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Pre-Crash and In-Crash Car Occupant Safety Assessment

Numerical Methods Toward Real-World Protection of Occupants

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Abstract

Tens of millions are annually injured in Road Traffic Accidents (RTAs) worldwide, while the estimated number of RTA fatalities amounted to 1.35 million in 2016. In Europe, car occupants hold the largest share (48%) of fatalities among all road users. The high fatality and injury numbers motivate the work of enhancing road traffic safety. A holistic safety assessment approach, considering both the pre- and the in-crash phase of a crash, has the potential to enhance real-world occupant protection evaluation, as well as facilitate the development of effective countermeasures.

In standardized car occupant safety assessments, occupant surrogates of standardized anthropometries are employed in standardized postures, with the seat adjusted to a single predefined position. The vehicle is then subjected to predefined crash configurations with meticulously described impact points and angles. In contrast, real-world traffic crashes involve occupants of different shapes and sizes, who adjust the position of the seat and their posture on the seat differently, and the vehicles are subjected to diverse crash configurations (multiple impact locations, impact directions, and speed combinations). The overall aim of this thesis is to develop and apply methods, spanning from the pre-crash to the in-crash phase, capable of evaluating and enhancing the real-world occupant protection of future vehicles.

The introduction of crash-avoidance systems has the potential to alter the crash configurations that future vehicles will be exposed to. A method for predicting crash configurations has been developed in this thesis and applied to highway driving, and urban intersection crashes. Performing counterfactual simulations of digitized real-world crashes, with and without the addition of a conceptual Automatic Emergency Braking system, provides a prediction of the remaining crashes. The use of a novel crash configuration definition, along with a purpose-designed clustering method, facilitates the reduction of the number of predicted crash configurations without sacrificing coverage of the diverse real-world situations. Three predicted crash configurations, representative of urban intersection crashes, were further analyzed during the in-crash phase. A Human Body Model was positioned in a wide range of occupant postures identified from the literature. The findings suggest that the lower extremity postures had the largest overall influence on the lower extremities, pelvis, and whole-body responses for all crash configurations. In the evaluated side-impacts, leaning the torso in the coronal plane affected the torso and head kinematics by changing the interaction with the vehicle's interior. Additionally, in far-side impacts supporting the occupant's arm on the center console resulted in increased torso excursions. Moreover, the upper extremity responses were consistently sensitive to posture variations of all body regions.

Keywords: Advanced Driver Assistance Systems (ADAS); Crash Configurations; Crashworthiness; Human Body Model; Intersection crashes; Occupant postures; Real-world safety;

Contents

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Appended Papers

Paper I

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Author's Contributions: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization

Paper II

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Abbreviations

AD	Autonomously Driven
ADAS	Advanced Driver Assistance System
AEB	Autonomous Emergency Braking
AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device
BMI	Body Mass Index
FCW	Forward Collision Warning
FE	Finite Element
HBM	Human Body Model
MIL	Model In the Loop
ODD	Operational Design Domain
PMHS	Post Mortem Human Subject
PMI	Permanent Medical Impairment
RTA	Road Traffic Accident
SCP	Straight Crossing Path
SD-ref	Same Direction rear-end frontal
SUV	Sport Utility Vehicle
USA	United States of America
v2v	Vehicle to vehicle
VRU	Vulnerable Road User

1 Introduction

Tens of millions are injured every year worldwide in Road Traffic Accidents (RTAs), while the estimated annual deaths in 2016 amounted to 1.35 million (World Health Organization, 2018). The share of RTA fatalities for occupants of four-wheeled vehicles was 29% globally and 48% for the European continent (World Health Organization, 2018). In addition, RTAs were among the top three leading causes of death in the United States of America (USA) for the age group 4 – 34 in the years 2016 and 2017 (NHTSA, 2020). Moreover, in a prospective cohort study comprising 64,007 injured car occupants in Sweden, it was found that occupants who sustained high Permanent Medical Impairment (PMI) injuries showed an increased probability of receiving disability pension two years after their injuries (Elrud et al., 2019). The high injury and fatality numbers, concomitant with quality of life reduction, are among the main motivators for enhancing road traffic safety.

In order to design effective countermeasures, a holistic safety assessment approach that considers the entire traffic system is required. The following sections describe the interaction of the traffic system and the layers within it, with a focus on the safety of passenger car occupants. The main components can be classified into three layers, inspired by the Haddon matrix; the occupant, the vehicle, and the environment. Similarly, a crash event can be split chronologically into the pre-crash phase, the in-crash phase, and the post-crash phase, Figure 1. The primary factors, relevant to the design of safe vehicles, will be explored in the subsections below.

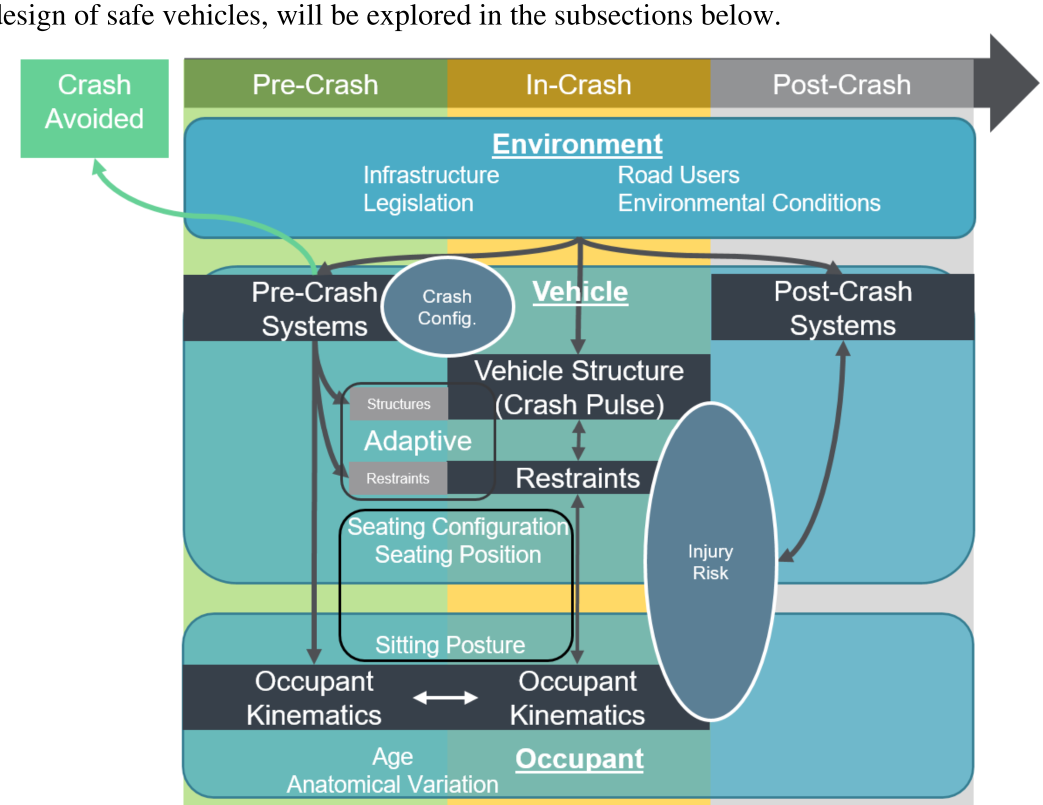

Figure 1. The traffic safety system, categorized into the occupant, vehicle, and environment layers, as well as chronologically in the pre-, in- and post-crash phases. The main components, from a four-wheeled vehicle occupant safety perspective, are visible in the figure.

1.1 Safety Assessment

Vehicle safety evaluation is a necessary step toward the development of safer vehicles. Through evaluation, safety challenges can be identified and addressed while the evaluation metrics can be used as (parts of) the objective function aiming at optimizing the vehicle's occupant protection capabilities.

There are different methods for assessing traffic safety; on the one hand, prospective methods take advantage of numerical or experimental techniques to predict the expected outcome of the countermeasure under evaluation. On the other hand, retrospective assessment can be done to study the real-world outcome using statistical databases years after the introduction of a countermeasure.

The capacity of retrospective, contrary to prospective methods, is inherently of limited value for the assessment of countermeasures during the development stage of new vehicles. However, they are valuable for identifying improvement areas, essential for understanding the operational design domain, and can be utilized to validate and improve the prediction accuracy of prospective methods.

Standardized vehicle safety assessment is typically performed independently for the pre-, in-, and post- crash phases. This is a fundamental limitation, considering the complexity of the traffic environment as well as the vehicle systems since potentially important interactions may be disregarded.

The development and introduction to the market of pre-crash vehicle systems necessitated the augmentation of vehicle safety evaluation with pre-crash system testing. Pre-crash vehicle technologies, aiming to avoid or mitigate crashes, are typically assessed in a physical test-track as part of standardized testing. However, due to the complexity of replicating real-world scenarios in a test-track environment, simulation techniques are also common. In a simulation environment, vehicles can be exposed to pre-crash events representative of what would be expected in real-world traffic, with multiple road users participating in the pre-crash event.

In-crash vehicle safety is evaluated by performing crash tests. Similarly to pre-crash assessment, such tests can today be both physical as well as virtual, and can be performed at full-scale or component level with impacts from multiple directions and speeds. In-crash vehicle crashworthiness assessment started with Anthropomorphic Test Devices (ATDs) as mechanical surrogates of occupants in physical vehicle crash tests.

Virtual assessment methods are vital for the research and development stage of new vehicles and safety systems, as they facilitate the evaluation of complex counterfactual scenarios and provide benefits with increased efficiency and repeatability. Numerical models of ATDs, as the computational counterpart of the physical ATDs, are currently frequently used in vehicle crashworthiness simulations for vehicle development.

Besides numerical models of ATDs, Human Body Models (HBMs) are available for virtual crashworthiness evaluation. Not hindered by the manufacturability and durability requirements of ATDs, HBMs are direct virtual representations of the human body and have many advantages compared to ATDs. HBMs can be more detailed, which allows them to capture human anatomy more accurately and paves the way for superior biofidelity and omni-directionality. HBMs can incorporate features such as active musculature, which allows them to be appropriate in the pre-crash phase during low-acceleration events (E. Larsson et al., 2019), and can be used for impacts from multiple directions. Another advantage of HBMs is their ability to be morphed into occupants of different anthropometries (K. J. Larsson et al., 2019), which allows them to better represent the diverse occupant population.

A study from Agnew et al. (2018) reported that the variability in the response of human ribs could better be predicted using rib-level predictors compared to individual-level predictors. The employment of Finite Element (FE) HBMs, facilitates the evaluation of tissue-level injury criteria, which can improve occupant injury risk prediction. Examples of implemented tissue-level criteria include a strain-based concussion risk prediction (Kleiven, 2007) and a rib fracture risk prediction based on rib strain (Iraeus and Pipkorn, 2019). Additionally, injury to organs, such as the lungs, liver, and spleen, can also be assessed using strain-based metrics (Miller et al., 2016). The use of tissue-level injury predictors could improve the prediction of real-world injuries compared to global criteria (Miller et al., 2016).

In a preliminary study, Forman et al. (2019) conducted an assessment of ATDs and HBMs as tools for examining restraint interaction, occupant kinematics, and occupant protection in reclined seats. The HBM was found to be capable of being positioned in reclined postures that the FE model of the ATD could not achieve. However, as the authors discussed, further studies are needed to evaluate the biofidelity of HBMs in reclined postures. The capability of assessing non-nominal postures, such as the reclined, is a prerequisite for the development of vehicles that could provide additional seating options for the occupants.

1.2 The Environment

Vehicle crashes are, by definition, the undesirable interaction of a vehicle with another vehicle, vulnerable road user (VRU), animal, or other objects in the environment. Thus, it is evident that the environment around a vehicle will influence occupant safety.

The design of the traffic infrastructure can influence the probability and characteristics of RTAs. Infrastructure design choices, such as separating traffic or introducing roundabouts, could influence the frequency and characteristics of traffic crashes. A meta-analysis (Elvik, 2017) of the safety effects of roundabouts concluded that converting junctions to roundabouts could reduce injuries by up to 40% and fatalities by up to 65%.

Additional environmental parameters, such as pavement and weather conditions, can influence the probability of being involved in a crash. Malin et al. (2019) analyzed 10,646 police-reported traffic accidents in Finland and identified that the relative accident risks were increased during poor road and weather conditions. Besides affecting the driver's control, environmental conditions such as sunlight and precipitation can also affect sensor performance and vehicle maneuvering capability for both manually driven and vehicles equipped with Advanced Driver Assistance Systems (ADAS).

During the event of a crash, vehicles can collide with vehicles or objects of different sizes, masses, or structural properties. The vehicle crash responses, such as acceleration and deformation patterns, can be greatly affected by the characteristics of either vehicle/object. Considering crash compatibility during the development of vehicles can lead to a reduction of serious injuries and fatalities (Johannsen et al., 2013). Furthermore, regulatory tests are performed as a prerequisite to the introduction of vehicles to the market, and rating tests are used with the intention of informing the public about the protection capabilities of vehicles. Those tests can impact the vehicle design parameters and, consequently, the occupant protection. In a simulation study, Hoffenson et al. (2013) found that optimizing the vehicle structure for higher-speed crashes could put occupants at higher risk of injury in frontal impacts at lower velocities, which are frequently seen.

The injury risk, and consequently, the occupant protection opportunities, are not limited to the pre- and in- crash phase. Subsequent to the event of a vehicle crash, a fast response from the first responders is an important aspect that can reduce the number of fatalities. The speed at which prehospital treatment had been provided and the time to the hospital arrival were associated with the observed increased mortality rates found in Alabama, USA, between rural vs urban environments (Gonzalez et al., 2009).

1.3 The Vehicle - Safety Countermeasures

Today, vehicle safety technologies are developed around two main principles; crash avoidance, aiming to avoid and mitigate crashes, and in-crash protection - vehicle structure and restraint systems - aiming to minimize the effects of a crash. Crash avoidance technologies represent one large part of ADAS and include, among others, systems that can brake, steer, or warn the driver about an imminent threat, contributing toward the protection of occupants. Additionally, Autonomously Driven (AD) vehicles, capable of unsupervised driving, are currently being developed and are expected to be introduced on the market soon. In the transitional phase, when AD and manually driven vehicles are mixed in traffic, the possibility of being involved in a crash cannot be disregarded. Therefore, in-crash protection systems will be relevant for years to come. Injury mitigation, during the in-crash phase, is typically achieved by optimizing the vehicle's structural response and using restraint systems to control the occupants' motion inside the vehicle.

When considering the three phases of a crash, vehicle safety technologies can be characterized by their expected activation time. Pre-crash systems are active before the impact and aim to avoid conflict situations or mitigate crashes. The outcome of a pre-crash system can be classified into three distinct states; crash-avoidance, no-intervention, or crash-mitigation (Figure 2). Evaluating the effectiveness of pre-crash systems is straightforward for the first two states. Injuries are not expected if a crash is avoided, while benefits of the pre-crash technology will not be discernible if a pre-crash system does not intervene in a specific situation. However, in the event of crash-mitigation through a pre-crash system intervention, estimating the safety benefit is challenging. The pre-crash intervention can potentially alter the crash configuration (impact location, direction, and velocities), as well as the initial in-crash posture and position of the occupant by inducing occupant kinematics in the pre-crash phase.

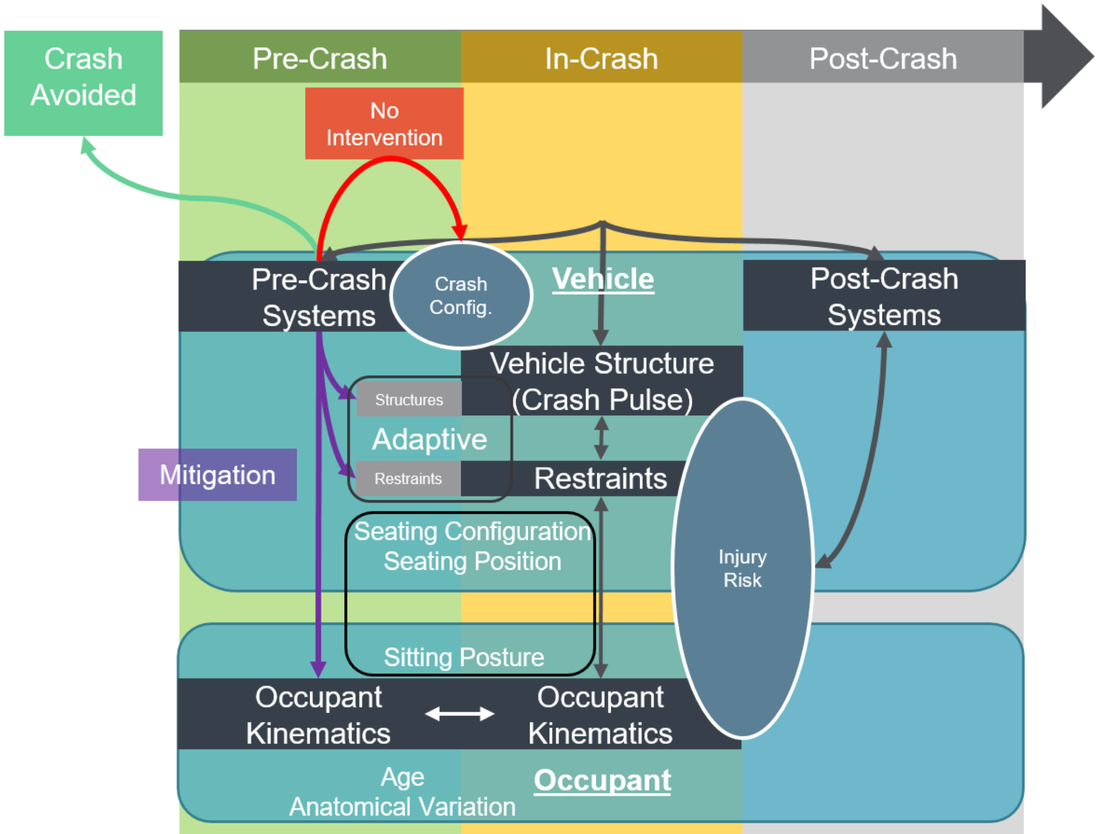

Figure 2. The three possible outcomes of the intervention of a pre-crash system. A pre-crash system could lead to avoidance (green-track), no-intervention (red-track), or mitigation of a crash (purple track).

In-crash systems, such as vehicle structure and restraint systems, are active during the in-crash phase and aim to minimize injuries, while post-crash systems become active after the in-crash phase has finished. The aim of post-crash systems is to support occupants after a crash, either by avoiding secondary impacts or calling for support and providing information for the type of crash to the first responders.

Adaptive vehicle structures have the potential to provide benefits by utilizing information from the pre-crash phase to tune the structural response according to the expected crash conditions. In a similar fashion, adaptive restraint systems could be utilized to tune the restraints for the expected crash pulse and occupant characteristics.

The effectiveness of several crash avoidance technologies has been summarized by Yue et al. (2018). Rear-end crashes showed the highest potential benefits, with crash avoidance rates approaching up to 70%. In an analysis (Cicchino, 2017) of police-reported accidents from 22 states in the USA, Forward Collision Warning (FCW) was found to reduce rear-end crashes by 27%, and in combination with Autonomous Emergency Braking (AEB), the crash-reduction rate reached 50%. AEB was also found to be effective in avoiding intersection crashes (Sander and Lubbe, 2018). If all vehicles on the road were equipped with an AEB system coupled to a wide field-of-view (180°) sensor, a crash avoidance rate of approximately 80% could be expected. Another study (Lubbe et al., 2018), investigating the potential safety benefits of AD vehicles, reported that road fatalities are expected to be substantially reduced; however, the authors did not expect that AD vehicles would be able to avoid all crashes.

Along with the benefits and the possibilities of AD vehicles, challenges in occupant protection are expected (Filatov et al., 2019). The anticipated introduction of AD vehicles could potentially influence the seating position preferences, occupant postures, and occupant activity patterns in future vehicles. An online survey comprising 552 participants, mainly from Australia, Lebanon, Spain, and Sweden, was conducted (Koppel et al., 2019) to understand seating configuration and position preference in AD vehicles. The most common desired activity when traveling with other participants was talking and reading when traveling alone. Although the traditional seating configuration (all seats facing the direction of travel) and the "driver's seat" were generally the most preferred options, preference variations were reported based on particular usage scenarios. A similar survey (Nie et al., 2020), conducted on 1,018 participants from China, suggested that the traditional seating configuration was the most preferred and that the rear seat was the most desirable position in the car.

A major limitation of the aforementioned studies is that the occupants responded with their preferred seating configurations without having experienced them in reality. Experience of various seating configurations in different usage scenarios could possibly change their actual preference. A static laboratory seating study (Bohman et al., 2020b) was performed with seats that were rotated 10° and 20° inboards. The 20° rotated configuration was preferred by 75% of the participants shorter than 170 cm and 70% of the participants taller than 170 cm while engaged in conversations with each other. Among the taller participants, strategies for avoiding leg interference, such as crossing the legs or locking the ankles, were observed.

In simulations (Kitagawa et al., 2017) of car collisions with unconventional (face-to-face) seating configurations, it was found that the backward-facing front seats were able to restrain the occupants in a frontal crash. The rear seat occupants, who were restrained by seatbelts, exhibited greater forward excursions. Additionally, in the second part of the study from Kitagawa et al. (2017), the seat orientation effect for reclined occupants was investigated. Increased T1 vertebra excursions were observed in the reclined position for rear-facing occupants, while no major variations were observed in the forward-facing configuration. Increased head rotational velocities were observed when the seat was positioned oblique relative to the crash pulse. A frontal impact was simulated (Gayzik et al., 2018) using an HBM in 13 seating configurations, rotated in 15° increments in the clockwise direction from 0° to 180°. The preliminary results suggest that the sagittal and coronal plane upper neck loading increased as the occupant rotated relative to the crash pulse direction. Jin et al. (2018) conducted a simulation study using an HBM to investigate the potential benefits of a conceptual rotatable seat in frontal collisions. The simulation results indicate that the backward-facing occupant was subjected to lower risk of head and chest injuries. Additionally, 200ms were sufficient to rotate the occupant by 45° without introducing further injuries. However, the effects of the altered occupant initial in-crash posture, due to the induced rotation, were not taken into account.

Updated restraint systems with sensing capabilities have been proposed as one of the solutions to the upcoming safety challenges (Filatov et al., 2019). In a simulation study (Ji et al., 2017), unfavorable kinematics for reclined occupants were observed in a laboratory setup. Placing a knee bolster close to the occupant's knees could potentially control the occupant's kinematics and lead to desirable upper body rotation around the pelvis. Additionally, repositioning the occupant from a reclined to an upright position was found to be beneficial in terms of head kinematics, however rotating the pelvis to the initial pelvic angle of the non-reclined occupant through seatback rotation was challenging (Östh et al., 2020).

Restraint system concepts have also been proposed, targeting the protection of vulnerable populations as well as addressing crashes from diverse directions. A simulation study (Östling et al., 2017) estimated that if the entire vehicle fleet was equipped with a 3+2 Criss Cross seatbelt, 22% and 25% of the Abbreviated Injury Scale (AIS)2+ chest injuries could be avoided, in the USA and Germany, respectively. Furthermore, a reduction in the chest injury risk for elderly occupants wearing an adaptive 3+2 Criss Cross seatbelt was reported in a simulation study (Mroz et al., 2018). Another concept, a prototype four-point suspender seatbelt, has also been developed and evaluated by Hu et al. (2018), targeting frontal oblique crashes. The left-right belt load limiters could be independently adjusted to adapt to different crash directions and control the rotation of the occupants, and the prototype belt reduced the chest deflection by transferring the load mainly through the clavicles. In order to be able to fully understand the potential real-world benefit of such systems, the user acceptance rate would also have to be considered.

1.4 The Occupant

With the overall objective of minimizing the injury risk of vehicle occupants, the humans inside the vehicle should always be the focus area of any safety evaluation. Vehicle occupant safety is typically evaluated using standardized procedures employing human surrogates in physical or virtual tests. The in-crash response and injury risk of the occupant are affected by many parameters, such as anatomical variation, age, sex, and posture. Additionally, the pre-crash kinematics of the vehicle can affect the occupant's state (posture, muscle bracing level, as well as velocity and position relative to the vehicle), which subsequently can influence the in-crash response. The occupant's awareness of the situation could also influence their response, as shown by Shibata et al. (2019) in low-speed far-side staged impacts with eight volunteers. In that study, the occupant's awareness of the situation influenced their head kinematics, with non-distracted drivers reaching lower peak head excursion values.

A retrospective analysis (Mallory et al., 2017), of police-reported crash data from the USA, identified that 68% of fatalities could be attributed to head and thorax injuries. Besides the substantial share of fatalities attributed to head and thorax injuries, one cannot disregard the importance of extremity injuries which accounted for approximately 74% of all disability-inducing injuries. A statistical analysis (Monchal et al., 2018), conducted on crash data containing at least one moving vehicle in France, reported that while abdominopelvic injuries are not very frequent in traffic injuries (6.2% of the occupants), they are associated with increased mortality rate.

Knowledge of occupants' injury tolerance is essential for the evaluation of occupant safety. As summarized by Forman et al. (2015), numerous studies have addressed the tolerance of the human body to external loads. The majority of the publications studied spinal injuries (20%), with the head (16%), thoracic (15%), and upper (19%) and lower (13%) extremity injuries also attracting researchers' interest. Abdominopelvic injuries were studied in 13% of the publications. Those studies are fundamental in the development of occupant surrogates, capable of predicting occupant injury risk, and are essential for the assessment of occupant safety.

1.4.1 Anatomical Variation & Injury Tolerance

Among the many parameters related to the injury risk of occupants, are age, Body Mass Index (BMI), and sex (Carter et al., 2014). For frontal, side, and rollover crashes, the injury risk of each body region substantially rose as the age of the occupant increased. The probability of lower extremity injuries in frontal crashes was increased for occupants of higher BMI. Additionally, increased risk of head injuries in side impacts and thoracic injuries in frontal impacts was observed for female occupants. Similarly, increased injury risk for obese occupants has also been identified in a matched-pair analysis of field data conducted by Viano et al. (2008). Obesity ($BMI \geq 30$) was associated with a 97% and 32% higher fatality risk compared to occupants with normal BMI ($18.5 \leq BMI < 30$) for drivers and passengers, respectively. Variations across the different sexes and age groups were also observed, with obesity significantly associated with increased injury risk for females, while the risk of serious injury for male occupants decreased. No effect was found for obese older drivers; however, obese younger drivers were 20% more likely to be seriously injured than young drivers with normal BMI.

Furthermore, stature and body shape affect driver injury risk, as found in a simulation study by Hu et al. (2017b). Morphed HBMs, representing drivers of varied statures and body shapes, were simulated in frontal crashes. This study observed that shorter females and taller males are exposed to higher injury risk compared to the mid-stature males. Additionally, obese drivers were at greater risk of injury for all statures simulated. The effect of obesity in occupant kinematic, dynamic, and injury responses were studied by Forman et al. (2009). Unfavorable kinematics were observed in frontal sled tests with obese Post Mortem Human Subjects (PMHSs), which exhibited significantly greater forward excursions of the pelvis and head compared to mid-sized subjects.

Besides posture, BMI, sex, and age, variations also prevail across different anatomical aspects of the human body, which can influence the response of an occupant. Sato et al. (2016) investigated spinal alignment patterns of occupants seated on an automotive seat and identified that the individual variations were more prominent in the combination of cervical spine curvature and thoracic kyphosis. Disc height, vertebral depth, and segmental size of the cervical spine, in which inherent variations exist between males and females, influenced vertebral rotations under combined loading as found in a sensitivity analysis (John et al., 2018). Additionally, Izumiyama et al. (2018) analyzed the individual differences in skeletal alignment using X-ray images of 75 individuals. The individuals were clustered in two groups based on their lumbar spine alignment; S-shaped & kyphotic. By comparing the responses of the two groups, differences in their pelvic response and brain injury risk were observed to have been caused by the altered lumbar spine alignment. The in-crash pelvic rotation and displacement were found to increase as the initial orientation of the pelvis was tilted rearward.

Muscular tension has the potential to affect the loading and, consequently, the injury risk of certain body regions. For example, a significant increase in tibial axial loading was observed when preloading the Achilles tendon (Kitagawa et al., 1998). The preloading contributed to reaching the fracture load threshold, and tibial fractures were observed. Comparably, in a simulation study (Chang et al., 2009), it was found that the lower extremity muscle activation due to the driver initiated emergency braking could increase the likelihood of femoral shaft fractures by 20% – 40% and shift the fracture location toward the mid-shaft of the femur. An appropriate prediction of the antagonistic muscle activation and force, lacking in this study, could also affect the stress/strain distribution.

1.4.2 Pre-Crash Kinematics

Occupant movement in the pre-crash phase can alter the initial in-crash occupant posture and affect the kinematics and loads of the occupant in the in-crash phase. For instance, the position of passengers may alter while the vehicle is braking (Carlsson and Davidsson, 2011) or cornering (Bohman et al., 2020a) in everyday traffic. Additionally, acceleration due to evasive driving maneuvers initiated by the vehicle, such as braking (Östh et al., 2013) or changing lanes (Ghaffari et al., 2018), can induce occupant movement during the pre-crash phase to drivers and passengers, respectively.

The effects of a pre-crash intervention on occupant injury risk were investigated by Guleyupoglu et al. (2017). Although the pre-crash braking reduced the occupants' injury risk by reducing the impact velocity, increasing the pre-crash deceleration (>1.0g) did not always result in reduced injury risk, because of the altered occupant pre-crash posture. In those simulations, the muscle activation was limited to the neck, and the injury prediction was performed using only global injury criteria.

An HBM, validated using PMHSs and volunteer tests, was used in an investigation (Kato et al., 2018) of muscular effects, and showed that muscle activation levels could have an effect on occupant kinematics and injury outcomes in frontal impacts with pre-crash decelerations. In another simulation study (Iwamoto et al., 2018), the muscle bracing level of drivers was shown to affect their injury risk when the vehicle was decelerating before being exposed to a rear-end impact. Braced drivers exhibited less risk of sustaining head and neck injuries, by changing their in-crash head kinematics.

1.4.3 Occupant Posture

The posture selected by occupants can be influenced by anatomical variations, as well as occupant seating comfort, individual preference, and vehicle interior/seat design. Additionally, passengers have the option of engaging in non-vehicle-control-related tasks, which also have the potential to introduce posture variations.

Zhang et al. (2004) published the result of a survey regarding front passenger postures and identified that the nominal passenger sitting posture accounted for 45% of the daily trips. Statistical models for predicting driver (Reed et al., 2002, Park et al., 2016a) and passenger (Park et al., 2016b) postures have been developed using data from a static laboratory environment. Reed et al. (2002) published a method to predict average driving postures, considering stature, BMI, seat design, and distance to vehicle landmarks. In a more recent publication, the driving posture was significantly associated with age (Park et al., 2016a), and gender-specific statistical models were provided. For rear-seat occupants (Park et al., 2016b), the seat configuration was additionally identified as a significant parameter.

Besides studies based on laboratory environments and surveys, naturalistic driving studies (Reed et al., 2020) have recently provided occupant postures, seating positions, and backrest angles for front-seat passengers. In that publication, the lower extremities were positioned in the nominal posture for less than 50% of the frames, while the seatback angle exceeded 35° in less than 1% of the recorded frames. Another study (Cutcliffe et al., 2017) indicated that male and female occupants displayed similar postures during typical riding; however, differences were found between drivers and passengers, with drivers displaying more protracted neck postures. Furthermore, according to Fice et al. (2018), drivers spend a larger proportion of time with their heads in non-neutral postures when the vehicle is stationary (17%) compared to when it is moving (8%).

A number of studies have highlighted the influence of the occupant's pre-impact posture on injury risk in vehicle crashes. Bose et al. (2010) used a multibody HBM to investigate the influence of occupant characteristics such as stature, mass, posture, and muscle bracing level on injury risk in frontal crashes, and identified that the occupant's posture generated the largest effect on the outcome.
The effect of spinal posture on predicted injury risk in vehicle crashes has attracted considerable interest from researchers. Predicted reaction forces and rib strains can be greatly affected by spinal posture both in frontal (Poulard et al., 2015) and side impacts (Poulard et al., 2014). Modifying the spinal posture created comparable variability in the impact response, as observed in PMHS experiments with different anthropometries (Poulard et al., 2014). A sensitivity analysis carried out by (Hwang et al., 2016) using an HBM showed that in side-impact conditions, the body posture was an important aspect for predicting the occupant impact responses and that the material properties were less influential in the chosen range. Gierczycka et al. (2015) published a comparative study regarding the sensitivity of HBMs and ATDs in arm positions during a side impact, in which the HBM demonstrated significant sensitivity to different arm positions. Aligning the arm with the body increased the load transmission to the thoracic region. Interaction with the restraint systems can also be sensitive to occupant postures, as shown by Gierczycka and Cronin (2017), who showed that the injury risk was more sensitive to the pre-crash arm position compared with the selection of restraint system combinations. Nie et al. (2017) investigated knee airbag designs for frontal and oblique impacts. Tibia bending moment and axial load were increased for occupants with a smaller gap between the knee and the instrument panel, indicating that the relative position of the lower extremities can be an important aspect of predicting the occupant's crash response.

Driver characteristics can affect the belt fit, as shown in a laboratory study by Reed et al. (2013). BMI, age, and stature were the characteristics that affected the driver's belt fit, while sex did not explain any important effects. The lap belt was positioned 150 mm further forward for drivers with the highest BMI (48) compared to drivers with the lowest BMI (17). The shoulder belt angle was associated with the driver's stature and was placed more outboard for taller drivers. In a laboratory vehicle mockup, the posture and belt fit of 24 passengers in four different seatback angles was investigated (Reed et al., 2019). Occupants with a larger BMI displayed a more upright torso and pelvis angle. As expected, reclining the seat increased the pelvis angle and the torso angle, which was also increased when the occupants used the headrest. The dominant predictor of lap belt position was BMI, with occupants of higher BMI being associated with a further forward and higher lap belt placement. The torso belt was on average further inboards as the seatback angle increased.

1.5 Aims

In regulatory and rating tests for car occupant safety assessment, occupant surrogates of standardized anthropometries are employed in standardized postures. During those tests, the seat is adjusted in a single predefined position, and the vehicle is subjected to a predefined crash configuration with meticulously described impact points and angles. In contrast, in real-world traffic crashes, occupants come in different shapes and sizes, adjust the seating position according to their particular needs, and position themselves on the seat in a variety of postures. In real-world crashes, the vehicles can be subjected to various pre-crash situations followed by diverse crash configurations with impact locations anywhere on the car, at multiple impact directions and varying speed combinations.

Pre-crash vehicle technologies bring benefits for occupant protection by avoiding and mitigating crashes. Even so, the assessment of occupant protection in the case of mitigated crashes is challenging. Pre-crash interventions have the potential of influencing many parameters of the crash, such as the impact location, direction, and velocity of the vehicle, as well as the occupant's posture and position. Assessment methods that consider the combined pre-crash and in-crash phase would therefore be advantageous and could further promote the development of safer vehicles. Occupant surrogates, that are capable of being used in the pre-crash and in-crash phase as well as for impacts from multiple directions are essential for the evaluation of the combined pre-crash and in-crash effects. Additionally, the anticipated introduction of highly automated vehicles is expected to enhance mobility and increase the quality of life of occupants by freeing up time for them. At the same time, occupants in such vehicles will likely have further opportunities of utilizing their time in more ways than today, including the potential of adopting more postures in vehicles in which the interior design has been updated. Hence, the necessity for new tools, methods, and protection strategies is increased.

The overall aim of the PhD project is to develop and apply methods, spanning from the pre-crash up to the in-crash phase, capable of evaluating and enhancing the real-world occupant protection of future vehicles.

Specifically, the research questions examined in the present licentiate thesis include:

- How can crash avoidance technologies be prospectively assessed, with a focus on connecting the pre-crash with the in-crash phase?
- How do crash avoidance technologies affect the expected crash configurations? How are the future crash configurations expected to be affected?
- How do the various postures, adopted by car occupants, affect their kinematic and kinetic responses in crash events?

In future studies, HBMs will be utilized to evaluate occupant protection principles and the safety of occupants in future vehicles under seating configuration/position, sitting posture, and anatomical variation uncertainties. Additionally, protection strategies will be investigated in order to address the identified challenges.

2 Summary of Appended Papers

2.1 Summary of Paper I

Objective: Traffic safety technologies revolve around two principle ideas; crash avoidance and injury mitigation in inevitable crashes. The development of relevant vehicle injury mitigating technologies should consider the interaction of the two above mentioned technologies, ensuring that the inevitable crashes can be adequately managed by the occupant and vulnerable road user (VRU) protection systems. A step toward developing such technologies is the accurate description of the expected crashes remaining when crash-avoidance technologies are available in vehicles. With the overall objective of facilitating the assessment of future traffic safety, this study develops a method for predicting crash configurations when introducing crash avoidance countermeasures. The predicted crash configurations serve as one important factor for prioritizing the evaluation and development of future occupant and VRU protection systems.

Methods: The method consists of four steps. As the first step, statistical analysis of a national database is used to identify the traffic challenged for a selected Operational Design Domain (ODD). By using real-world traffic accident data from in-depth crash databases, the baseline can be established as the second step of the method. Thereafter, based on the baseline, counterfactual model-in-the-loop (MIL) pre-crash simulations are performed, in order to predict the change in traffic situations (vehicle crashes) provided by vehicles equipped with crash avoidance technologies. In the final step, the predicted remaining crashes are clustered to identify the most representative crash configurations. A novel crash configuration definition, which provides an accurate description using a limited number (five) of parameters, is employed, supporting further analysis of the in-crash phase. By clustering and grouping the remaining crashes, a limited number of crash configurations can be identified, still representing and covering the real-world variation.

Results: The developed method was applied using Swedish national- and in-depth accident data related to urban intersections and highway driving, and a conceptual Autonomous Emergency Braking system (AEB) computational model. Based on national crash data analysis, the conflict situations Same-Direction rear-end frontal (SD-ref) representing 53% of highway vehicle-to-vehicle (v2v) crashes, and Straight Crossing Path (SCP) with 21% of urban v2v intersection crashes were selected for this study. Pre-crash baselines, for SD-ref (n =1010) and SCP (n =4814), were prepared based on in-depth accident data and variations of these. Pre-crash simulations identified the crashes not avoided by the conceptual AEB, and the clustering of these revealed five (5) and 52 representative crash configurations for the highway SD-ref and urban intersection SCP conflict situations, respectively, to be used in future crashworthiness studies.

Conclusions: The introduction of crash avoidance systems could shift the impact points toward the vehicle's corners. The results demonstrate that the proposed method is feasible for identifying, predictively, relevant crash configurations for in-crash testing of injury prevention capabilities.

2.2 Summary of Paper II

Objective: Car passengers are frequently seated in non-nominal postures and are able to perform different activities since they are not limited by tasks related to vehicle control. The anticipated introduction of Autonomously Driven (AD) vehicles could allow "drivers" to adopt similar postures and being involved in the same activities as passengers, allowing them a similar set of non-nominal postures. Therefore, the necessity to investigate the effects of non-nominal occupant sitting postures during relevant car crash events is becoming increasingly important. This study aims to investigate the effect of different postures of passengers in the front seat of a car on kinematic and kinetic responses during intersection crashes.

Methods: A Human Body Model (HBM) was positioned in the front passenger seat of a midsize Sports Utility Vehicle (SUV) in a total of 35 postures, including variations to the lower and upper extremities, torso, and head postures. Three crash configurations, representative of predicted urban intersection crashes, were assessed in a simulation study: two side impacts, a near-side and a far-side, respectively, and a frontal impact. The occupant kinematics and internal loads were analyzed, and any deviations between the nominal and altered posture responses were quantified using cross-correlation of signals to highlight the most notable variations.

Results: Posture changes to the lower extremities had the largest overall influence on the lower extremities, pelvis, and whole-body responses for all crash configurations. In the frontal impact, crossing the legs allowed for the highest pelvis excursions and rotations, which affected the whole-body response the most. In the two side-impacts, leaning the torso in the coronal plane affected the torso and head kinematics by changing the interaction with the vehicle's interior. Additionally, in far-side impacts supporting the upper extremity on the center console resulted in increased torso excursions. Moreover, the response of the upper extremities was consistently sensitive to posture variations of all body regions.

Conclusions: The influence of body region postures on body region and whole-body responses has been quantified using cross-correlation techniques for three diverse crashes. The lower extremities and torso were found to be influential for the frontal and side crashes, respectively. Furthermore, the response of the upper extremities was sensitive to posture variations of all body regions, suggesting that future studies aiming to address upper extremity injuries should carefully consider the occupant's posture variability. Additionally, the torso posture, which in previous studies has been shown to be sensitive to vehicle kinematics, was identified as an important parameter for predicting the occupant's torso and head response for all applied crash configurations. Bridging the development and evaluation of pre-crash and in-crash vehicle technologies could benefit real-world occupant protection.

3 Discussion

To meet the aim of bridging the evaluation of vehicle technologies spanning from the pre-crash to the in-crash phase, a method for predicting crash configurations, considering the introduction of crash avoidance technologies, was developed and applied in Paper I. The developed method is modular, compatible with a variety of pre-crash predictive evaluation techniques and aims to predict the expected crash configurations, which can further be used for assessing and enhancing occupant safety of future vehicles.

The strength of this method is that the end-result focuses on the remaining crashes following the introduction of a pre-crash countermeasure and provides accurate crash configurations that can be applied for in-crash simulations, compared to past studies, which frequently have been limited to reporting crash avoidance rates. The results of the method developed herein, suggest that the share of impacts to the vehicle's corners are expected to be increased after the introduction of a conceptual AEB system, which is in agreement with the results of previous retrospective studies (Cicchino and Zuby, 2019; Isaksson-Hellman and Lindman, 2016). Furthermore, a similar method (Östling et al., 2019) has been previously applied on data from a different database, proving its adaptability.

The foundation of the method incorporates a novel crash configuration definition, proven to be able to accurately describe crash configurations using only five parameters. The crash configurations act as a link facilitating the transition from pre-crash to in-crash vehicle assessment. Describing the impact location on the vehicles with normalized angles enables the comparison of impacts between objects of different dimensions. Additionally, those crash configurations can then be applied as boundary conditions to set up crash-tests with vehicles of varying dimensions. Special care must be taken when crash configurations derived from different types of vehicles are compared, as the in-crash response is expected to be different due to different structural properties. To combat such issues, the proposed method suggests analyzing crashes involving different types of vehicles separately.

With computational efforts of in-crash vehicle assessment in mind, a clustering method was proposed, which can identify the most representative crash configurations and limit the in-crash evaluations needed to cover the diverse scenarios observed in the real-world. The clustering method classifies "similar" crash configurations based on user-defined thresholds, which should be selected considering the structural robustness of the vehicle being tested. Compared to the study by Östling et al. (2019), the introduction of the threshold-based clustering facilitates the comparison of data from different sources by addressing the sensitivity to sample size, and enhances the applicability of the predicted crash configurations to vehicles with varying structural properties.

The focus of Paper I was the development of the method; therefore, the application of the method was limited to evaluating straight-crossing-path urban intersections and highway driving. Those ODDs were selected to assess the effectiveness of the method in a complex scenario (urban intersections) in which many parameters are affected simultaneously, and in situations (highway driving) in which the main effect of ADAS systems is speed reduction.

The proposed methodology is modular to the fidelity of the simulation environment. For the purpose of acting as a proof of concept for the methodology and being publishable without limitations due to intellectual property, a conceptual AEB system was selected, coupled in a simplified simulation environment, excluding modelling interactions between the vehicle and the driver or other road users. In order to consider system capabilities and limitations, it is essential to include models that can represent the vehicle and the behavior of the road users in the traffic environment. The use of generic models can still provide results, suitable as an indicator of the expected changes induced by the evaluated pre-crash system.

The main limitation of the above mentioned method is that the pre-crash motion of the vehicle, which could affect the occupant's pre-crash crash motion and consequently the occupant's initial in-crash posture, was not included in the clustering stage of the crash configuration. A parametric description of the vehicle pre-crash motion could limit the parameters required to describe the motion and would facilitate their inclusion in the predicted crash configurations. Additionally, to have a more complete overview of the expected crash configurations, the method could be applied to further ODDs, and the remaining crash configurations could be clustered jointly.

The method developed in Paper I can, when used with the appropriate prospective assessment techniques, provides insights for future in-crash occupant protection needs. The derived results hint toward the relatively more frequent occurrence of impacts closer to the vehicle corners in urban intersections.

In Paper II, a systematic evaluation of the occupant kinematics and kinetics for an extensive set of non-nominal postures was performed using crash pulses derived from crash configurations predicted in Paper I. The kinematic and kinetic responses of non-nominal occupant postures were compared with the responses of the nominal posture using cross-correlation. The main contribution is represented by the identification of the body region postures that have the greatest influence on the in-crash occupant response.

The lower extremity postures were highlighted as a major contributing factor for the whole-body kinematic and kinetic responses of the occupant. In contrast, in the study by Bose et al. (2010), the lower extremity postures mainly influenced the lower extremity responses. This dissimilarity could be explained by the inclusion of the crossed legs postures, which were the most influential for the occupant's response. Crossed leg postures were associated with altered initial and dynamic pelvic angles (Izumiyama et al., 2018) which have been linked to an increased submarining risk in frontal impacts (Uriot et al., 2015). The positioning of the FE HBM could have disclosed the dependence between body-region postures, which might have resulted in a more accurate whole-body posture. Additionally, the use of FE compared to multibody HBM may have improved the restraint system interaction prediction.

The torso posture was especially important for predicting the response of the torso and head. As found in the Paper II, in side impacts leaning away from the impact location delayed the coupling with the restraint system, making the occupant reach a higher lateral velocity relative to the vehicle. In far-side impacts, supporting the arm on the center console affected the interaction with the center console and increased the torso and head lateral displacement. Standardized rating tests, such as the recently introduced Far Side Assessment (EuroNCAP, 2020), are not considering non-nominal occupant postures and are evaluated using ATDs, such as the WorldSID 50th Male, which do not include the forearm region.

Semi-reclined occupants were subjected to increased lumbar loads in frontal impacts. Meanwhile, in side impacts, the response of semi-reclined occupants was less sensitive to variations of the torso's posture in the coronal plane. Leaning forward, on the other hand, was shown to affect the occupant's response considerably, as also found by Hwang et al. (2016). Those findings draw attention not only to the protection of semi-reclined occupants but also to occupants that are leaning forward. When a vehicle is performing a pre-crash maneuver prior to a crash, the probability of the occupant being moved to a leaning-forward posture may increase. The inclusion of pre-crash phase simulation with HBMs could enhance the safety assessment by predicting the initial in-crash posture as well as serve as a tool for evaluating protection strategies, that could control the occupant motion during the pre-crash events, for example.

Additionally, the response of the upper extremities was sensitive to variations of all body region postures for all evaluated crash configurations, which could have implications for the upper extremity protection of occupants. Consequently, injury assessment should be performed in a variety of postures to ensure the robustness of vehicles and restraint systems.

An advantage of this study is that three diverse crash pulses derived from predicted real-world crash configurations were evaluated. The crash pulses were derived through simulations of v2v crashes using models representative of current vehicles of the same type. Thus, potential changes in the vehicles' structural response or vehicle incompatibilities, which could lead to altered crash pulses, were not considered.

Among the findings of Paper II was that the forward-leaning occupant responses, such as head kinematics and upper neck loading, were more sensitive to torso posture in the coronal plane. This brings attention to pre-crash interventions, which could induce occupant movement and position the occupant in those postures through braking and steering (Guleyupoglu et al., 2017; Kato et al., 2018; Östh et al., 2020) prior to a crash. Simulations of pre-crash events, which could potentially exaggerate the torso leaning postures, were outside the scope of Paper II, due to the added computational effort requirements. The included torso postures can be considered either as an occupant choice or as a result of a pre-crash intervention.

The in-crash simulations, included in Paper II, covered a wide range of posture variations as found in the literature, which takes occupant safety assessment one step closer to real-world crashes, compared to standardized testing. The simulations were performed using an HBM of one anthropometry, the 50th percentile male. In future studies, further anthropometries will be evaluated, based on the findings of previous publications, to assess occupant protection of a diverse population of occupants. Additionally, aspects of individual anatomical variations will be included in the evaluation. Including occupants of varying shapes and sizes will promote the evaluation of real-world situations even further.

The study focused on the influence of occupant posture on kinematic and kinetic responses, which, as shown in previous studies (e.g. Gabler et al., 2016), can be considered as injury indicators. Injury risk prediction was not performed, as it might be more sensitive to diverse occupant groups and vehicle interior designs, which could hinder establishing generic observations. In subsequent studies, the intention is to investigate the effectiveness of current strategies and potentially propose new occupant protection strategies, targeting real-world safety considering occupant diversity.

The findings of the conducted studies place emphasis on the connection between the pre-crash and in-crash phases. The inclusion of crash-avoidance technologies has the potential of influencing the crash configurations that vehicles will be exposed to, which will subsequently affect the in-crash response of the vehicle and potentially pose additional occupant protection challenges. Furthermore, findings from previous studies have shown that the pre-crash vehicle motion can alter the occupant's initial in-crash posture.

Besides pre-crash vehicle kinematics, the occupant's posture could also be varied based on anatomical variations and personal preferences. The occupant's initial in-crash posture was shown to influence the occupant's response in the in-crash phase. The lower extremity postures were associated with considerable differences in the whole-body response, while the torso had a major influence over the torso and head responses. Including a wide range of postures, expected in the real-world, takes the extra step toward evaluating and enhancing real-world occupant protection.

Considering the effects of crash-avoidance technologies for occupant protection through the pre-crash and in-crash phase sequence could be beneficial. Enhancing the knowledge of expected future crashes would facilitate the development of relevant in-crash systems. Additionally, knowledge of the occupants' in-crash responses could also guide the development and support establishing requirements for future pre-crash and in-crash protection systems. Using occupant surrogates, capable of describing the in-crash and pre-crash occupant responses in events and crashes from multiple directions, is a facilitator for evaluating real-world occupant protection.

4 References

Agnew, A.M., Murach, M.M., Dominguez, V.M., Sreedhar, A., Misicka, E., Harden, A., Bolte IV, J.H., Kang, Y.-S., Stammen, J., Moorhouse, K., 2018. Sources of Variability in Structural Bending Response of Pediatric and Adult Human Ribs in Dynamic Frontal Impacts. SAE Technical Paper 2018-22-0004, 2018. doi:10.4271/2018-22-0004

Bohman, K., Jakobsson, L., Nurbo, P., Olander, A., Andersson, A., 2020a. Lateral Movement of Front Seat Passengers in Everyday Traffic. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2020. Paper No IRC-20-53.

Bohman, K., Örtlund, R., Kumlin Groth, G., Nurbo, P., Jakobsson, L., 2020b. Evaluation of users' experience and posture in a rotated swivel seating configuration. Traffic Inj. Prev. doi:10.1080/15389588.2020.1795149

Bose, D., Crandall, J.R., Untaroiu, C.D., Maslen, E.H., 2010. Influence of pre-collision occupant parameters on injury outcome in a frontal collision. Accid. Anal. Prev. 42(4), 1398–1407. doi:10.1016/j.aap.2010.03.004

Carlsson, S., Davidsson, J., 2011. Volunteer occupant kinematics during driver initiated and autonomous braking when driving in real traffic environments. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2011. Paper No IRC-11-43.

Carter, P.M., Flannagan, C.A.C., Reed, M.P., Cunningham, R.M., Rupp, J.D., 2014. Comparing the effects of age, BMI and gender on severe injury (AIS 3+) in motor-vehicle crashes. Accid. Anal. Prev. 72, 146–160. doi:10.1016/j.aap.2014.05.024

Chang, C.Y., Rupp, J.D., Reed, M.P., Hughes, R.E., Schneider, L.W., 2009. Predicting the effects of muscle activation on knee, thigh, and hip injuries in frontal crashes using a finite-element model with muscle forces from subject testing and musculoskeletal modeling. Stapp Car Crash J. 2009; 53:291-328. PMID:20058559

Cicchino, J.B., 2017. Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. Accid. Anal. Prev 99, 142-152. doi:10.1016/j.aap.2016.11.009

Cicchino, J.B., Zuby, D.S., 2019. Characteristics of rear-end crashes involving passenger vehicles with automatic emergency braking. Traffic Inj. Prev. 20(sup1),112-118. doi:10.1080/15389588.2019.1576172

Cutcliffe, H.C., Ólafsdóttir, J.M., Östh, J., Davidsson, J., Brolin, K., 2017. Gender differences in Occupant Posture during Driving and Riding. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2017. Paper No IRC-17-12.

Elrud, R., Friberg, E., Alexanderson, K., Stigson, H., 2019. Sickness absence, disability pension and permanent medical impairment among 64 000 injured car occupants of working ages: A two-year prospective cohort study. Accid. Anal. Prev. 127, 35–41. doi:10.1016/j.aap.2019.02.019

Elvik, R., 2017. Road safety effects of roundabouts: A meta-analysis. Accid. Anal. Prev. 99, 364–371. doi:10.1016/j.aap.2016.12.018

European New Car Assessment Programme (EuroNCAP), 2020. Far Side Occupant Test & Assessment Procedure Version 2.0.1. Available at: https://cdn.euroncap.com/media/58231/euro-ncap-far-side-test-and-assessment-protocol-v201.pdf. Accessed 15 January 2021

Fice, J.B., Blouin, J.-S., Siegmund, G.P., 2018. Head postures during naturalistic

driving. Traffic Inj. Prev. 19(6), 637–643. doi:10.1080/15389588.2018.1493582
Filatov, A., Scanlon, J.M., Bruno, A., Danthurthi, S.S.K., Fisher, J., 2019. Effects of innovation in automated vehicles on occupant compartment designs, evaluation, and Safety: A review of public marketing, literature, and standards. SAE Technical Paper 2019-01-1223 . doi:10.4271/2019-01-1223
Forman, J., Lin, H., Gepner, B., Wu, T., Panzer, M., 2019. Occupant safety in automated vehicles. Int. J. Automot. Eng. 10(2), 139–143. doi:10.20485/jsaeijae.10.2_139
Forman, J., Lopez-Valdes, F.J., Lessley, D., Kindig, M., Kent, R., Bostrom, O., 2009. The effect of obesity on the restraint of automobile occupants. Ann. Adv. Automot. Med. Assoc. Adv. Automot. Med. Annu. Sci. Conf. 53, 25–40. PMID: 20184830
Forman, J.L., Lopez-Valdes, F.J., Duprey, S., Bose, D., del Pozo de Dios, E., Subit, D., Gillispie, T., Crandall, J.R., Segui-Gomez, M., 2015. The tolerance of the human body to automobile collision impact – a systematic review of injury biomechanics research, 1990–2009. Accid. Anal. Prev. 80, 7–17. doi:10.1016/j.aap.2015.03.004
Gabler, L.F., Crandall, J.R., Panzer, M.B., 2016. Assessment of Kinematic Brain Injury Metrics for Predicting Strain Responses in Diverse Automotive Impact Conditions. Ann. Biomed. Eng. 44, 3705–3718. doi:10.1007/s10439-016-1697-0
Gayzik, F.S., Koya, B., Davis, M.L., 2018. A preliminary study of human model head and neck response to frontal loading in nontraditional occupant seating configurations. Traffic Inj. Prev. 19(sup1), S183–S186. doi:10.1080/15389588.2018.1426915
Ghaffari, G., Brolin, K., Bråse, D., Pipkorn, B., Svanberg, B., Jakobsson, L., Davidsson, J., 2018. Passenger kinematics in Lane change and Lane change with Braking Manoeuvres using two belt configurations: Standard and reversible pre-pretensioner. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-10.
Gierczycka, D., Cronin, D.S., 2017. Occupant thorax response variations due to arm position and restraint systems in side impact crash scenarios. Accid. Anal. Prev. 106, 173–180. doi:10.1016/j.aap.2017.05.017
Gierczycka, D., Watson, B., Cronin, D., 2015. Investigation of occupant arm position and door properties on thorax kinematics in side impact crash scenarios-comparison of ATD and human models. Int. J. Crashworthiness 20(3), 242–269. doi:10.1080/13588265.2014.998000
Gonzalez, R.P., Cummings, G.R., Phelan, H.A., Mulekar, M.S., Rodning, C.B., 2009. Does increased emergency medical services prehospital time affect patient mortality in rural motor vehicle crashes? A statewide analysis. Am. J. Surg. 197(1) , 30–34. doi:10.1016/j.amjsurg.2007.11.018
Guleyupoglu, B., Schap, J., Kusano, K.D., Gayzik, F.S., 2017. The effect of precrash velocity reduction on occupant response using a human body finite element model. Traffic Inj. Prev. 18(5), 508–514. doi:10.1080/15389588.2016.1269896
Hoffenson, S., Reed, M.P., Kaewbaidhoon, Y., Papalambros, P.Y., 2013. On the impact of the regulatory frontal crash test speed on optimal vehicle design and road traffic injuries. Int. J. Veh. Des 63(1), 39-60. doi:10.1504/IJVD.2013.055558
Hu, J., Boyle, K., Fischer, K., Schroeder, A., Adler, A., Reed, M.P., 2018. A new prototype 4-point seatbelt design to help improve occupant protection in frontal oblique crashes. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-18.

Hu, J., Zhang, K., Fanta, A., Jones, M.L.H., Reed, M.P., Neal, M., Wang, J.T., Lin, C.H., Cao, L., 2017. Stature and body shape effects on driver injury risks in frontal crashes: A parametric human modelling study. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2017. Paper No IRC-17-85.

Hwang, E., Hu, J., Chen, C., Klein, K.F., Miller, C.S., Reed, M.P., Rupp, J.D., Hallman, J.J., 2016. Development, Evaluation, and Sensitivity Analysis of Parametric Finite Element Whole-Body Human Models in Side Impacts. Stapp Car Crash J. 60, 473–508.

Iraeus, J., Pipkorn, B., 2019. Development and validation of a generic finite element ribcage to be used for strain-based fracture prediction. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2019. Paper No IRC-19-35.

Isaksson-Hellman, I., Lindman, M., 2016. Using insurance claims data to evaluate the collision-avoidance and crash-mitigating effects of Collision Warning and Brake Support Combined with Adaptive Cruise Control, Proceedings of the IEEE Intelligent Vehicles Symposium. doi:10.1109/IVS.2016.7535538

Iwamoto, M., Nakahira, Y., Kato, D., 2018. Finite element analysis for investigating the effects of muscle activation on head-neck injury risks of drivers rear-ended by a car after an autonomous emergency braking. Int. J. Automot. Eng. 9(3), 124–129. doi:10.20485/jsaeijae.9.3_124

Izumiyama, T., Nishida, N., Iwanaga, H., Chen, X., Ohgi, J., Mori, K., Hayashi, T., Sakuramoto, I., Asahi, R., Sugimoto, S., Ueno, M., 2018. The analysis of an individual difference in human skeletal alignment in seated posture and occupant behavior using HBMs. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-84.

Ji, P., Huang, Y., Zhou, Q., 2017. Mechanisms of using knee bolster to control kinematical motion of occupant in reclined posture for lowering injury risk. Int. J. Crashworthiness 22(4), 415–424. doi:10.1080/13588265.2016.1275430

Jin, X., Hou, H., Shen, M., Wu, H., Yang, K.H., 2018. Occupant kinematics and biomechanics with rotatable seat in autonomous vehicle collision: A preliminary concept and strategy. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-17.

Johannsen, H., Adolph, T., Edwards, M., Lazaro, I., Versmissen, T., Thomson, R., 2013. Proposal for a Frontal Impact and Compatibility Assessment Approach Based on the European FIMCAR Project. Traffic Inj. Prev 14(sup1), S105-115. doi:10.1080/15389588.2013.790538

John, J.D., Kumar, G.S., Arun, M.W.J., Yoganandan, N., 2018. Which geometric variations in the cervical spine influence vertebral rotations under combined loading?. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-22.

Kato, D., Nakahira, Y., Atsumi, N., Iwamoto, M., 2018. Development of human-body model THUMS version 6 containing muscle controllers and application to injury analysis in frontal collision after brake deceleration. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-32.

Kitagawa, Y., Hayashi, S., Yamada, K., Gotoh, M., 2017. Occupant Kinematics in Simulated Autonomous Driving Vehicle Collisions: Influence of Seating Position, Direction and Angle. Stapp Car Crash J. 61, 101–155. PMID: 29394437

Kitagawa, Y., Ichikawa, H., Pal, C., 1998. Lower leg injuries caused by dynamic axial loading and muscle testing. Proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Paper No. 98-S7-O-09

Kleiven, S., 2007. Predictors for traumatic brain injuries evaluated through accident reconstructions. Stapp Car Crash J. 51, 81-114. PMID: 18278592

Koppel, S., Jiménez Octavio, J., Bohman, K., Logan, D., Raphael, W., Quintana Jimenez, L., Lopez-Valdes, F., 2019. Seating configuration and position preferences in fully automated vehicles. Traffic Inj. Prev 20(sup2), S103-S109. doi:10.1080/15389588.2019.1625336

Larsson, E., Iraeus, J., Fice, J., Pipkorn, B., Jakobsson, L., Brynskog, E., Brolin, K., Davidsson, J., 2019. Active human body model predictions compared to volunteer response in experiments with braking, lane change, and combined manoeuvres. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2019. Paper No IRC-19-50.

Larsson, K.J., Pipkorn, B., Iraeus, J., Bolte, J.H., Agnew, A.M., Hu, J., Reed, M.P., Sunnevång, C., 2019. Evaluation of the benefits of parametric human body model morphing for prediction of injury to elderly occupants in side impact. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2019. Paper No IRC-19-33.

Lubbe, N., Jeppsson, H., Ranjbar, A., Fredriksson, J., Bärgman, J., Östling, M., 2018. Predicted road traffic fatalities in Germany: The potential and limitations of vehicle safety technologies from passive safety to highly automated driving. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-11.

Malin, F., Norros, I., Innamaa, S., 2019. Accident risk of road and weather conditions on different road types. Accid. Anal. Prev. 122, 181–188. doi:10.1016/j.aap.2018.10.014

Mallory, A., Kender, A., Moorhouse, K., 2017. Opportunities for crash and injury reduction: A multiharm approach for crash data analysis. Traffic Inj. Prev. 18(sup1), S1–S8. doi:10.1080/15389588.2017.1309651

Miller, L., Gaewsky, J., Weaver, A., Stitzel, J., White, N., 2016. Regional Level Crash Induced Injury Metrics Implemented within THUMS v4.01. SAE Technical Paper. 2016-01-1489. doi:10.4271/2016-01-1489

Monchal, T., Ndiaye, A., Gadegbeku, B., Javouhey, E., Monneuse, O., 2018. Abdominopelvic injuries due to road traffic accidents: Characteristics in a registry of 162,695 victims. Traffic Inj. Prev. 19(5), 529–534. doi:10.1080/15389588.2018.1447669

Mroz, K., Pipkorn, B., Sunnevång, C., Eggers, A., Bråse, D., 2018. Evaluation of adaptive belt restraint systems for the protection of elderly occupants in frontal impacts. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2018. Paper No IRC-18-15.

NHTSA, 2020. Motor Vehicle Traffic Crashes as a Leading Cause of Death in the United States, 2016 and 2017, National Highway Traffic Safety Administration. 1200 New Jersey Avenue SE, Washington, DC 20590. DOT HS 812 927

Nie, B., Crandall, J.R., Panzer, M.B., 2017. Computational investigation of the effects of knee airbag design on the interaction with occupant lower extremity in frontal and oblique impacts. Traffic Inj. Prev. 18(2), 207–215. doi:10.1080/15389588.2016.1219728

Nie, B., Gan, S., Chen, W., Zhou, Q., 2020. Seating preferences in highly automated vehicles and occupant safety awareness: A national survey of Chinese perceptions. Traffic Inj. Prev. 21(4), 247–253. doi:10.1080/15389588.2020.1738013

Östh, J., Bohman, K., Jakobsson, L., 2020. Evaluation of Kinematics and Restraint Interaction when Repositioning a Driver from a Reclined to anUpright Position Prior to Frontal Impactusing Active Human Body Model Simulations. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2020. Paper No IRC-20-50.
Östh, J., Olafsdóttir, J.M., Davidsson, J., Brolin, K., Östh, J., Ólafsdóttir, J.M., Davidsson, J., Brolin, K., 2013. Driver Kinematic and Muscle Responses in Braking Events with Standard and Reversible Pre-tensioned Restraints: Validation Data for Human Models. SAE Technical Paper 2013-22-0001. doi:10.4271/2013-22-0001
Östling, M., Jeppsson, H., Lubbe, N., 2019. Predicted crash configurations for Autonomous Driving vehicles in mixed German traffic for the evaluation of occupant restraint system. VDI Fahrzeugsicherheit. Conference.
Östling, M., Saito, H., Vishwanatha, A., Ding, C., Pipkorn, B., Sunnevång, C., 2017. Potential benefit of a 3+2 criss cross seat belt system in frontal and oblique crashes. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2017. Paper No IRC-17-57.
Park, J., Ebert, S.M., Reed, M.P., Hallman, J.J., 2016a. Statistical Models for Predicting Automobile Driving Postures for Men and Women Including Effects of Age. Hum. Factors. 58(2), 261–278. doi:10.1177/0018720815610249
Park, J., Ebert, S.M., Reed, M.P., Hallman, J.J., 2016b. A statistical model including age to predict passenger postures in the rear seats of automobiles. Ergonomics. 59(6), 796-805 .doi:10.1080/00140139.2015.1088076
Poulard, D., Subit, D., Donlon, J.-P., Lessley, D.J., Kim, T., Park, G., Kent, R.W., 2014. The Contribution of Pre-impact Spine Posture on Human Body Model Response in Whole-body Side Impact. Stapp Car Crash J. 58, 385–422. PMID: 26192961
Poulard, D., Subit, D., Nie, B., Donlon, J.-P., Kent, R.W., 2015. The Contribution of Pre-impact Posture on Restrained Occupant Finite Element Model Response in Frontal Impact. Traffic Inj. Prev. 16, 87–95. doi:10.1080/15389588.2015.1064529
Reed, M.P., Ebert, S.M., Hallman, J.J., 2013. Effects of driver characteristics on seat belt fit. Stapp Car Crash J. 57, 43-57, PMID:24435726
Reed, M.P., Ebert, S.M., Jones, M.L.H., 2019. Posture and belt fit in reclined passenger seats. Traffic Inj. Prev. 20(sup1), S38–S42. doi:10.1080/15389588.2019.1630733
Reed, M.P., Ebert, S.M., Jones, M.L.H., Hallman, J.J., 2020. Prevalence of non-nominal seat positions and postures among front-seat passengers. Traffic Inj. Prev. doi:10.1080/15389588.2020.1793971
Reed, M.P., Manary, M.A., Flannagan, C.A.C., Schneider, L.W., 2002. A statistical method for predicting automobile driving posture. Hum. Factors. 44(4), 557-68. doi:10.1518/0018720024496917
Sander, U., Lubbe, N., 2018. Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents. Accid. Anal. Prev. 115, 178–188. doi:10.1016/j.aap.2018.03.025
Sato, F., Odani, M., Miyazaki, Y., Nakajima, T., Makoshi, J.A., Yamazaki, K., Ono, K., Svensson, M., Östh, J., Morikawa, S., Schick, S., Perez, A.F., 2016. Investigation of whole spine alignment patterns in automotive seated posture using upright open MRI systems. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2016. Paper No IRC-16-23.
Shibata, P., Roberts, J., Sprague, J., Light, A., Stegemann, J., Meza-Arroyo, M.,

Capser, S., 2019. The kinematic analysis of occupant excursions and accelerations during staged low speed far-side lateral vehicle-to-vehicle impacts. SAE World Congr. Exp. WCX 2019. doi:10.4271/2019-01-1030

Uriot, J., Potier, P., Baudrit, P., Trosseille, X., Richard, O., Douard, R., 2015. Comparison of HII, HIII and THOR dummy responses with respect to PMHS sled tests. Proceeding of the International Research Council on the Biomechanics of Injury (IRCOBI) 2015. Paper No IRC-15-55.

Viano, D.C., Parenteau, C.S., Edwards, M.L., 2008. Crash Injury Risks for Obese Occupants Using a Matched-Pair Analysis. Traffic Inj. Prev. 9(1), 59–64. doi:10.1080/15389580701737645

World Health Organization, 2018. Global Status Report on Road Safety 2018, Geneva: World Health Organization; 2018 (WHO/NMH/NVI/18.20). World Health Organization, Geneva. ISBN: 9789241565684

Yue, L., Abdel-Aty, M., Wu, Y., Wang, L., 2018. Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems. Accid. Anal. Prev. 117, 55-64. doi:10.1016/j.aap.2018.04.002

Zhang, L., Chen, L., Vertiz, A., Balci, R., 2004. Survey of front passenger posture usage in passenger vehicles. SAE Technical Papers 2004-01-0845. doi:10.4271/2004-01-0845