do we assess the protection of the heterogeneous passenger population in future vehicle crashes enabling occupant protection in unsupervised AD, providing the extended customer benefits of those cars? This paper summarizes relevant state-of-art research in the area and identifies topics for further research focusing on methods and tools for occupant protection assessment.

Future unsupervised AD cars, in addition to future manually driven cars, are likely to be exposed to crashes. Hence, the occupants' need to be protected is obvious, as today. The paradigm shift is driven by and relates to the mindset on car usage and occupant requests. It calls for new ways of addressing crashworthiness evaluation, emphasizing the large effort in research and knowledge creation needed, as well as a new setup in procedures and responsibilities of stakeholders involved. It likely requires addressing expanded crash set-ups, taking the whole event into account (including pre-crash maneuvers), in addition to a larger population of occupants, and a larger range of seat positions, seating configurations and sitting postures. A human-centric approach is proposed as the way forward. Being an alternative to a technology-driven approach (e.g. the SAE levels of automation), the human-centric approach sets the human needs and abilities in focus, and designs technology around them.

Substantial data on sitting postures and behavior in cars today needs to be collected and analyzed, to enhance the interpretation of existing real world data and to form the knowledge foundation towards the future challenges. Furthermore, user studies of future expectations are desired, especially in the light of changes in mobility trends. Simplified crash test dummy designs will not be sufficient. There is a need of continuous development of today's human body models facilitating the expansion in sitting postures and sizes, enhanced injury predictability and capable of simulating pre-crash kinematics. This includes generation of validation data and biomechanics research on injury mechanisms as well as material data such as adipose tissues. Pediatric occupant tools need special attention, in addition to investigating and cooperating around the protection of children in future cars.

In order <u>not</u> to be a stopper for enabling the customer benefits in the development of autonomous drive, the occupant protection challenges need to be addressed. This paper discusses some different aspects of this, however being a paradigm shift, a common discussion and cooperation among stakeholders is needed to cover the whole spectra of aspects.

INTRODUCTION

Passenger car occupant protection today is evaluated through a limited number of crash tests. Although extensive, a limited number of situations are evaluated through the safety standards, such as the FMVSS and UN ECE. In most cases, the standard specifies a certain crash scenario using a single specific occupant size, in one sitting posture. Child restraints are mainly considered add-on devices, certified using a generic rig. In addition, the consumer test programs (eg. performed by IIHS and EuroNCAP) add to the tests for which most cars are evaluated in. In addition, some additional real-world situations form the platform for occupant protection. However, when difficult to protect, the passengers will be informed and/or restricted in usage, through the user manual or similar. Examples of this are compulsory seat belt use, and information on limitations in protection if the seat is substantially reclined.

When moving towards unsupervised autonomous driving (AD) and the customer expectations with those self-driving cars, the approach, tools and methods used today are likely not sufficient. Single sitting postures, limited sizes of occupants and crash test set-ups used today will not cover the situations arising for occupant protection evaluations.

The objective of this paper is to elaborate on and concretize the research needed, specifically targeting the question: How do we assess the protection of the heterogeneous passenger population in future vehicle crashes enabling occupant protection in unsupervised AD, providing the extended customer benefits of those cars?
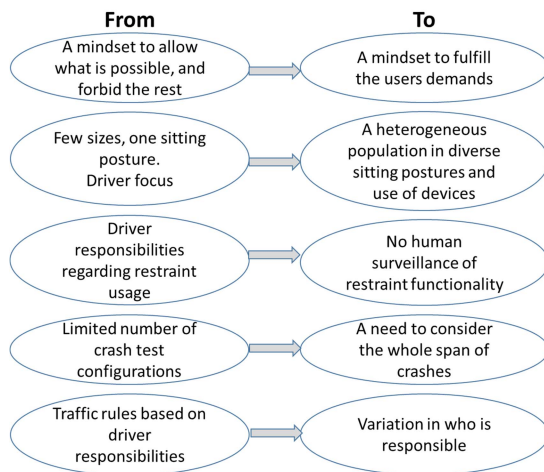
THE PARADIGM SHIFT IN CRASH SAFETY?

As shown in several studies, the extended customer benefits of future cars include other activities and seating configurations as of today. Extended ways of using the car are foreseen. A qualitative study in Sweden, Jorlöv et al. (2017) showed user expectations of seating configuration facing each other, when travelling together with friends and families for a longer trip. In the shorter trip scenario, the users were less in desire to rotate the seat, but instead aspiring to recline the seat into a more relaxed position enabling relax, sleep, surf the internet, work, or read. Similar findings were found when the study was repeated in Shanghai, China (Östling and Larsson, 2019).

Using online survey with 1,000 respondents in Germany, Fraedrich et al. (2016) investigated use-case-oriented mindsets on several topics for different types of automated concepts, For trips in the city and with shopping and luggage haulage, 'Parking Pilot' was seen as helpful while 'Highway Pilot' was deemed most positive on longer trips and journeys. Both of these allow a driver to disengage from the driving task, but the driver needs to be prepared to take over whenever requested. While, among the steering-wheel free concepts, the so called 'Fully Automated Vehicle' was perceived as being more useful than the 'Vehicle on Demand' (e.g. "robotaxi"), likely related to that a larger share of the respondents could not really picture what that concept was. Long distance trips, longer journeys and cross country trips were the trip types most stated as being helpful for the so called 'Fully Automated Vehicle'.

Hence, new ways of using the cars could include long trips, where the car replaces the train or even the plane. Examples of this was shown with this business model of using the car as a comfortable experience for replacing short-haul flights, such as the Volvo 360c concept (Volvo Cars, 2018). This concept can transform from a comfortable seat, possible to recline in different degrees, into a sleeping compartment, providing an alternative to the flight. The concept is capable of taking you to the meeting in the other city during the night, from door to door; arriving more relaxed than after a flight travel. Some other variants of interior concept models were shown within the Volvo 360c concept. One of them being a business case of an office on wheels, e.g. replacing the need for an expensive office in an attractive city location, enabling use of pick-up time, in addition to use the parked car as the meeting place. The set-up of such a car would include face-to-face seating, table and devices needed for meetings. When addressing the user's demands in these examples, occupant protection challenges includes activities and a range of sitting postures, including lying down.

The other end of new ways of using the cars is exemplified by the 'robotaxi'/'robocab', enabling transportation of passengers during shorter trips. On one hand, the sitting postures and activities might not deviate substantially from today's cars, with the addition of increasing degree of rearward facing. On the other hand, those vehicles will likely pick-up new passengers frequently, and there will be protection challenges accommodating the variety of passengers, including children, in addition to the lack of dedicated on-board human support and supervision.

Introducing new types of vehicles will add to the variations in traffic. It will likely be a combination of mixed traffic, including AD, driver assistance and manually driven cars, and fully autonomous traffic, both having their challenges. Simply, it will provide a larger variety of cars that need to be addressed from a crashworthiness perspective, on top of adding the complexity in the rules/ guidelines on responsibility set-up.

From	To
A mindset to allow what is possible, and forbid the rest	A mindset to fulfill the users demands
Few sizes, one sitting posture. Driver focus	A heterogeneous population in diverse sitting postures and use of devices
Driver responsibilities regarding restraint usage	No human surveillance of restraint functionality
Limited number of crash test configurations	A need to consider the whole span of crashes
Traffic rules based on driver responsibilities	Variation in who is responsible

Figure 1. Examples of aspects in the paradigm shift

As illustrated in Figure 1, we need to move towards a mindset of addressing the demands of the user, from a reality today of allowing what is possible, and to forbid the rest. An example of this is when reclining the seatback to get a more relaxed position. Although it is possible to recline most front seats today, it is requested in most cars' user manuals to have the seat in an upright position, according to the certified position.

Applying such mindset of addressing customer demands, also includes that everyone should be equally protected, in their chosen sitting posture and activity. Today, the capabilities of the occupant tools are limited, restricting the inclusion in a regulative perspective. There is a need for increased focus on passengers of all sizes and ages, expanding the scope of today with few occupant sizes, one sitting posture and a driver focus.

Today, there is a driver having an overall responsibility (or at least a possibility to have) to ensure usage of restraints. It could be the seat belt or child restraints usage, or simply ensure that the passengers are seated within dedicated space. In the future non-driver environment, this is a challenge that needs to be taken care of.

The limited number of crash test set-ups that the vehicles are certified for today, will likely not be sufficient in the context of tomorrow. As a result of the advancements in occupant protection over the years, more unique cases are needed to be addressed. In addition, the rapid implementation of collision mitigation technologies is seen. Hence, an important topic is the need to handle the large span of crashes, in addition to that the crash will be dependent by the collision mitigation technology, or the autonomous drive systems. Today, the influence of an autonomous pre-crash intervention (e.g. braking or steering) is usually not taken into consideration in the crash testing for evaluating crashworthiness, while they in real world situations could contribute to the occupant protection by reducing speed. From a real-world perspective, today as well as in the future, enabling the automated pre-crash maneuvers to be a part of the design of the crashworthiness evaluation is desired.

As also listed in Figure 1, the role of the driver today to obey the traffic rules plays an important part of the traffic system. In future cars without dedicated drivers, the aspects of this role need to be included in the context as well.

Summing this up, fundamental changes in evaluation approach and underlying assumptions are foreseen, similar to a paradigm shift.

The paradigm shift can be summarized by the following main points:
- The mindset
- The population
- New seating configurations, seat positions and sitting postures
- Responsibilities; who takes over the driver's role in occupant protection?
- The span of crashes and whole crash events to understand and handle

In order not to be a stopper for enabling the customer benefits in the development of autonomous drive, the occupant protection challenges need to be addressed. This paper discusses some different aspects of this, however being a paradigm shift, a common discussion and cooperation among stakeholders is needed to cover the whole spectra of aspects.

HUMAN-CENTRIC SAFETY

The development towards autonomous drive has been ongoing for more than a decade, starting with driver support systems in car-following situations, followed by autobrake functionality including when turning in front of an oncoming vehicle in intersections (Ljung Aust et al., 2015). Assisting the driver when inattentive or distracted, the auto brake and/or auto steer functionalities will add to the proportion of crashes which are preceded by a maneuver. Hence, moving towards higher degree of automation, a large share of the crashes that occur are likely to have exerted the occupants to a pre-crash kinematics exposure (e.g. from deceleration), caused either by the driver or the technology.

From an occupant protection point of view, it does not make much difference whether a human driver is driving the car, or the machine. Except, for the driver for whom the steering wheel would be included in the protection systems, and the differences in his/her pre-crash kinematics. What really influences the occupant protection needs are the business cases for which the vehicles are designed for (e.g. those described in the 360c concept above); adding customer values influencing the use of the car, including possible sitting postures and seating configurations.

From a human-centric point of view, the SAE levels of automation (SAE J3016) do not provide a relevant framework. This is quite obvious with respect to occupant protection. In addition, even from a driver's role perspective it does not provide sufficient structure. A human-centric approach calls for a need to clarify the driver's role, reducing the confusion on whether the automation is driver assistance which requires driver engagement and responsibility or whether the automation is designed for the operator to safely do something else while relieved from the driving task (unsupervised AD). Driver assistance systems only partly support the driving task (e.g. headway control with some degree of steering assistance), and the driver is still required to supervise the driving and intervene at sensing or actuation limits (e.g. conflict situations). In contrast, unsupervised AD enables either (1) periods of drive-free time where the driver assumes a temporary role of a passenger for a period of time or (2) full trips where the user delegates full control and responsibility to the vehicle (e.g. 'robotaxis'). Until unsupervised AD exists and the driver can switch roles to become a passenger, automation is assistance and the driver is not free to disengage from the driving task to freely do non-driving related activities. The driver must clearly understand when automation provides a role switching from a driver role to a passenger/operator role.

Thus, different types of automation are associated with and designed for different expectations on the driver or passengers. For example systems could be designed to allow all occupants to sleep, or could be designed to expect a driver to monitor and act when automation encounters its limitations. Clearly, knowledge regarding human limitations is key to setting constraints. Safe, human-centric automation sets the human needs and abilities in focus, and designs technology around this. Safe, human-centric types of automation is to be seen as an alternative to the technology-driven approach, which the SAE levels of automation represents.

Human-centric safety relies on three parts, as illustrated in Figure 2. The three parts are based on areas in which human limitations can help create a platform of knowledge and implementation. 'Human cognitive abilities, skills and behavior' and 'Safe user experience' are the two complements to the more established 'Human injury tolerances'. The latter will be further addressed in this paper.
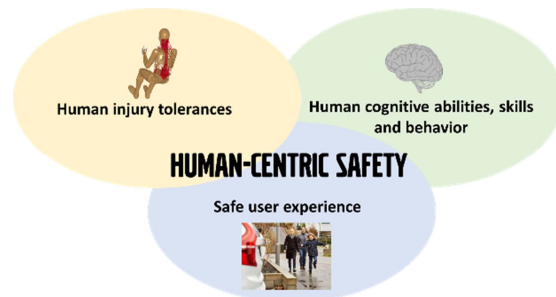
Figure 2. Human-centric safety at Volvo Cars

Human injury tolerances are the foundation in occupant protection. Biomechanics and fundamental principles of protection are the guiding essentials and the paradigm aspects (as presented in prior chapter) and type of automation is a crucial context.

FOCUS AREAS FOR HUMAN INJURY TOLERANCES

Future unsupervised AD cars, in addition to future manually driven cars, are likely to be exposed to crashes. Hence, the occupants' need to be protected is obvious, as today. As described in previous chapter, the current situation for occupant protection calls for fundamental changes in evaluation approach, underlying assumptions and role of different

stakeholders. This includes new research and application of this research.

Following a summary of *Biomechanical Principles*, this chapter provides a description of the major challenges within knowledge needed to encompass the wide spectra of future cars. The challenges include the *Complete Crash Event*, *Occupant Sitting Postures at Impact* and *Occupant Protection Principles* described in a human-centric perspective.

Biomechanical Principles

The fundamental biomechanical principles for impact trauma apply. The most important are summarized as follows:

- Restrain strong body parts
- Early coupling
- Distribute load
- Minimize relative motion between body parts
- Reduce contact forces to interior

Strong body parts are pelvis, shoulder, thorax and femur, including axial direction through the lower extremities, including the feet. Protection should be achieved by adapting the force distribution over various body regions by controlling and adapting kinematics and restraint forces. The three-point seat belt is an example of interaction with strong body regions, see Figure 3.


Figure 3. Example of interacting with strong body parts. The three point seat belt should be positioned over the pelvis and across the chest and shoulder.

As emphasized by (Kent and Forman, 2015), early coupling of the occupant is beneficial. This means achieving occupant deceleration similar to the vehicle deceleration, in contrary to an unrestrained occupant that does not benefit from the vehicle deceleration

and will thus experience higher forces when contacting. This occupant/vehicle coupling can be referred to as "ride down of the vehicle deceleration". By the use of the whole time of the crash and to distribute the load during the whole event, the internal loadings will be less. The distance include both interior space and vehicle crush zone, in addition to the contribution of crash mitigation time. It is essential to maintain the coupling during the complete crash event (also including a pre-crash maneuver), to ensure control of the occupant kinematics and force control.

Distributed loads are essential to minimize deformation to the body tissues and reduce loads between body parts. As an example, the spine is sensitive to shear forces if applied locally, but can withstand high forces if distributed over a larger area (Crandall et al., 1997, Kent et al., 2001). By distributing the load over e.g. the whole ribcage, or by supporting the head and torso together, as for astronauts when launched in space, or the principles of a rearward facing child seat (Aldman, 1964, Figure 4), needed protection is achieved.
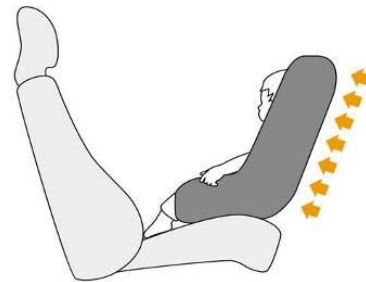
Figure 4. A child in a rearward facing seat, illustrating the protection principle of distributed loads, in case of a frontal impact.

The principle of minimizing relative motion between body parts is essential. Unbalanced head and neck kinematics may result in neck injuries, including whiplash injuries (Siegmund et al., 2009). Unbalanced pelvis and upper torso kinematics may contribute to submarining (Adomeit and Heger, 1975). It is vital to control kinematics and restraint forces to manage the relative motion between body parts.

If the distances are not enough for a smooth "ride down of the vehicle deceleration", the forces when the occupant impacts the interior surface should be controlled. Padding and airbags are means to control the stiffness of interior surfaces. The challenge is higher when short distance between the occupant and the interior, such as for an occupant today in a side impact. To control contacts include means to help protect the occupant, e.g. knee contact with the

interior, assisting in the early coupling. Car body strength is an enabler to help keep the intruding structure (magnitude and velocity) into the vehicle compartment low, and thereby the loading to the occupant.
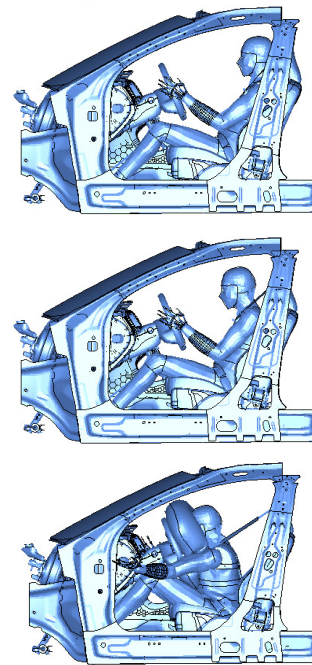
Complete Crash Event
In most of the crashes, the AD car will likely perform a maneuver prior to the crash targeting avoidance or mitigation. Already today, occupants are exposed to braking and steering prior to a crash, and technology influencing the crash configuration is available. However, in the standardized crash testing today, the cars are not exposed to pre-crash maneuvers, and the crash test dummies used are limited in their capabilities. As example, the crash test dummies designed for frontal impact tests are not capable of capturing biofidelic kinematics nor injury mechanisms in side impacts. None of them are designed for biofidelic kinematics in braking or steering movements.

There are two main concerns in this area. Firstly, it is relevant to include the influence of pre-crash kinematics into the occupant protection evaluation. In that way, the collision mitigation technology can be evaluated as part of the occupant protection. A simple example is how an autobrake in car-following situations can serve the purpose of reducing the occupant impact exposure in the same way as a well-designed energy absorption of the front structure. Occupant tools are needed that are capable of humanlike kinematics throughout a complete crash event, including the preceding event. Secondly, it is relevant to develop methods and tools that are omnidirectional in kinematics and injury prediction capabilities, i.e. possible to use independent of direction of impact. This will enable the possibility to design collision mitigation technologies that influence the crash configuration as a part of the occupant protection. An example of this is that for an intersection autobrake system, the activation algorithms can be further developed together with the interior restraint systems and car body design.

Today, the most capable tools to address these concerns are human body models (HBM). As compared to crash test dummies, HBMs have biofidelic sensitivity to different loading directions and differences in acceleration levels and can represent different occupant sizes, gender, and anthropometry. In addition, if muscle tonus is implemented in the models, so called Active HBMs, they have the potential to predict the occupant response in pre-crash and emergency events (Östh et al. 2015). An example of an active HBM capable of

occupant simulation comprising a maneuver and crash event was used in studies on braking and/or lane-change followed by frontal impacts (Östmann and Jakobsson, 2016, Saito et al, 2016, Pipkorn and Wass, 2017, Östh, 2018). Figure 5 is an illustration of the model and the sequences, taken from the study by Östmann and Jakobsson (2016).

Figure 5. Illustration of an active HBM capable of simulating a brake event prior to a crash event. Top: initial position, Middle: at time of impact, Bottom: at most forward head position

Methods to evaluate complete crash events need to be in focus for future occupant protection assessment. The methods and tools should be capable of including maneuvers and simulating occupant movements prior to the crash, in addition to being capable of injury prediction, independent of direction of impact.

Occupant Sitting Postures at Impact
In real world crashes, the occupants' sitting postures at impact are influenced by the selected sitting posture and the sitting posture as a result of the vehicle motion prior to the crash. This was described by Stockman (2016) and Jakobsson et al. (2017), focusing children in the rear seat. Driving studies with children showed that children choose a range of common user positions, which includes upright sitting posture, as well as forward leaning positions, including bending their necks forward when using

e.g. electronic hand-held devices (Osvalder et al., 2013, Andersson et al., 2010, Jakobsson et al., 2011, Arbogast et al., 2016, Cross et al., 2017). This is referred to as voluntary sitting postures, driven by comfort and the activities they engage into. Studies with children exposed to steering and braking maneuvers illustrate examples of non-voluntary sitting postures, moving the occupants forward or sidewise, even moving out of the shoulder belt (Stockman et al., 2013, Bohman et al., 2011b, Baker et al., 2017, Baker et al., 2018). It was hypothesized that the influence of the sitting posture at time of impact could explain why children sustained head impact related injuries, although they were correctly restrained according to the dataset analyzed (Bohman et al., 2011a). Based on this work, Jakobsson et al. (2017) emphasized that it is essential to monitor occupant postures and kinematics for enhanced understanding of protection needs at time of impact.

There is limited knowledge on voluntary sitting postures of front seat adult passengers, with only a few studies available on the topic. Zhang et al. (2004) made a survey with 560 participants. They identified 29 sitting postures for adult passengers and estimated the frequency of those. Upright selected posture was the most common (45%), followed by leaning inboards (8%) and leaning outboards towards b-pillar (8%). In an observational study by Bingley et al. (2005), front seat occupants were observed from the outside of the car. Passenger head centerline to vehicle centerline was collected, in addition to use of seatbelts, hand positions and activities.

Studies on front seat passenger kinematics in evasive maneuvers have been performed with the primary purpose of creating validation corridors for active human body models (Ólafsdottir et al., 2013, Ghaffari et al., 2018). The studies provide evidence on non-voluntary movements in braking and lane-change maneuvers. Although not comparable in set-up, the adult front seat passengers seemed more restricted in sidewise movements, as compared to the child rear seat passengers, likely due to more side support by the seat in the front seat, and probably more likely to support themselves with the feet than the children were .

Sitting posture influences injury outcome in case of a crash, in vehicles today. McMurry et al. (2018) analyzed data from CIREN and NASS-CDS, and found an elevated injury risk for occupants registered in the data as in an out-of-positions, e.g. reclined position, as compared to the occupants registered as in-position. Real world case studies have shown the limitations of protection in reclined sitting postures in existing cars, causing submarining resulting in injuries to the abdomen as well as cervical spine (Jeffery and Cook 1991, Rehm and Goldman 2001, Dissanaike et al. 2008). Investigating thoraco-lumbar spine injury mechanisms, it was seen that a forward bended occupant posture, due to kinematics in run-off road events, influenced the occurrence of spine injuries at the sudden stop (Jakobsson et al., 2006).

Using multibody human body models, Bose et al. (2010) investigated influence of sitting posture on injury outcome in frontal impacts, as one of four occupant parameters. They found several of the eight sitting postures evaluated to increase the risk of injury. Another study, using finite element human body models, showed that reclined sitting postures with state-of-art restraint system increase the risk of submarining (Lin et al. 2018).

Substantial data on sitting postures and behavior in cars today needs to be collected and analyzed, to form the knowledge foundation for the future challenges. Furthermore, user studies of future needs and expectations should be conducted, especially in the light of changes in mobility trends

Occupant Protection Principles
Traditionally, occupant protection principles have been related to principle direction of force (PDOF) of the crash and with the seats facing forward of the direction of travel. In future seating configuration, we may see seats rotated in various degrees, taking any direction up to turned rearward facing relative to the travel direction. Hence, it is more logical and constructive to relate the protection principles to the direction of force for which the occupant will be exposed to. This means taking into account both PDOF of the vehicle and the seating configuration. Therefore, we will refer to e.g. "forward", "rearward", "lateral", "oblique" movement of the occupant, irrespectively what direction the occupant and the seat is facing in the car. This is an example of human-centric approach, referring to the human instead of the car or crash.

No matter direction of occupant movement, the protection should to be designed around the occupant, e.g. both the seat belt as well as the seat itself. Future technical solutions are likely different from today's in order to work in new seating configuration. New seating configurations may include other direction of travel than today, as well as traditional support surfaces such as the instrument panels may not be available. The purpose of the description of the occupant protection principles in this chapter is to describe and exemplify the human-

centric approach, which should be valid, irrespectively of the boundary conditions.

Restraining the occupant in a pure forward movement (sagittal-anterior, such as a forward facing occupant in a frontal impact), the hipbone (pelvis) is essential to catch – allowing for controlled forward motion of the upper body. The conventional three point seat belts work in line with these principles. An essential part is the lap belt anchorage placement below the hips, as stated already when introduced in 1959 (Bohlin, 1964 and 1981). The seat structure is also a fundamental part of the protection. Airbags could be used to reduce relative motions between body parts and to distribute the load, but they may be designed differently than in today's vehicles. Load paths using the knees or feet could be effective means, especially when the occupant is reclined, helping to restrain the forward motion of the pelvis. It will be more challenging when using conventional restraints since it is more difficult to restrain a pelvis when it is rotated rearwards from its initial position. The real world case studies reported on injures passengers exposed to frontal impacts when substantially reclined confirm the challenges of today's technologies (Jeffery and Cook, 1991, Rehm and Goldman, 2001, Dissanaike et al. 2008).

Restraining the occupant in a pure rearward movement, has been a successful way of reducing injuries to the youngest children. By distributing the load of upper torso, neck and head over the whole the seat back (Figure 4), risk of injury is reduced. It is essential that the occupant remains supported by the seat back and head restraint during the whole crash, and does not slip off the seat back or head restraint, in order to control the relative motion between the head and torso.

Protecting the occupant in a pure lateral movement and all oblique combinations follows the fundamental biomechanical principles, as presented above. However, depending on the seating configuration and the surrounding interior structure, it will be more or less challenging. Likely, these situations are driving the most challenging needs of developments of tools, methods and new restraint strategies.

Studies have already provided insights into the challenge of maintaining the occupant in its protection as the occupant movement becomes oblique (Kitagawa et al. 2017). Already in today's vehicles, oblique frontal impacts, as well as far-side side impacts, for forward facing occupants are demanding in terms of controlling the kinematics of the upper torso and head. The way forward is to base the protection on the biomechanical principles, including an early coupling of the occupant,

restraining the strong body parts and distribute the loads. Likely, this means that the seat belt plays the fundamental role of protection but may need to be supported by other technical solutions in order to control the loading to the occupant and the kinematics of the occupant.

Specific concerns for children: Two major areas of concerns are special for children, otherwise the basic principles of occupant protection are valid, and independent of size and age. The two areas are neck vulnerability for the infants and toddlers, and pelvic bone size and shape for children up to puberty.

The infants and toddlers are especially vulnerable for relative motion between the head and the upper body. The special concern for this group is due to a combination of relatively large head size/weight (see Figure 6) and an immature neck with more horizontal vertebra which grow stronger when bone is replacing cartilage. It is therefore essential that the forces are distributed over a larger part of body, which can be achieved by riding in a seat with the back towards the travel direction (illustrated in Figure 4), also having side supports close to the body for lateral support.
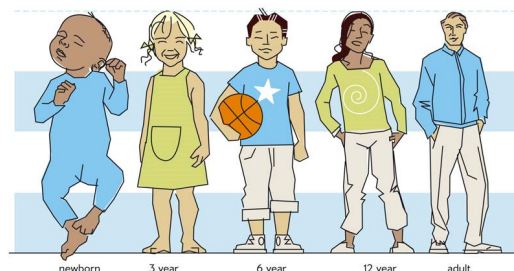
Figure 6. Body proportions for different ages

For children with relatively smaller pelvic body, using an adult designed seat belt, usually need to be adjusted in height to benefit from the same principles in the forward movement as explained above. However, from a principle perspective there are no major difference, although the shorter limbs and body regions call for comfort adjustments to accommodate a comfortable ride in the protected mode. As an example, if the seat cushion is too long for the child's legs to be comfortably bended, he/she will likely slouch forward whereby the intended interaction with the seat belt is missed.

DISCUSSION

The paper suggests that fundamental changes in evaluation approach and underlying assumptions are foreseen, similar to a paradigm shift. The paradigm shift is driven by and relates to the mindset on car

usage and occupant requests. It calls for new ways of addressing crashworthiness evaluation, emphasizing the huge effort in research and knowledge creation needed, as well as a new set-ups in procedures and responsibilities of stakeholders involved. It likely requires addressing expanded crash test set-ups, taking the whole event into account, in addition to a larger population of occupants, and a larger range of seat positions and sitting postures.

This is not the first time the crashworthiness challenges in unsupervised AD are addressed. In 2016, NHTSA published a Federal Automated Vehicles Policy as agency guidance to speed the delivery of an initial regulatory framework and best practices to guide manufacturers and other entities in the safe design, development, testing, and deployment of highly automated vehicles (NHTSA, 2016). Occupant protection, as part of crashworthiness, was addressed as one of 15 safety assessment topics. They stated that manufactures and other entities should exercise and demonstrate due care to provide countermeasures that will fully protect all occupants given any planned seating or interior configurations, and the tools to be used need not be limited to physical testing but also could include virtual tests with vehicle and human body models.

In Europe the focus on AD challenges is also high. Thatcham states that the rapid development of AD may force regulators to consider alternative and faster regulatory approaches than today, highlighting the need of fully redundant systems for robust automated driving solutions and how to prevent systems sold as 'Automated' when they require driver intervention to be safe (Thatcham, 2017). Euro NCAP describes in their road map 2025 a focus on the assessment of automated driving systems and driver/vehicle interaction (Euro NCAP, 2017). However, at this point neither Thatcham nor EuroNCAP address how occupant protection in AD cars should be assessed.

Safe Kids Worldwide organized a Blue Ribbon panel on children in autonomous vehicles, since they identified there is a great focus on adults and autonomous vehicles but there is lack of understanding the unique needs of children in this context. (Safe Kids Worldwide, 2018). They summarize five areas of actions encompassing safety standards, usability testing, inclusive design, appropriate supervision and marketed standards, emphasizing that children should be included in all phases. The report concludes that it is time to act straightaway, as it is necessary to build the knowledge of the needs of the children and the

families now, enabling them to be addressed in the ongoing rapid development of the technology.

Future unsupervised AD cars are likely to be exposed to crashes. The AD cars will be mixed with human-driven cars. Hence, the occupants' need to be protected is obvious. This paper suggests a human-centric approach as the way forward to address fundamental changes in evaluation approach, underlying assumptions and role of different stakeholders. This includes new research and application of this research. A human-centric approach applied to occupant protection is based on human injury thresholds. It addresses the needs of the occupants based on who they are, how they are sitting and what forces they are exerted to, according to the human reference system. It is also about a mindset, of changing from e.g. forward facing occupant in frontal impact; to understanding the occupant's sitting posture at impact, as a result of the whole crash event, and referring the protection principles to the human instead of the interior setting of the car or the impact type.

Based on the state-of-art tools and methods today, substantial knowledge gaps are evident, which we need to address through collective research in several areas. This paper highlights three main areas important for occupant protection assessments; the whole crash event, the sitting postures at impact and challenges regarding protection principles applied for relevant real world situations.

Occupant protection in cars is continuously improving. The large steps in injury reduction taken in the past, exemplified by introduction of e.g. seat belts, airbags, advanced front vehicle structures and side impact protection structure, are likely to be less frequent in the future. Instead, as result of the efficient work, the remaining priorities are more unique cases, in which tools and methods replicating a larger variety of crash and occupant characteristic are necessary. In addition, the rapid implementation of collision mitigation technologies calls for methods and tools including the pre-crash phase into the evaluation. Hence, methods and tools to evaluate complete crash events need to be in focus, considering maneuvers and occupant kinematics prior to the crash, in addition to all directions of impact.

Today, passenger cars are mainly designed to protect upright sitting occupants, who are centralized in their seat. At least, this is the way the crash test dummies are designed to be used. To change this and to form the knowledge foundation towards the future challenges, research in this area is needed both to interpret the real world data today, i.e. what are the

ranges of postures that are reflected by the data in the databases, as well as to understand future priorities.

Different activities will result in different sitting postures, for example a comfortable resting position will be different from a working position. It should be acknowledged, that changing sitting posture is part of our natural way of gaining comfort. To enable protection, the different postures need to be understood, and if not possible to protect based on available technology, ways of guiding the occupant into a preferred posture based on comfort should be in focus. Hence, data on sitting postures are also essential to understand the preferences of humans and how to address their preferences with respect to protection in the best way.

Substantial data, especially on passengers, needs to be collected during standard car drives, in addition to evasive maneuvers, quantifying differences between individuals as well as situations. Manual analysis of naturalistic driving studies is time consuming. Development of more automatic analysis methods has recently been initiated (Reed et al., 2018), and should be further enhanced capturing details on sitting postures as well as restraint positions.

Furthermore, user studies of future needs and expectations should be conducted, especially in the light of changes in mobility trends. Staged studies investigating seating configurations and sitting postures in relation to future perceived needs when moving towards higher degree of automation will help guide the development of functionalities not available in traffic today. Jorlöv et al. (2017) and Östling and Larsson (2019) are examples of such studies on seating configurations and activities.

Being the most capable tools to address the whole crash event and inherently designed with human properties, HMBs including muscle activation are today the most promising tools. Already today it can be used for combination of pre-crash events and impacts in different directions. This is needed when moving towards including the crash mitigation technologies being a part of the occupant protection. Just as important as being capable of recreating human kinematics in different types of maneuvers, is the ability to compare injury prediction responses resulting from different directions and contact points of a body region, resulting from a change in impact configuration due to the collision mitigation technology. Further, there is a need to include similar research for child occupant tools and to develop relevant physical tools (crash test dummies) as complement enabling hardware validation.

Substantial research is required to support the development of the occupant tools needed in the future. The research includes foundation for validation, development of relevant injury prediction, in addition to understand and take into account individual differences of all aspects.

New morphing techniques of HBM opens up the possibility of developing the families of HBM that can represent the population to a much wider extent, than the limited sizes of crash test dummies and HBMs currently available. There is need of research to determine what that population should look like, and if different families are needed for the difference in crashes and seating configuration. Knowledge is needed to understand who is vulnerable in the specific situation, but also to complement with other representatives of the population to ensure the wide range of occupants will be protected. The families include children as well. The biofidelic validation of existing pediatric tools (crash test dummies and HBMs) is lagging behind the work ongoing for adult tools, due to lack of data.

The morphed family needs to be validated, since it is not enough to morph the occupant to a relevant shape and size. The need of validation data include kinematics and muscle responses in maneuvers in addition to biomechanical data providing validation corridors for occupant movement directions and interactions. Especially there is a lack of validation data for occupants in a non-upright seat position.

NHTSA recently started a research program, including generation of validation data in reclined seat positions. Pure forward occupant movements and pure rearward occupant movements (simulating rear facing occupant in a frontal impact) are within the scope (Reed, 2019). In addition to the reclined postures, the inclusion of high severity rearward occupant movement is new. The latter providing a good complement to the available extensive rear-end impact research at lower severity. In addition, and just as important, validation data in lateral and oblique directions is urgently needed.

Applying the protection principles on new seating configurations and seat positions is challenging and it will require more advanced tools. In the development of new types of restraints, the tools are needed to help predict occupant interaction in a variety of sitting postures and occupant sizes. Hence, detailed models and biomechanical data is required, especially for the load bearing body parts. Restraint interaction with the pelvis is essential as this is a basic structure to use as load path. Interaction with the shoulder will likely continue to be an essential part of the protection system, ensuring the occupant remains restrained,

especially in oblique occupant movements. The load to lumbar spine may be increasing depending on how the load path in reclined sitting positions can be solved, and it is essential to have tools that can predict loads to the spine. Another challenge is valid representation of soft tissues, which today is very limited in any of the tools used for occupant protection. One example is the importance of adipose tissues influencing the position of the restraints, as well as the time of restraint interaction to the skeleton. Reed et al. (2012 and 2013) showed how the lap belt will be positioned more forward of the pelvis bones if the occupant has high body mass index (BMI) compared to occupants with normal BMI.

For children, smart adaption of protection is a focus area with increasing importance in the future. Today the children's needs are addressed by adding child restraint systems into the vehicle. The majority of these solutions are aftermarket solutions, while only a few cars offer built-in solutions, such as booster seats (Jakobsson et al., 2007). In line with the increased shared mobility, it is essential that the solutions for child occupant protection are convenient, easy to use and provide adequate safety in case of a crash. Jakobsson et al. (2017) summarized that from a real-world safety perspective, the vehicle and child restraint should be designed together targeting a range of acceptable common user positions; sitting postures preferably guided by comfort and positive means. Such designs will ensure robust function of the protection systems for these young occupants, and advance the development of countermeasures that protect children in real-world crashes, also including dynamic events prior to a crash. Again, a human-centric approach understanding the users' specific needs, is likely the most successful way.

We foresee a paradigm shift in occupant protection. It is partly driven by the unsupervised AD, especially concerning change in mindset of enabling an expanded user request, exemplified by sitting postures and activities in the cars. It is also driven by the fact that less people are injured in cars today, and therefore improved methods and tools are needed to address the remaining cases. The paradigm shift will impact the assessment tools and underlying knowledge for occupant protection, as elaborated on in this study. It will require synchronized cooperation among stakeholders to collect and create the needed real world data, validation data and tools. In addition we need to raise our view and perspective in the area. Specifically, it requires a consensus that we together need to take this step on development of assessment methods, as well as taking on the discussion of the whole picture, exemplified by issues like who will take care of the occupant protection relevant tasks as the driver has today.

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