THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Heterogeneity in Car Occupant Safety

Using Numerical Simulations to Address Real-world Safety

ALEXANDROS LELEDAKIS

Department of Mechanics and Maritime Sciences
Division of Vehicle Safety

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Department of Mechanics and Maritime Sciences
Division of Vehicle Safety
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
A Venn diagram depicting factors from the environment, the vehicle, and the occupant contributing to crash heterogeneity. For a more detailed explanation, see Section 1.1.

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ALEXANDROS LELEDAKIS
Department of Mechanics and Maritime Sciences—Division of Vehicle Safety
Chalmers University of Technology

Abstract

This thesis ultimately aims to enhance occupant protection by incorporating aspects of real-world crash heterogeneity, often overlooked within current safety assessments. By investigating the effects of crash heterogeneity and broadening the comprehensiveness of occupant safety assessments, it seeks to support the development of more effective future vehicle safety systems. Specifically, the thesis focused on developing and applying methods to incorporate a range of heterogeneity aspects—from crash characteristics to occupant posture, anthropometry, and seat adjustments—into vehicle safety assessments.

To predict how crash avoidance systems might change the configurations of the remaining crashes, a method using counterfactual simulations was developed. The use of a novel crash configuration definition, along with a purpose-designed clustering method, reduced the number of predicted crash configurations—while being able to maintain coverage of diverse real-world situations. Three crash configurations were selected to be used in the following studies.

Non-nominal sitting postures, body sizes, and seat adjustments can influence the occupant's response during a crash. These aspects were investigated in simulation studies employing numerical Human Body Models (HBMs) and tailor-made analysis methods. The methods focused on quantifying the influence of these aspects (including interaction effects) on the occupant's response during a crash. Additionally, techniques were developed to streamline the setup and analysis of numerical experiments using HBMs.

The application of the methods indicated that autonomous emergency braking systems tend to move the crash locations towards the vehicle's corners. Additionally, further studies showed that the occupants' posture, anthropometry, and seat adjustments influenced their kinematic and kinetic crash response. Variations in lower extremity postures had the greatest effect on whole-body response across all tested crash scenarios. For example, in frontal collisions, sitting cross-legged increased pelvic movement, while seat adjustments altered load distributions between the pelvis and the lower extremities. Moreover, occupant characteristics could also induce differences: greater Body Mass Index (BMI) or stature correlated with larger lower extremity loading in frontal impacts. In side impacts, occupants were more sensitive to lateral movement when leaning forward.

Furthermore, the influence of individualising the shoulder belt placement on the occupant-to-belt interaction, without changing any other belt parameter, was investigated. The findings revealed that while improved initial belt placement over the shoulder is important, it alone does not guarantee improved seat belt interaction. This approach, by investigating seat belt interaction challenges for occupants with varying characteristics, paves the way for analysing further modifications in belt characteristics towards tailored occupant restraint systems.

By incorporating aspects not typically included in current safety assessments, this thesis demonstrates the potential to further enhance assessment for future vehicle safety systems, accommodating a broader range of real-world situations.

Keywords: Real-world safety; Vehicle safety assessment; Crash Configurations; Finite element; Human Body Model; Occupant posture; Anthropometric variation; Seat adjustment; Individualised Restraint Systems; Sensitivity analysis

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Contents

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Preface and Acknowledgements

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As I reflect on the journey of this thesis, I am grateful to many who have guided and supported me along the way. In the limited space of this page, I want to thank everyone who has been a part of this journey. I apologise in advance to those who do not see their names here.

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Gothenburg 2024-01

ALEXANDROS LELEDAKIS

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List of Appended Papers

The thesis consists of the following papers, referred to by Roman numerals:

I

Leledakis, A., Lindman, M., Östh, J., Wågström, L., Davidsson, J., Jakobsson, L., 2021. A method for predicting crash configurations using counterfactual simulations and real-world data.
Accident Analysis & Prevention 150, 105932. doi:10.1016/j.aap.2020.105932

Author's Contributions: Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing—Original Draft, Visualisation

II

Leledakis, A., Östh, J., Davidsson, J., Jakobsson, L., 2021. The influence of car passengers' postures in intersection crashes.
Accident Analysis & Prevention 157, 106170. doi.org/10.1016/j.aap.2021.106170

Author's Contributions: Conceptualisation, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing—Original Draft, Visualisation

III

Leledakis, A., Östh, J., Iraeus, J., Davidsson, J., Jakobsson, L., 2022. The influence of occupant's size, shape and seat adjustment in frontal and side impacts.
Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference, Porto: pp.549–584. IRC-22-75.

Author's Contributions: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data curation, Writing—original draft, Visualisation.

IV

Leledakis, A., Östh, J., Iraeus, J., Davidsson, J., Jakobsson, L., 2023. Influence of an individualised shoulder belt position for diverse occupant anthropometries on seatbelt interaction in frontal and side impacts.
Proceedings of the International Research Council on Biomechanics of Injury (IRCOBI) Conference, Cambridge: pp.639–664. IRC-23-82.

Author's Contributions: Conceptualisation, Methodology, Software, Formal analysis, Investigation, Data curation, Writing—original draft, Visualisation.

Other publications by the author relevant to, but not included in, this thesis:

Wågström, L., **Leledakis, A.**, Östh, J., Lindman, M., Jakobsson, L., 2019. Integrated safety: establishing links for a comprehensive virtual tool chain,
Proceedings of the 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Eindhoven. Paper Number 19-0177.

Author's Contributions: Formal analysis, Software, Writing—Review & Editing.

Abbreviations & Definitions

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AIS3+	Abbreviated Injury Scale, 3+ indicates a severity of three or greater.
ATD	Anthropomorphic Test Devices
AV	Autonomous Vehicle
BMI	Body Mass Index
CCD	Central Composite Design
Conflict type	The kinematic sequences leading to potential collisions; for example: "Left turn across path/ Opposite-direction" is a conflict type.
Crash configuration	The information needed to perform physical or virtual crash testing.
Crash pulse	The profile of a vehicle's acceleration (encompassing all directions and rotations) experienced during a crash, typically represented as a time series of accelerations or velocities.
CT	Computer Tomography
DALYs	Disability-Adjusted Life-Years
DoE	Design of Experiments
Euro NCAP	European New Car Assessment Program
FARS	Fatality Analysis Reporting System
FCW	Forward Collision Warning
FE	Finite Element
GHBMC	Global Human Body Model Consortium
GIDAS	German In-Depth Accident Study
GSA	Global Sensitivity Analysis
HANES	Health and Nutrition Examination Survey
HBM	Human Body Model
Host vehicle	The vehicle (involved in a crash), which is the focus of the safety assessment
H-III	Hybrid-III (an Anthropomorphic Test Device)
IIHS	Insurance Institute for Highway Safety
ISBP	Individualised Shoulder Belt Position
KDE	Kernel Density Estimation
LDW	Lane Departure Warning
LHS	Latin Hypercube Sampling
LKA	Lane Keeping Aid
LSA	Local Sensitivity Analysis
LYL	Life Years Lost
MCS	Monte Carlo Simulation
MDB	Moving Deformable Barrier
MIL	Model-in-the-Loop
MRI	Magnetic Resonance Imaging
NASS—CDS	National Automotive Sampling System—Crashworthiness Data System
NCAP	New Car Assessment Program
NHANES	National Health and Nutrition Examination Survey
OAT	One-At-a-Time
ODD	Operational Design Domain
PDF	Probability Density Function

(List continues on the following page...)

PMHS	Post Mortem Human Surrogate
PMI	Permanent Medical Impairment
RTC	Road Traffic Crash
SA/DP	Sickness Absence or Disability Pension
SCP	Straight Crossing Path
SD—ref	Same Direction—rear-end-frontal
STRADA	Swedish Traffic Accident Data Acquisition
THUMS	Total Human Model for Safety
US	United States (of America)
US NCAP	US New Car Assessment Program
v2v	vehicle-to-vehicle
VCTAD	Volvo Cars Traffic Accident Dataset

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1 Introduction

Road Traffic Crashes (RTCs) are a pressing global concern, with a profound negative impact on human lives. In 2016, RTCs resulted in an estimated 1.19 million deaths worldwide (World Health Organization, 2023). In the US, RTCs were among the top three leading causes of death for 4–34-year-olds in 2016 and 2017 (NHTSA, 2020).

Beyond fatalities, RTCs result in tens of millions of injuries or disabilities annually. Using the disability-adjusted life-years (DALYs) measure, which captures both premature deaths and years lived with disabilities, RTCs emerge as the top cause of DALYs for those aged 10–49 globally (GBD 2019 Diseases and Injuries Collaborators, 2020).

Recent research further underscores the long-term repercussions of these injuries. A study by Elrud et al. (2021) examined the long-term effects of RTCs, analysing data from approximately 55,000 injured car occupants who were not on sickness absence or disability pension (SA/DP) prior to their injury. Approximately 7% of these individuals sustained injuries leading to Permanent Medical Impairment (PMI). Notably, those with PMI injuries experienced a higher mean number of days on SA/DP compared to those without PMI, reflecting the substantial and lasting impact these injuries can have on their lives.

Occupants of four-wheeled vehicles, including drivers and passengers, account for 30% of RTC fatalities globally, a number that jumps to 49% in Europe (World Health Organization, 2023). An analysis by Mallory et al. (2017) of police-reported crashes from the US reported that 68% of car occupant fatalities could be attributed to head and thorax injuries. However, the importance of extremity injuries, which accounted for approximately 74% of all disabling injuries, cannot be overlooked. Additionally, Monchal et al. (2018) analysed French crash data, specifically examining crashes involving at least one moving vehicle. They reported that while abdominopelvic injuries are not frequent in traffic injuries (found in 6.2% of the occupants), they are associated with an increased mortality rate. Given the diverse injuries and their varied impacts on survival and quality of life, there is a compelling need for comprehensive occupant safety assessments.

The subsequent section delves into the heterogeneity within the traffic safety system. Then, occupant safety assessment methods are presented, including an introduction to standardised tests. The section concludes by providing examples of research investigating the effects of heterogeneity aspects on occupant protection. The goal of this section is to provide a comprehensive overview and identify factors that are important for the enhancement of occupant protection.

1.1 Traffic Safety System Heterogeneity

The statistics on vehicle crash-related injuries and fatalities suggest that a systematic analysis of the contributing factors can support the development of more effective countermeasures. The Haddon matrix (Haddon, 1972) offers a framework for understanding occupant safety aspects within the broader traffic safety system. In this framework, the traffic safety system consists of three interconnected layers: the traffic environment, the vehicle, and the occupant—and a crash can be analysed in three phases: pre-crash, in-crash, and post-crash (Figure 1).

During the pre-crash phase, factors such as driver behaviour, road conditions, traffic regulations, and vehicle pre-crash systems affect the frequency and type of vehicle crashes. At the onset of the in-crash phase, the crash configuration is set, which includes the crash characteristics needed to assess the crash outcome. In the in-crash phase, important factors include crash configuration, design of vehicle structure and occupant restraint systems, as well as occupant characteristics. The aftermath of a crash, or the post-crash phase, involves factors related to emergency responders and medical care. The outcome of potential occupant injuries is determined by a combination of factors in both the in-crash and post-crash phases.

A comprehensive understanding of the variability and characteristics of each layer and phase can advance safety evaluations and support the development of more effective occupant protection countermeasures.

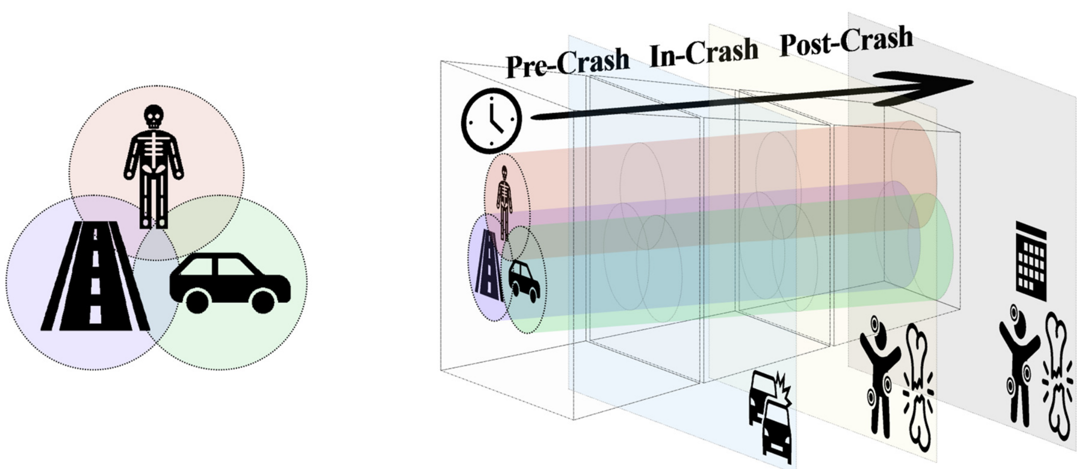

Figure 1. The three interconnected layers of the road traffic safety system: the traffic environment, vehicle, and occupant (on the left). Chronologically, the system has three phases: pre-, in-, and post-crash phases (on the right). The crash configuration is set at the in-crash onset. The occupant injury outcome is determined by a combination of in-crash and post-crash factors.

1.1.1 The Traffic Environment

This section explores factors in the traffic environment that can influence occupant safety, focusing on how infrastructure design, environmental conditions, and other factors of the broader traffic ecosystem can influence crash rates and characteristics and, consequently, occupant safety (Figure 2). Understanding these factors is important for setting relevant requirements to guide the development of enhanced occupant protection systems.

The design of traffic infrastructure can play an important role in shaping the probability and characteristics of RTCs. For example, roundabouts can alter crash frequency and severity: a meta-analysis by Elvik (2017) concluded that converting intersections to roundabouts could reduce injuries by up to 40% and fatalities by up to 65%. Notably, the author also reported that the occurrence of non-injurious crashes might increase.

In addition to infrastructure design, traffic environment factors, including road and weather conditions, can alter the crash likelihood. An analysis by Malin et al. (2019) of police-reported crashes in Finland identified a relative increase in crash risks under poor road and weather conditions. Furthermore, weather conditions, like direct sunlight or precipitation, can affect not only the driver's control and vehicle manoeuvring capability, but also the performance of sensors and pre-crash vehicle systems (Hussain et al., 2019; Heinzler et al., 2019).

An integral component of the broader traffic ecosystem is the composition and characteristics of the vehicle fleet, which can considerably influence crash exposure and characteristics. An analysis of the National Automotive Sampling System Crashworthiness Data System (NASS—CDS) database highlighted a mass compatibility issue: a large share of injuries resulted from collisions involving lighter vehicles colliding with heavier ones (Suarez-del Fueyo et al., 2021). This disparity, dictated by the conservation of momentum in a crash, can put occupants in smaller vehicles at a disadvantage, as also reported in previous studies (Gabler et al., 1998). Crash compatibility also depends on factors like stiffness differences and structural interactions (Teoh et al., 2012). A study using the Spanish Road Accident Database found that occupants of newer cars had a lower likelihood of injury during car-to-car crashes; however, it is worth noting that some of this effect could come at the cost of occupants in the older (opponent) vehicles, indicating that newer vehicles demonstrate increased crash aggressivity (Méndez et al., 2010). A recent study by Monfort et al. (2019) indicated that while vehicle incompatibility is reduced in newer vehicles, further efforts in advancing safety systems could address the residual challenges in crash aggressivity.

In addition to the physical infrastructure and vehicle characteristics, the broader traffic safety ecosystem also encompasses the efficiency and capacity of emergency response and health care systems. The rapid response of first responders can be important in reducing fatalities and serious injuries. Increased mortality rates in rural vs urban environments have been associated with prehospital treatment and time to hospital arrival (Gonzalez et al., 2009).

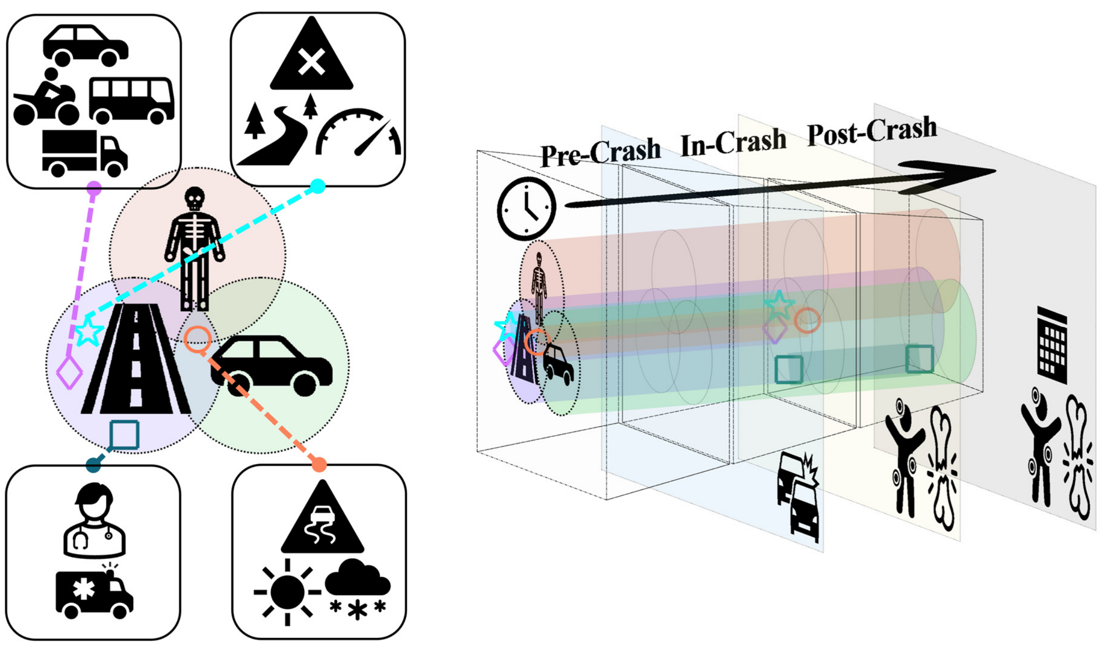

Figure 2. The main factors of the traffic environment are the road users' characteristics, the infrastructure, the environmental conditions, and access to medical care.

To conclude: The traffic environment can influence crash rates and characteristics, and consequently occupant safety. Understanding this influence can be beneficial for developing more effective occupant protection systems.

1.1.2 The Vehicle

Vehicle safety systems can be developed to improve occupant safety. Based on the specific crash phase they aim to address, they can be classified into pre-crash, in-crash, post-crash, and multi-crash-phase systems, as illustrated in Figure 3. Pre-crash systems aim to prevent or mitigate crashes, while in-crash systems aim to minimise the injury risk during a crash. Post-crash systems, on the other hand, aim to support occupants by preventing further impacts, facilitating the extrication process, alerting first responders, and providing them with vital crash-related information. Multi-crash-phase systems can offer a more integrated approach to occupant safety, by operating throughout multiple crash phases. (While multi-crash-phase systems are also referred to as "integrated safety" systems in the literature, the term is loosely defined and therefore not used in this thesis.)

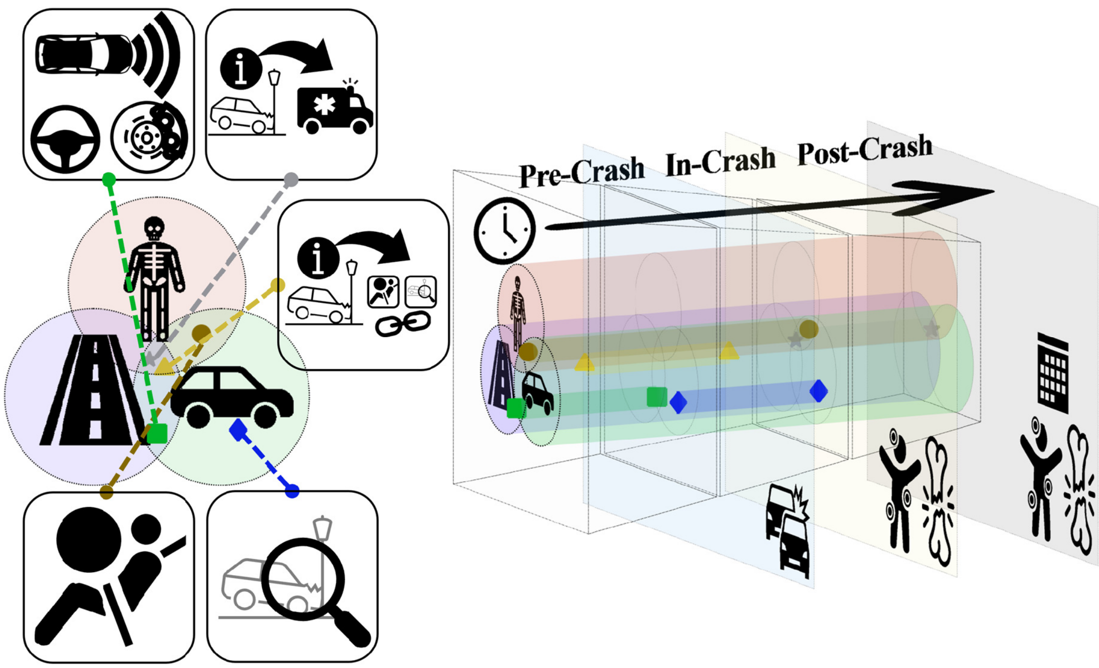

Figure 3. Vehicle safety systems consist of pre-crash (such as crash avoidance systems), in-crash (such as structure and restraints), post-crash systems (information to first responders), and multi-crash-phase systems (such as adaptive structures and restraints).

Pre-Crash Systems

Pre-crash systems include crash avoidance and mitigation systems (hereafter called "crash avoidance systems"), which are designed to avoid or mitigate the severity of potential vehicle crashes in critical situations—either independently or in conjunction with the driver. Crash avoidance systems, a component of the Advanced Driver Assistance Systems (ADAS), use a range of sensors to monitor the traffic environment (and potentially also the driver's state, such as sleepiness or cognitive distraction). Algorithms process the gathered information to analyse the situation and determine the most appropriate course of action. If intervention is deemed necessary, it could involve braking or steering adjustments and alerting the driver to imminent danger (Zhao et al., 2017). See the example in Figure 4.

Pre-crash systems have shown great potential in improving occupant safety across various methodologies, as summarised in a review by Yue et al. (2018). This study suggests that these systems could reduce overall crash incidents by up to 50%. Notably, the systems showed the highest potential benefits for Same Direction—rear-end-frontal (SD—ref) collisions, with avoidance rates approaching 70% (Yue et al., 2018).

A retrospective analysis conducted by Cicchino (2017) examined police-reported crashes across 22 US states. The findings indicate that a Forward Collision Warning (FCW) system led to a 27% reduction in SD—ref crashes. Furthermore, when FCW was combined with the Autonomous Emergency Braking (AEB) system, the reduction reached 50%. Another retrospective assessment indicated that vehicles equipped with Lane Departure Warning (LDW) systems experienced a 30% reduction in run-off-road crashes without traction loss (Isaksson-Hellman et al., 2018).

Additionally, the broader category of ADAS encompasses not only crash avoidance systems but also other systems that enhance comfort and safety during normal driving conditions. These systems, including functions like Lane Keeping Aid (LKA) and Adaptive Cruise Control (ACC), can pre-emptively help prevent critical situations from arising. Furthermore, the ongoing development of Autonomous Vehicles (AVs), which aim to operate without human supervision, further accelerates the advancements in pre-crash systems (Fagnant et al., 2015). As AV technology advances, it holds the potential to revolutionise road traffic safety and pave the way for a future where vehicles seldom crash. While AVs might eventually prevent most crashes, their widespread adoption requires time (Zheng et al., 2020). In the transitional period, when they coexist with manually driven vehicles on the roads, it is crucial not to ignore the possibility of crashes. A study investigating AVs' potential safety benefits reported that road fatalities are expected to be substantially reduced (Lubbe et al., 2018). However, the authors noted that AVs would not be expected to avoid all crashes. Therefore, in-crash systems remain essential to mitigate the consequences of crashes and protect occupants, especially in the transitional phase of AV adoption.

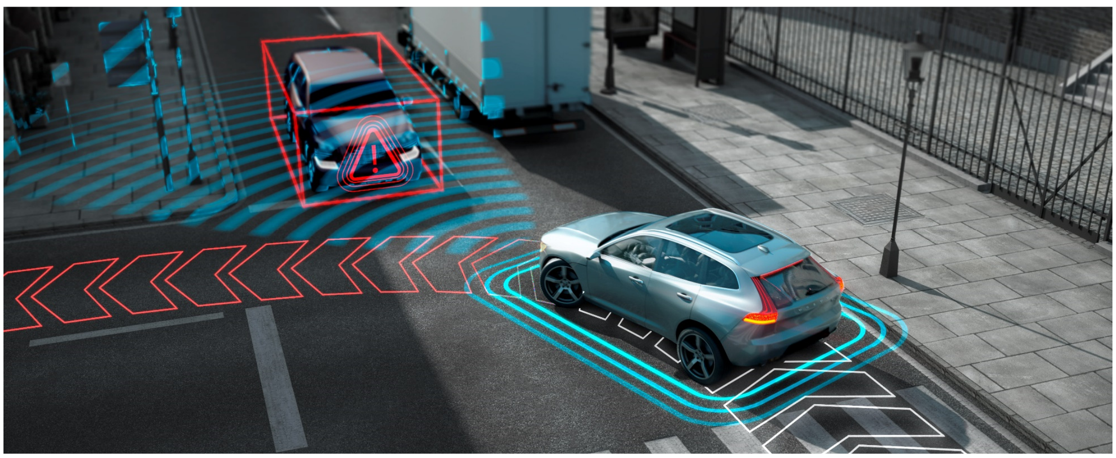

Figure 4. An example of a pre-crash intervention. The host vehicle (surrounded by a blue box) uses sensors to scan the environment in front of it. If a collision threat (car highlighted with red frame) is detected, then the host vehicle can take action to help avoid the crash or mitigate its severity. [source: Volvo Cars]

Crash avoidance systems, when activated, lead to one of two outcomes: crash avoidance, where the system successfully prevents a crash; or crash mitigation, where the system intervenes but cannot completely avoid the crash. Evaluating the effectiveness of pre-crash systems, particularly considering mitigated crashes, is challenging. The interventions can alter the crash configuration, influencing factors like the crash's location, direction, and velocities. In addition, the interventions could also affect the occupant's initial in-crash posture by inducing kinematics just before the crash. To have a complete picture of the crash avoidance system's performance, factors that could potentially influence in-crash response should be considered.

In-Crash Systems

In-crash systems aim to minimise the effects of a crash on the car occupants—also called "self-protection"—as well as on the other potential crash participants. Self-protection in-crash systems are based on two core design principles. The first is maintaining the structural integrity of the vehicle's occupant compartment to help control interactions between the occupant and deforming vehicle structures. The vehicle's acceleration during a crash—often referred to as the "crash pulse"—is controlled using deformation zones on the vehicle. The geometrical and mechanical properties of the vehicle (Figure 5) and the object it collides with, dictate the crash pulse and potential deformations into the occupant compartment. Simultaneously, restraint systems help protect the occupants by controlling their motions throughout the crash. Components of vehicle restraint systems include seat belts (Figure 6), airbags, and interior components like seats and interior structures.

Advancements in in-crash safety systems have played an important role in reducing the number of fatalities and serious injuries in vehicle crashes. A study based on approximately 70,000 crashes from the NASS—CDS database found that newer vehicles were associated with reduced mortality rates (Ryb et al., 2011). Furthermore, an analysis of NASS—CDS data revealed that newer vehicles posed lower risks of occupant injuries than older vehicles (Forman et al., 2019a). These findings demonstrate the positive impact of in-crash safety system advancements on protecting vehicle occupants during collisions.

Figure 5. Different materials, indicated by different colours, selected to maintain the structural integrity, and absorb energy. [source: Volvo Cars]

Figure 6. Photo of the Volvo 3-point seat belt with its inventor, Nils Bohlin. [source: Volvo Cars]

Beyond crash compatibility issues arising from the composition and characteristics of the vehicle fleet (see Section 1.1.1), crash characteristics, such as impact location or angle between vehicles, introduce further variability that in-crash systems must account for. For example, severe small-overlap collisions, in which only a small proportion of the front structure engages during a crash, present different occupant protection challenges compared to full-width crashes. These challenges are often associated with an increased risk of deformations into the occupant compartment, a characteristic of such crashes (Planath et al., 1993). Similar effects were observed in simulation setups, indicating a potential for greater occupant compartment deformations in small-overlap crashes compared to their larger-overlap counterparts (Wågström et al., 2013a). Conversely, large-overlap crashes might result in crash pulses of greater magnitude, posing different occupant protection challenges (Wågström et al., 2013a). Understanding the diversity in crash characteristics and their potential challenges is important for effectively designing and implementing in-crash protection systems.

Multi-crash-phase systems, such as pre-crash triggered adaptive structures and restraint systems, could be developed to address the heterogeneity of crash scenarios. For example, adaptive vehicle structures can leverage information from the pre-crash phase to tune the structural response (Wågström et al., 2013b) according to the anticipated crash. Similarly, adaptive restraint systems could prepare for an upcoming crash based on the expected crash pulse and occupant characteristics (Distner et al., 2009; Schoeneburg et al., 2011). These examples demonstrate the integration of pre-crash and in-crash protection systems, highlighting their complementary roles in enhancing occupant safety.

To conclude: Vehicle safety systems encompass pre-crash, in-crash, post-crash and multi-crash-phase systems, each playing an important role in occupant safety. Those systems work together to avoid crashes and mitigate their consequences. Pre-crash systems have demonstrated their effectiveness in reducing crashes. Similarly, the evolution of in-crash systems, including vehicle structures and restraint systems, has contributed to enhance occupant safety. However, pre-crash interventions that lead to crash mitigation can alter multiple parameters of the crash configurations, which complicates the safety benefit assessment. Occupant safety could be improved by developing multi-crash-phase systems.

1.1.3 The Occupant

Occupants can differ in many ways. Aggregate occupant characteristics, such as stature, Body Mass Index (BMI), sex, and age—as well as posture, seat adjustment choices, and belt fit, vary within the population. This variability can affect the occupant's response and injury outcome during a crash. Beyond aggregate occupant characteristics, individual variability, such as differences in bone shape, spinal alignment, and material properties, can also influence the occupant's response (Figure 7). Understanding the effects of occupant variability has the potential to further enhance the safety of the diverse car occupant population.

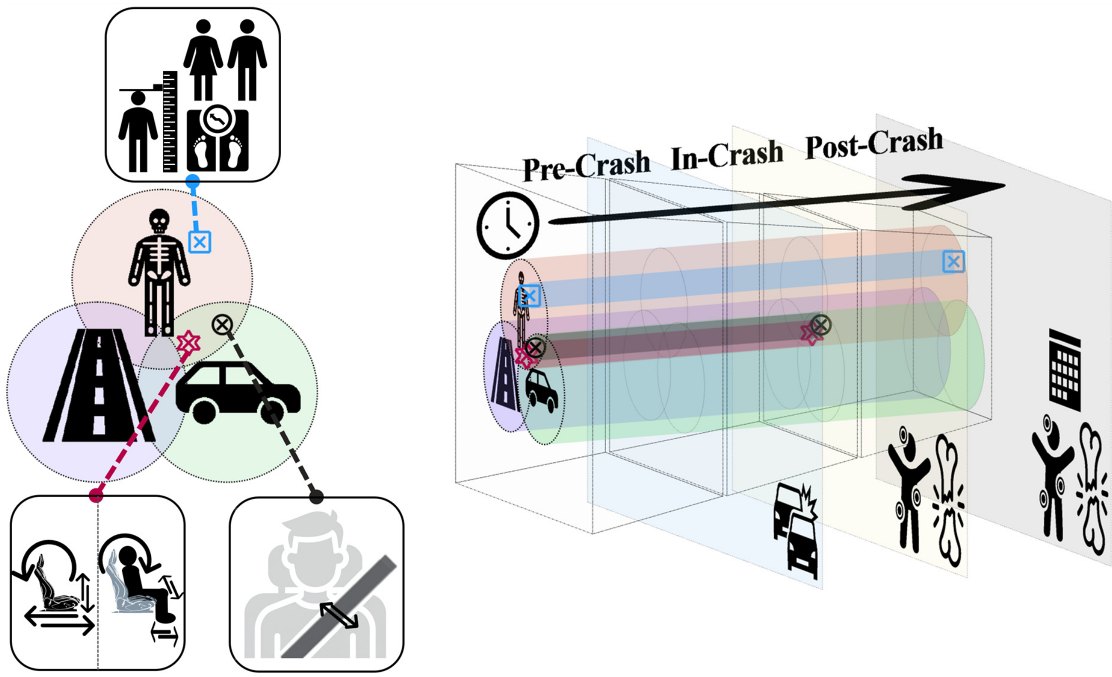

Figure 7. Occupant characteristics, such as stature, Body Mass Index (BMI), sex, as well as seat adjustment choices, posture and belt fit, can influence the occupant's injury risk.

Anatomical Variability

Carter et al. (2014) conducted a statistical analysis of vehicle crashes in the US using data from 2000 to 2010 to characterise the effects of age, BMI, and sex on injury risk. For frontal, side, and rollover crashes, the injury risk of each body region substantially rose as the occupant's age increased. The probability of lower extremity injuries in frontal crashes was higher for occupants with greater BMI. Additionally, an 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 97% and 32% higher fatality risk for drivers and passengers, respectively, compared to occupants with normal BMI (18.5$\leq$ BMI <30). Variations across the sexes and age groups were also observed, with obesity significantly associated with increased injury risk for females, but decreased risk of serious injury for males. No effect of obesity was found for older drivers; however, obese young drivers were 20% more likely to be seriously injured than young drivers with normal BMI. Additionally, the occupants' stature might be associated with the type and severity of lower extremity injuries (Chong et al., 2007).

Individual variability is also an important factor across various anatomical aspects of the human body. Studies exploring anatomical variability, including the geometry of the ribcage (Wang et al., 2016; Holcombe et al., 2017; Larsson K.J. et al., 2022), long bones (Klein et al., 2015), pelvis (Brynskog et al., 2021), lumbar spine (Tang et al., 2022), and abdominal organs (Yates et al., 2016; Yates et al., 2018), have shown that factors like sex, age, stature, and BMI alone are inadequate for fully describing human anatomy. Additionally, research on the mechanical properties of biological tissues, such as bones (Kemper et al.,2005; Katzenberger et al., 2020) and ligaments (Woo et al., 1991; Chandrashekar et al., 2006), indicates that while age, sex, and anthropometric measurements can influence material properties, they do not capture the entirety of the variability observed.

Occupant Posture and Choice of Seat Adjustment

The occupants' posture depends on many factors, such as individual preferences and anatomical variations, as well as the vehicle's interior design. Various methods, such as laboratory tests, moving-vehicle experiments, and naturalistic driving studies, have been employed to study the occupants' posture.

Unlike drivers, passengers are not obligated to control the vehicle through the steering wheel and pedals. Instead, they can engage in non-vehicle-control-related activities, which can lead to increased posture variability. A study comparing the postures of male and female vehicle occupants revealed similar postures during typical riding (Cutcliffe et al., 2017). However, differences were observed between drivers and passengers, with drivers exhibiting a more protracted neck.

Statistical models have been developed to predict driver (Reed et al., 2002) and passenger (Park et al., 2016a) postures, relying on data from static laboratory environments. Reed et al. (2002) introduced a method that considers factors like stature, BMI, seat design, and distance to vehicle landmarks to predict average driving postures. In a more recent publication, Park et al. (2016b) found a significant association between driving posture and age, and they provided sex-specific statistical models. In addition, Park et al. (2016a) identified seat configuration as an influential parameter for the posture of rear-seat occupants.

A recent naturalistic driving study has yielded valuable data on front-seat occupant postures (Reed et al., 2020a, 2020b). The publication revealed that their lower extremities were positioned in non-nominal postures in over 50% of the video frames; head rotations were observed in 33%, torso rotations in about 10%, and torso forward-pitch in almost 10%. Another naturalistic driving study conducted by Fice et al. (2018) investigated head postures among drivers. The study reported that drivers tend to have their heads in non-neutral postures more frequently when the vehicle is stationary (17%) than when in motion (8%).

Additionally, occupants have the option to adjust not only their posture but also their seat positions. A study conducted with 154 participants in a laboratory environment using a stationary vehicle examined the driver's selected seat adjustment variability (Jonsson et al., 2008). The study revealed that 69% of the variation in seat horizontal movement could be attributed to the driver's sex, stature, and weight (Jonsson et al., 2008).

Passengers, particularly those in the front seat, have a broader range of seat adjustment possibilities than drivers, potentially leading to increased variability. In a naturalistic driving study, approximately 50% of front-seat passengers chose to maintain the vehicle's seat settings without altering the seat fore-aft position or seat backrest angle (Reed et al., 2020b). The study's findings also included seat position and backrest angle distributions, indicating that front-passenger seats were usually positioned towards the rear half of the fore-aft range and that the seatback angle rarely exceeded 35°.

In addition to occupant posture preferences and various factors influencing their posture, pre-crash vehicle manoeuvres can induce occupant movement in the pre-crash phase. Those pre-crash manoeuvres can be initiated by the driver or by a pre-crash system. Scanlon et al. (2015)

analysed crashes at US intersections and reported that most drivers performed an evasive manoeuvre prior to a crash. Those manoeuvres can lead to altered occupant posture, as indicated by studies investigating evasive braking or steering (Carlsson et al., 2011; Östh et al., 2013; Ghaffari et al., 2018; Reed et al., 2018, 2021). Additionally, even cornering in everyday traffic can also induce occupant movement (Bohman et al., 2020).

Belt Fit

Belt fit, the placement of the seat belt on an occupant's body, can potentially affect the occupant's response and injury risk during a crash. Various factors can influence belt fit, including the occupant's characteristics, posture, and seat belt design. Several methods can be employed to measure belt fit, from stationary laboratory tests to driving studies.

A recent study by Makris et al. (2023) compared occupant postures and belt fit between a stationary laboratory setup and a driving study. While no statistically significant differences in average posture and belt fit between the two setups were found for most occupants, specific body types exhibited distinct variations, especially those with a larger chest. For those individuals, the shoulder belt moved closer to the neck during the driving study. This finding suggests that driving studies might provide insights not captured in stationary setups for certain demographic groups.

In a laboratory study on drivers conducted by Reed et al. (2013), the influence of BMI, age, and stature on belt fit was investigated. It was found that a greater BMI was associated with a higher, more forward lap belt placement relative to the pelvis. Another study by Reed et al. (2019), which also used a laboratory vehicle mock-up, analysed the belt fit and posture of 24 passengers across different seatback angles. It was observed that occupants with larger BMIs tended to exhibit a more upright torso and pelvis angle. Additionally, reclining the seat increased both pelvis and torso angles, which were further increased when the headrest was used. Notably, BMI remained the dominant factor influencing lap belt position. Moreover, as the seatback angle increased, the shoulder belt tended to be positioned further inboard (on average).

In a stationary vehicle setup, differences in belt fit between younger and older occupants were observed (Bohman et al., 2019). These disparities were partly attributed to variations in posture, including a more kyphotic torso in older individuals. In another study utilising a laboratory vehicle mock-up, Jones et al. (2021) found that, after controlling for stature and BMI, sex was associated with differences in both lap and shoulder belt fit. Additionally, variations in the seat belt anchorage locations can also cause differences in belt fit, with shoulder belt fit being more influenced by the anchorage location than by high BMI. However, occupant characteristics and belt anchorage locations could predict only 40% of the variation in lap belt fit and 54% in shoulder belt fit.

To Conclude: Occupant heterogeneity encompasses anatomical variability and variations in posture and belt fit. Anatomical variability in bone geometry, organ shape, and mechanical properties of tissues is influenced by factors such as sex, age, stature, and BMI, as well as individual variability. Furthermore, occupant posture is subject to occupant characteristics, individual preferences, vehicle design, and pre-crash kinematics, adding another layer of complexity. These anatomical and postural differences, compounded by vehicle motion of pre-crash manoeuvres, can also affect belt fit, potentially influencing the seat belt's effectiveness.

1.2 Occupant Safety Assessment

Occupant safety assessments evaluate the capability of individual vehicles (or vehicle fleets) to protect their occupants. The assessment can identify safety challenges, and its metrics can also be used as parts of the objective function to optimise the vehicle's safety systems.

Several methods are used for assessing occupant safety. On the one hand, retrospective assessments can be done to study the real-world outcome by analysing statistical databases years after the introduction of a countermeasure. On the other hand, prospective methods take advantage of numerical or experimental techniques to predict the expected outcome of the evaluated countermeasure. Retrospective methods are inherently of limited value for assessing countermeasures during the development stage of new vehicles. However, they are valuable for identifying improvement areas and essential for understanding the Operational Design Domain (ODD), which refers to the specific conditions under which a given vehicle or system is intended to operate. They are also useful for validating and improving the prediction accuracy of prospective methods.

Prospective vehicle safety assessments can be conducted with physical tests (using prototype or production vehicles) and virtual tests (using simulations with numerical models to represent the vehicle being tested). Physical assessments offer the advantage of accurately representing the vehicle's response during a crash. However, they are often time-consuming and expensive. Moreover, recreating complex real-world crash conditions poses challenges. In contrast, virtual assessments are cost-effective, provide faster iterations, and have the capability to simulate complex crash scenarios commonly encountered in real-world crashes. Nevertheless, the accuracy of virtual assessments, which relies heavily on the fidelity of numerical models, must typically be validated through physical tests. Therefore, a combination of physical and virtual testing is often used to overcome the limitations and leverage the strengths of both methods.

To conclude: Occupant safety assessments include retrospective analysis of real-world data and prospective methods like physical tests and numerical simulations. These assessments play a vital role in identifying safety challenges and are, therefore, integral to the development of safer vehicles.

1.2.1 Standardised Tests

The standardised vehicle safety tests consist of regulatory and consumer information tests. Regulatory tests are obligatory to ensure that vehicles meet the specific minimum safety standards set by governing authorities, allowing the vehicles to be sold in a particular country or region. On the other hand, consumer information tests are conducted to provide consumers with information about the safety performance of passenger vehicles, in order to assist them in making informed choices. Examples of car assessment programmes are the European New Car Assessment Program (Euro NCAP), the US New Car Assessment Program (US NCAP), and the Insurance Institute for Highway Safety (IIHS) in the US.

Standardised tests can target all crash phases. Pre-crash assessments involve subjecting test vehicles to critical driving situations, with the primary aim of evaluating how effectively the vehicle's crash avoidance systems intervene. Additionally, in-crash safety assessments assess the vehicle's safety performance during a crash. This assessment can take two forms: full-scale crash testing (see example in Figure 8) or system testing. Full-scale crash testing entails crashing the test vehicle into other vehicles or objects to examine the vehicle's structural integrity, assess the performance of its restraint systems, and estimate the risk of injury to vehicle occupants. Meanwhile, system testing involves subjecting vehicle systems or components to various tests, such as simulating head impacts on the vehicle interior or subjecting seat and head restraints to accelerations in a simplified sled environment to emulate rear-end impacts. As an example of post-crash safety evaluations, the force required to open doors or release seat belts can indicate the ease of occupant extrication after a crash.

Figure 8. A photo of a car at barrier contact; an example of a standardised crash test. [source: Volvo Cars]

Standardised tests have been instrumental in improving vehicle safety performance. For instance, through its test protocols, the Euro NCAP has encouraged enhancements in vehicle structural response, resulting in reduced deformations into the occupant compartment (van Ratingen et al., 2016). Additionally, NCAP programs have been linked to higher adoption of safety features like Intelligent Seat Belt Reminders and AEB (van Ratingen et al., 2016). Retrospective studies have further demonstrated the undeniable role of standardised tests in advancing vehicle safety. A retrospective analysis of approximately 200,000 car-to-car crashes from the Swedish Traffic Accident Data Acquisition (STRADA) database showed a consistent improvement in vehicle safety performance over the years, as indicated by the decrease in injury risk at all severity levels (Kullgren et al., 2019). Moreover, vehicles rated with five stars in Euro NCAP demonstrated a 34% lower risk of severe injuries (AIS3+) than those rated with two stars, indicating a correlation between Euro NCAP performance and real-world safety (Kullgren et al., 2019). Similar findings were observed in studies using US databases. A strong association was found between performance in IIHS side crash tests and real-world driver fatality risk, based on data from the Fatality Analysis Reporting System (FARS) database from 2000 to 2016 (Teoh et al., 2022). Similarly, an analysis of 143 near-side crashes from the NASS—CDS database between 2010 and 2015 indicated that the performance in the Moving Deformable Barrier (MDB) test from the US NCAP programme was a significant predictor of injury risk (Bareiss et al., 2020).

To conclude: Standardised tests, encompassing regulatory and consumer information tests, can drive vehicle design and safety feature improvements. Studies have indicated that good test performance correlates with real-world safety and reduced injury risk. However, as of today, standardised assessments cannot fully account for the variability seen in real-world crash scenarios, due to their focus on a limited number of reproducible scenarios.

1.2.2 Occupant Surrogates

Relying solely on the vehicle's response during a crash to assess the safety of humans is insufficient. The use of human surrogates is thus crucial to gain insights into potential injuries for vehicle occupants. In the early stages of crash testing, before the advent of virtual testing methods, physical testing was the primary approach, leading to the development and employment of physical devices known as Anthropomorphic Test Devices (ATDs), or more commonly "crash test dummies".

Standardised tests heavily rely on ATDs, which may not fully capture the range of human anatomical variability. Efforts are being made to enhance standardised tests by incorporating more virtual assessment methods (Galijatovic et al., 2022; Klug et al., 2023). However, despite these advancements, there are practical challenges in conducting a large number of physical or virtual tests for every vehicle on the market. The sheer scale and complexity of such testing would be monumental and likely unfeasible.

Due to the complexity of manufacturing a device that would be able to replicate and measure human responses in the entire range of crash scenarios, each ATD is specifically designed to capture occupant responses in a specific type of crash, such as frontal, side, or rear-end. That is, different ATDs are used for distinct loading directions, in order to achieve a biofidelic representation of the physical responses for specific crashes.

However, real-world crashes often occur at oblique angles, involving impacts that are not strictly frontal, side, or rear, but rather combined directions, resulting in a crash pulse direction that can also vary over time. Since ATDs are predominantly designed and validated for specific loading scenarios, they may not be suitable for all real-world crashes since they may not provide a biofidelic occupant response in all loading directions.

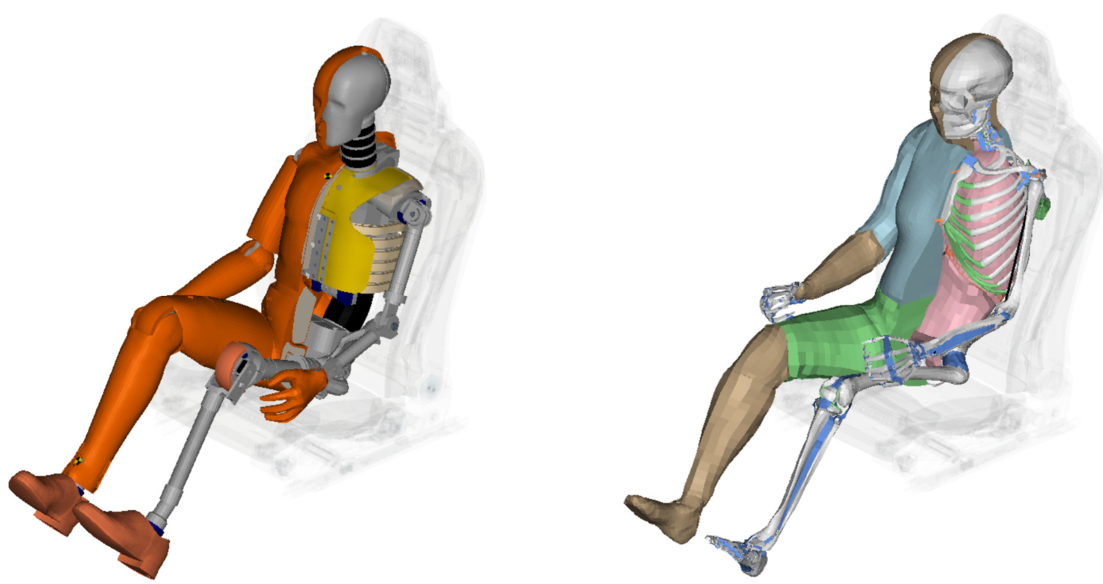

Figure 9. Illustration of numerical models of an ATD (on the left) and an HBM (on the right). The ATD is a mechanical surrogate model of an occupant. In contrast, the HBM is a direct numerical model of an occupant.

In virtual safety assessments, numerical models of both ATDs and Human Body Models (HBMs) are utilised (Figure 9). Unlike ATDs, which are mechanical surrogates constrained by physical manufacturing and durability, HBMs are direct virtual representations of the human body, offering more detailed and accurate depictions of human anatomy. Commonly used Finite Element (FE) HBMs include the Global Human Body Model Consortium (GHBMC) HBM

(Davis et al., 2015), the SAFER HBM (Pipkorn et al., 2019), the Total Human Model for Safety (THUMS) (Iwamoto et al., 2015), and the VIVA+ HBM (John et al., 2022). The more detailed and accurate representations of the human body in HBMs, pave the way for superior biofidelity and omnidirectionality. The omnidirectionality allows HBMs to simulate impacts from multiple directions as well as complex kinematics, often resulting from real-world crashes. Additionally, features such as active musculature make them suitable for assessing occupant response even during low-acceleration events in the pre-crash phase (Larsson E. et al., 2019).

HBMs have the potential to perform tissue-based injury prediction and do not need to rely solely on global measurements like accelerations and forces. HBMs simulate the stresses and strains in specific body regions during a crash simulation using detailed geometrical models with mechanical properties of biological tissues. Tissue-based criteria enable a more accurate and localised assessment of potential injuries, as they can take into account the response and tolerance of different tissues to different loadings. Examples of implemented tissue-level injury criteria include strain-based concussion risk prediction (Kleiven, 2007) and rib fracture risk prediction based on rib strain (Iraeus et al., 2019). Additionally, injury to organs, such as the lung, liver, and spleen, can also be assessed using strain-based metrics (Miller et al., 2016). Tissue-level injury predictors could improve the prediction of real-world injuries compared to global criteria (Miller et al., 2016).

An additional advantage of the detailed modelling of the human anatomy in HBMs is that they can be used to investigate aspects of human variability, such as anatomical differences. "Morphing" is a method used for this purpose; it alters the geometry of HBM, enabling the creation of HBMs with varied anthropometries (see Figure 10) that better represent real-world population diversity (Hwang et al., 2016a). Moreover, morphing can be applied to specific body parts to capture individual anatomic variability.

The increased level of detail in HBMs not only provides enhanced biofidelity but also introduces potential challenges in setting up virtual assessment experiments. One of the challenges is positioning them in the seat. This positioning is typically achieved using either the "marionette method" or morphing techniques. The marionette method uses one-dimensional elements to pull specific body landmarks to the desired position, effectively placing the HBM in the desired posture (Poulard et al., 2015a). While this method utilises the biomechanical properties of the HBM to provide realistic postures, it can be time-consuming due to the need for FE simulations. On the other hand, morphing techniques are computationally more efficient as they do not require simulations. However, they may result in element quality artefacts, particularly for large postural variations (Beillas et al., 2017).

Further, during the HBM positioning simulations, stresses and strains are generated within the tissues. A recent simulation study in which a cervical spine segment was subjected to various loading modes demonstrated that the initial stress state could alter the kinetics and kinematics, as well as failure modes (Boakye-Yiadom et al., 2018). However, knowing the neutral posture across individuals is not trivial.

Additionally, the soft-tissue material of HBMs is typically softer than that of ATDs, allowing the HBM's external surface to conform to the vehicle's seat. Since the occupant's position in the seat could influence the crash response, recent studies have used Magnetic Resonance Imaging (MRI) to investigate how seat parameters and deformation of the HBM's soft-tissue relate (Wang et al., 2021). Furthermore, MRI analysis methods are being developed to extract quantifiable measurements of occupant postures and belt fit (Booth et al., 2022).

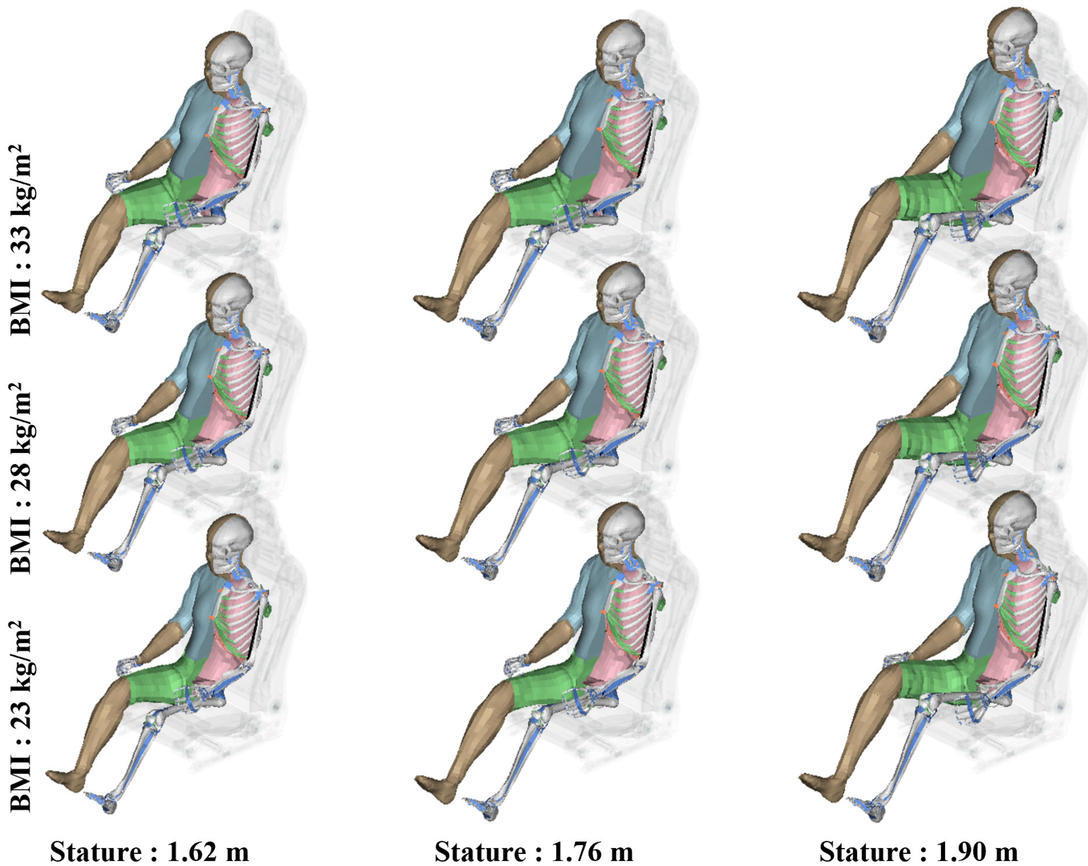

Figure 10. Illustration of morphed Human Body Models (HBMs) featuring male body geometries with a BMI range of 23–33 kg/m² and stature extending from 1.62 to 1.9 meters.

Another limitation of most morphed HBMs regarding seat belt fit is that neither the methods typically used to collect data on the occupants' outer surface, nor the morphing techniques can capture or recreate folds in soft tissue. This limitation is particularly relevant for obese occupants, because a fold in the abdominal area could alter the interaction with the lap belt and thus create inaccuracies in the models (Lebarbé et al., 2020).

To conclude: Occupant surrogates, such as ATDs and HBMs, are essential for assessing occupant safety in crashes. ATDs are mechanical occupant surrogates, designed to capture occupant responses in specific crashes, and have limited ability to represent the full range of occupant sizes and impact directions. HBMs are numerical occupant surrogates and offer greater biofidelity, omnidirectionality, and injury prediction capabilities. Additionally, with the use of morphing techniques, HBMs can account for anatomical variability, which enables the assessment of diverse anthropometries. However, employing HBMs in safety assessments poses challenges due to their complexity.

1.3 Research on the Effect of Heterogeneity Aspects

State-of-the-art studies beyond standardised tests encompass virtual assessment methods, advanced simulation techniques, and data-driven analyses. With these methods, the interactions within the road traffic safety system and the effect of crash variability can be explored. As our understanding increases, occupant protection can be enhanced.

1.3.1 Pre-Crash Systems Assessment

Given the rarity of vehicle crashes and the complexity of the traffic safety system, establishing the safety performance and reliability of AVs presents a formidable challenge. For example, conventional testing methods would probably require AVs to drive hundreds of millions or even billions of kilometres on the road in order to acquire enough scenarios to capture the "real-world" and demonstrate their safety performance (Kalra et al., 2016). An alternative is the "scenario-based approach", in which potentially dangerous or challenging scenarios for AVs are identified and tested. However, identifying such scenarios can also be difficult, and the vast array of parameters involved may result in an overwhelming number of potential scenarios. Consequently, employing advanced techniques could be beneficial to effectively reduce the number of scenarios for testing and evaluation (Amersbach et al., 2019).

Counterfactual simulations of reconstructed crashes have been used to assess the safety performance of AV systems. In one counterfactual approach, simulations of severe events assess the system to an estimated equivalent of driving extremely long distances in real traffic (Scanlon et al., 2021). The findings from these simulations are promising, revealing that the system could potentially avoid approximately 80% of all crashes and reduce the severity of an additional 10%. However, one limitation of this approach is the inherent uncertainties (due to the lack of information about the reconstructed crashes derived from police reports), which may alter the results (Scanlon et al., 2021).

Prospective studies have also demonstrated the potential benefits of crash avoidance systems. Specifically, AEB has demonstrated efficacy in avoiding intersection crashes. Hypothetically, if every vehicle on the road incorporated an AEB system paired with a wide field-of-view (180°) sensor, a staggering 80% reduction in crashes could be expected (Sander et al., 2018). Furthermore, a study analysing fatal car crashes in 2010 in Sweden concluded that LDW could potentially avoid about a third of all head-on and single-vehicle fatal crashes (Sternlund, 2017).

In other studies, researchers have delved into the potential impact of pre-crash systems, such as AEB and LKA, as well as AVs, on injuries in future vehicles. These investigations have focused on predicting the types of vehicle crashes that may occur in the future (Östling et al., 2019b), even identifying specific detailed crash configurations that are likely to happen (Östling et al., 2019a). Understanding the details of the crashes that are expected to remain can promote the design of relevant in-crash occupant protection systems.

As noted, when pre-crash interventions do not lead to crash avoidance, they have the potential to alter not only the vehicles' speeds but also other aspects of the crash configurations. By simulating multiple crash configurations, Simon et al. (2019) estimated the crash severity of those configurations based on deformations into the occupant compartment. The pre-crash systems could use this information to select the actions that would lead to the lowest possible severity in the case of an unavoidable crash. The ability to generate this knowledge enables the possibility of considering pre-crash systems not only as "collision avoidance systems" but also as "collision reconfiguration systems" (Parseh et al., 2021).

Virtual assessment methods can be used to explore the pre-crash system's performance under a wide range of potential conflict situations and conditions. This approach enables a more extensive evaluation of those systems in addition to supporting the development of more robust and effective pre-crash systems, ultimately leading to safer vehicles.

To conclude: In the realm of pre-crash systems assessment for AVs, new approaches are needed. A scenario-based approach is suggested to identify and assess challenging scenarios. Counterfactual simulations of reconstructed challenging scenarios have been used for evaluating the safety of AVs, but due to a lack of data on the reconstructed crashes, uncertainties remain. Additionally, the influence of pre-crash systems on future crash configurations has been investigated. Recent studies have also investigated how crash characteristics could be altered in unavoidable crashes, expanding the role of crash avoidance systems to "collision reconfiguration systems".

1.3.2 Whole-Sequence Assessment

In addition to altering the expected crash configurations, pre-crash safety systems can change the pre-crash vehicle kinematics, potentially altering the occupant's posture, muscle bracing level, as well as velocity and position relative to the vehicle's interior. These altered occupant states, in turn, may affect the occupant's in-crash response during a potential collision.

In a proof-of-concept study conducted by Östmann et al. (2016), HBMs were shown to be applicable throughout the entire crash sequence, covering both the pre-crash and in-crash phases. By simulating a pre-crash braking intervention followed by a frontal crash, the study demonstrated that active muscles in the HBM could be used to replicate changes in occupant posture during the pre-crash phase. In a similar study by Saito et al. (2016), different electrical reversible seat belt retractor forces were tested in order to quantify the resulting changes in occupant excursion. This approach allowed the evaluation of the combined performance of pre-crash and in-crash systems in mitigated crashes.

Guleyupoglu et al. (2017) examined the effects of pre-crash interventions on occupant injury risk. Their research revealed that pre-crash braking reduced occupants' injury risk by decreasing the impact velocity. However, increasing the pre-crash deceleration above 1g did not consistently reduce injury risk, perhaps due to the altered pre-crash posture of the occupants imposed by the vehicle deceleration. Notably, their simulations only considered muscle activation in the neck and relied solely on global injury criteria for injury predictions. Seeking to enhance the understanding of occupant kinematics and injury outcomes during frontal impacts with pre-crash decelerations, Kato et al. (2018) developed an HBM with whole-body skeletal muscles. Their study indicated that muscle activation could affect both occupant kinematics and injury outcomes. Specifically, occupants who braced themselves during pre-crash decelerations exhibited a reduced risk of injury. Additionally, Iwamoto et al. (2018) explored the effect of the level of muscle bracing by drivers when exposed to a deceleration before rear-end impacts. They distinguished between "relaxed" and "braced" drivers, with the latter actively bracing by applying forces to the steering wheel and pedals. Reduced strains in the neck and brain for braced drivers were observed in the HBM simulations, suggesting a potential for reduced injury risk for braced drivers, which was attributed to altered in-crash kinematics.

Building on this concept, subsequent studies explored the transfer of information from the pre-crash to the in-crash phase while considering the altered crash configuration during pre-crash interventions (Wågström et al., 2019). This approach not only assessed the pre-crash intervention effects but also enabled the investigation of potential strategies benefiting from the synergies of the vehicle's braking system. For instance, Östh et al. (2020) conducted a simulation study using active HBMs, demonstrating that pre-crash braking could reposition reclined occupants through their inertia. However, they noted challenges in adjusting the occupants' initial in-crash pelvis posture, which could influence the interaction between the lap belt and the occupant.

To conclude: Pre-crash safety systems can alter occupant kinematics and posture at the start of the in-crash phase. Since the occupants' posture can potentially affect their in-crash responses, whole-sequence assessment methods are beneficial. Muscle activation during pre-crash manoeuvres can alter occupant kinematics. Studies have shown that active HBMs can be used to predict occupant movement in the pre-crash phase and, therefore, to evaluate combined pre-crash and in-crash safety systems. This application of HBMs enables the assessment of the whole crash sequence and the exploration of additional strategies to enhance occupant safety.

1.3.3 In-Crash Systems Assessment

The occupant's in-crash response, and hence safety, during a crash may be influenced by a range of parameters, including occupant variability, crash characteristics variability, and vehicle design characteristics. This section offers a survey of recent studies that utilise advanced numerical techniques to assess the effect of some of those parameters.

In an early study, researchers delved into the impact of occupant sizes beyond the sizes of available crash test dummies (Happee et al., 1998). They developed and implemented a method to scale 30 multi-body models of crash test dummies (based on the H-III ATDs). The study demonstrated that the range of predicted injury risk when using these models exceeded the injury risk values observed from the standardised ATDs in standardised frontal crashes. These results indicated that the three ATD sizes commonly utilised in standardised tests were unable to fully represent the real-world population (Happee et al., 1998).

Parametric Human Body Models—Occupant Size and Shape

In their literature review, Hu et al. (2012) explored the influence of sex, age, and obesity on traffic injuries, considering recent HBM developments. The review suggested that parametric FE HBMs could form the basis of a framework that incorporates up-to-date knowledge of human anthropometry and tissue mechanics. This framework could enable population-based assessments of vehicles, leading to improved occupant safety for a broader demographic group.

One of the first studies to investigate occupant variability aspects using parametric FE HBMs was conducted by Shi et al. (2015). By morphing HBMs to represent occupants with different BMI levels through statistical models of the ribcage and external body shape, the authors demonstrated the viability of using morphed HBMs for investigating injury risks across different population groups. The study predicted increased risks of thoracic and lower extremity injuries for obese occupants compared to occupants with nominal BMI (Shi et al., 2015).

Following a similar approach, Schoell et al. (2015) utilised statistical shape models of more body parts, including the brain, head, thorax, pelvis, femur, and tibia (along with their biomechanical properties), to morph an HBM to represent a 65-year-old midsize male occupant. Through simulations of standardised frontal crashes, the morphed model predicted higher injury risks for the head and thorax than those predicted by the original model.

Further advancing the research on morphed HBMs, Hwang et al. (2016a) presented a novel method to rapidly generate morphed HBMs based on sex, age, stature, and BMI. Their primary goal was to develop parametrised HBMs that could represent a wide range of human characteristics while maintaining element quality comparable to the original model. Subsequently, the biofidelity of the morphed HBMs was evaluated using data from Post Mortem Human Surrogate (PMHS) tests in side crash conditions (Hwang et al., 2016b). For each PMHS test, three HBM variants were considered: the original model, a parametric HBM (based on sex, age, stature, and BMI), and an individualised HBM (based on Computer Tomography, CT, scans). The results indicated that both morphed models were superior to the original model at predicting the PMHS impact response. A similar evaluation by Larsson K.J.

et al. (2019) confirmed the findings of improved kinematic responses for morphed HBMs, while also highlighting the challenge of accurately predicting rib fractures solely through the occupant's rib geometry.

Furthermore, stature and body shape were found to affect driver injury risk, as seen in a study with frontal crash simulations by Hu et al. (2017). They observed that shorter females and taller males were exposed to higher injury risk than mid-stature males. Additionally, obese drivers were at greater risk of injury across all simulations. It was concluded that driver body size and shape affect the occupants' interactions with the restraint systems, along with their kinematics, and injury risk in frontal crashes.

In one of the first large-scale studies examining the impact of occupant anthropometric variability, Hu et al. (2019) conducted frontal crash simulations using 100 parametric HBMs with different combinations of sex, age, stature, and BMI to represent a large portion of the US adult population. The study revealed that the drivers' stature and BMI had notable effects on their interactions with the restraints, leading to altered kinematics and injury risks. The study also found correlations between age and sex and the risk of chest injuries: older females were at higher risk. Additionally, the study identified an increased risk of lower extremity injuries for obese drivers.

Local Anthropometric Variability

Despite the undeniable advancements made by morphed HBMs based on parameters like sex, age, stature, and BMI, it is widely acknowledged that these models can only account for a portion of the anthropometric variability in the real-world population. Consequently, researchers have undertaken further investigations to understand the influence of individual variability in specific body regions on the occupant's response during crashes.

In a sensitivity analysis aiming to quantify the effect of pelvis variability on force and strain during lateral impact simulations, Brynskog et al. (2022) considered both pelvic shape and material properties. The study revealed that both factors affected the pelvic response and were important for predicting pelvic fractures in lateral loading simulations. A third factor, pelvic orientation, also exists in the population. Pelvic orientation and lumbar lordosis were found to influence the HBM's interaction with the lap belt in frontal impact simulations: the HBMs were less likely to slide under the lap belt when the pelvis was less reclined (Nishida et al., 2021). In another study examining the influence of lap belt loading characteristics, pelvic angle, and adipose tissue material properties on lap belt interaction, Naseri et al. (2022) reported that subcutaneous adipose tissue thickness played a significant role in the interaction between the HBM and the lap belt.

In a sensitivity analysis conducted by Larsson K.J. et al. (2023), the influence of 15 geometrical and material properties of the ribcage on the risk of rib fractures during frontal and side-crash simulations was investigated. The study revealed that cortical bone thickness, material properties, and cross-sectional width had the greatest effect on the risk of rib fractures. The fact that while those properties of the ribcage can be associated with sex, age, stature, and BMI, but only a portion of their variability can be explained by these factors, indicates that individual variability beyond these parameters can play a vital role in determining the ribcage's response to crash forces.

In a study conducted by Liu et al. (2022), the influence of morphological variations of the human brain on the tissue-level impact response under rear, oblique, and side impacts was investigated. The brain volume explained most of the variance (51.3%) and was highly correlated with strain prediction, indicating that brain size could also be associated with brain injury risk during a crash.

Occupant Posture

Occupant posture emerges as a crucial determinant of crash response and injury risk. One of the first studies that delved into the influence of occupants' posture on their crash response utilised multi-body HBMs (Bose et al., 2010). This study examined how occupant characteristics such as stature, mass, posture, and muscle bracing level altered injury risk in frontal crashes. Their findings indicated that the overall injury risk of the occupant was strongly associated with the occupant's posture. Studies using FE HBM simulations to replicate PMHS tests also support those findings. Notably, in side (Poulard et al., 2014) and frontal (Poulard et al., 2015b) impacts, the occupant's posture considerably affected the predicted reaction forces and rib strains. The observed variability in HBM responses was comparable to that in the PMHS experiments, emphasising the importance of quantifying occupant posture in physical experiments and considering it in HBM simulations.

Noteworthy insights into arm positions during side impacts were shared by Gierczycka et al. (2015). This study underscored the substantial sensitivity of HBMs to different arm positions (in contrast to ATDs). More specifically, aligning the arm with the body's orientation increased load transmission to the HBM's thoracic region in side impacts. The intricate interplay between occupant postures and restraint systems was further elucidated by Gierczycka et al. (2017), who revealed that pre-crash arm positions exerted a more pronounced influence on injury risk than restraint system properties. This relationship underscores the importance of addressing variable occupant posture in side impact crash evaluations.

A more recent simulation study conducted by Gierczycka et al. (2021) explored diverse simulation setups, ranging from pendulum tests to full-vehicle interior simulations, in order to investigate the influence of the upper extremities' posture on thoracic loading. The study reaffirmed the observed increase in thoracic compression when the arm aligns with the thorax, which is consistent with previous findings. However, this effect was most pronounced in full-vehicle interior simulations and hardly observed in pendulum impacts. This outcome highlights the importance of incorporating realistic boundary conditions, such as those found in full-vehicle simulations, when examining occupant responses within the context of side impacts. Such boundary conditions include the interactions between the occupant, seat, and vehicle interior, all of which can be important in predicting the occupant's response.

Investigations of Vehicle Interior and Restraint Systems Aspects using HBMs

Human Body Models can also be used to investigate the influence of vehicle interior configurations and restraint systems on occupant crash responses. In a simulation study, Forman et al. (2019b) evaluated the use of ATDs and HBMs to analyse restraint interaction, occupant kinematics, and protection challenges in reclined seats. This investigation revealed that HBMs could be positioned in reclined postures that the FE model of the ATD could not achieve, highlighting their potential in assessing non-nominal positions. However, as the authors discussed, further studies are required to establish the biofidelity of HBMs in reclined postures, a crucial step towards developing vehicles that can safely provide additional seating options for occupants.

Moreover, in a study focused on frontal impacts, Ji et al. (2017) conducted simulations investigating countermeasures for the unfavourable kinematics exhibited by reclined occupants in a laboratory setup. The study indicated that introducing a knee bolster close to the knees could induce desirable upper-body rotation around the pelvis, thereby mitigating the unfavourable kinematics observed with reclined occupants. Investigations of other countermeasures, such as knee airbag designs for frontal and oblique impacts, were carried out by Nie et al. (2017). This study revealed that the relative position of the lower extremities, particularly the gap between the occupant's knee and the instrument panel, influenced not only the occupant kinematics but also the lower extremity loading, such as the tibia axial force and bending moment. Additionally, the knee airbags were able to significantly alter the occupant's kinematic and kinetic response through early coupling with the vehicle and the distribution of contact forces across a larger area.

Furthermore, Rawska et al. (2019) examined the sensitivity to submarining using three HBMs of varying sizes, four different distances between the knee bolster position and the occupant and three different backrest angles. The findings revealed that increasing the occupant-to-knee bolster distance or the backrest angle led to more submarining cases. Additionally, the study observed different submarining thresholds based on the occupant's size, with smaller females being more sensitive and larger males less sensitive than the average male anthropometry. Adding depth to the investigations of seat adjustment effects, Grébonval et al. (2021) examined the influence of seat pan and pelvic angles on submarining risk, utilising an HBM of average male anthropometry. Their findings indicated that submarining occurrence increased with reduced seat pan angles or greater pelvic recline.

Rawska et al. (2021) investigated the effect of different restraint countermeasures on submarining occurrence across various seat configurations. The findings revealed that different restraint configurations were more beneficial for different population groups, indicating that none of the investigated countermeasures was capable of preventing all submarining cases. Boyle et al. (2020) investigated the potential benefits of adapting restraint systems based on the occupants' specific shape, size, and posture. The study employed four morphed HBMs, representing different occupant sizes, and examined two different postures, nominal and leaning forward, during frontal impacts. For each situation, the researchers identified injury concerns and manually updated the restraint systems. The study concluded that adaptive restraints could potentially improve occupant safety. Similarly, HBM simulations and metamodelling techniques were used to optimise restraint configurations for obese and non-obese occupants, indicating that the optimal configurations may differ for the two HBMs (Joodaki et al., 2021b).

Ressi et al. (2022) used FE HBM simulations to investigate the effect of rearward-adjusted seats, considering variability in crash severity, crash direction, and restraint system characteristics. The researchers found that, compared to the typical seat adjustment, increased injury risks were predicted for all body regions, except the head and upper extremities. These findings suggest that the rearward seat configuration may have potential safety implications, warranting further assessment.

Population Assessment

In pursuing comprehensive vehicle safety assessment, researchers have extended their focus beyond occupant variability to encompass other potentially relevant sources of variability, including vehicle and restraint system designs. Iraeus et al. (2016) developed a generic FE vehicle interior model that could be parametrised to represent different vehicle designs. The model was simulated in 1000 crashes based on real-world crash distributions and validated against data from retrospective studies, thus demonstrating its ability to match rib fracture risk among the senior occupant population.

In a more recent study by Perez-Rapela et al. (2020), a method was proposed to address occupant response variability in vehicle safety assessment. The researchers employed machine learning methods, like neural networks, to create metamodels capable of predicting occupant responses beyond explicitly tested parameters. The method was demonstrated with 405 far-side vehicle crash simulations, incorporating variables such as anthropometrical measurements, crash severity, and restraint systems parameters.

In the realm of advanced methodologies, Joodaki et al. (2021a) applied machine learning techniques to support the design of vehicle restraint systems. The authors examined 15 variables associated with vehicle restraint systems via 450 simulations of crashes involving obese and non-obese occupants. The study aimed to create metamodels with the capacity to forecast occupant Life Years Lost (LYL) in frontal crashes based on restraint system design inputs. The study highlighted the importance of selecting the appropriate machine learning method and carefully configuring its settings to generate accurate metamodels. In a study by Schneider et al. (2022), an approach was presented to generate metamodels for predicting kinematic and strain-based injury metrics, while considering variability in both occupant and crash characteristics. The results showed that the metamodels were successful in predicting kinematic-based injury criteria. However, challenges arose when predicting strain-based criteria, such as rib fracture risk.

To conclude: Pre-crash safety systems can influence crash characteristics and occupant kinematics and posture prior to a potential crash, which in turn can affect in-crash responses (and thus potential injury outcomes). HBMs and numerical techniques have been employed to understand these complex interactions in whole-sequence assessments. Additionally, morphed HBMs have proven valuable for exploring the effect of human shape variability. They have been utilised to assess injury risks across the diverse population, in order to identify specific demographic groups with increased risks, such as those with high BMI. Furthermore, advanced methodologies, such as machine learning and metamodelling, have been employed to predict occupant responses beyond tested parameters, aiming for more efficient safety assessment evaluations.

2 Aims

Road traffic crashes can have a profound negative impact on humans' lives and well-being, motivating the need for enhanced occupant protection. While current safety assessments and research have and will contribute to advancing occupant safety, they cannot fully reproduce the heterogeneity seen in real-world crashes. Human Body Models (HBMs) are promising tools for addressing specific aspects of this heterogeneity, such as anatomical diversity and occupant posture. However, using HBMs for safety assessments introduces its own set of challenges. Hence, there is a need for methods and techniques to leverage the benefits of HBMs and embrace the complexity of real-world crashes, ultimately providing insights that can shape the next generation of vehicle safety systems.

With the overall purpose of developing safer vehicles through improved occupant protection evaluation, this PhD project aimed to improve our comprehension of the effect of heterogeneity in real-world crashes. Specifically, the aims were to:

1. Incorporate additional crash heterogeneity aspects into occupant safety assessments, by developing methods that:
    - Predict vehicle crash exposure distributions for vehicles equipped with crash avoidance functionality.
    - Account for variability in occupant anthropometry, sex, and posture, as well as seat adjustment during the crash phase.
2. Analyse the influence of occupant heterogeneity factors, such as anthropometry, sex, posture, seat adjustment, and restraint configurations, on occupant crash responses for vehicles with crash avoidance systems, by employing large-scale simulation studies.

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3 Outline of the Thesis

Four interconnected studies were conducted (Figure 11) to incorporate more heterogeneity into safety assessments and thus support the development of future vehicle safety systems.

Paper I focused on assessing the effect of crash avoidance systems, by predicting the remaining crash configurations in urban intersections. Counterfactual simulations were conducted based on crash databases, with the Monte Carlo (MC) method employed to account for uncertainties, to predict the remaining crash configurations. A novel clustering method was used to select a limited number of representative crashes. From these, three specific crash configurations—Near-Side, Far-Side, and Intersection Frontal—were selected for analysis in subsequent studies.

In **Paper II**, the focus shifted to non-nominal occupant postures. Structural simulations based on the predicted crash configurations (from Paper I) provided the crash pulses for the HBM simulations. A multi-stage HBM positioning technique was implemented, and a Local Sensitivity Analysis (LSA) was performed to investigate the influence of occupant posture on their kinematic and kinetic responses.

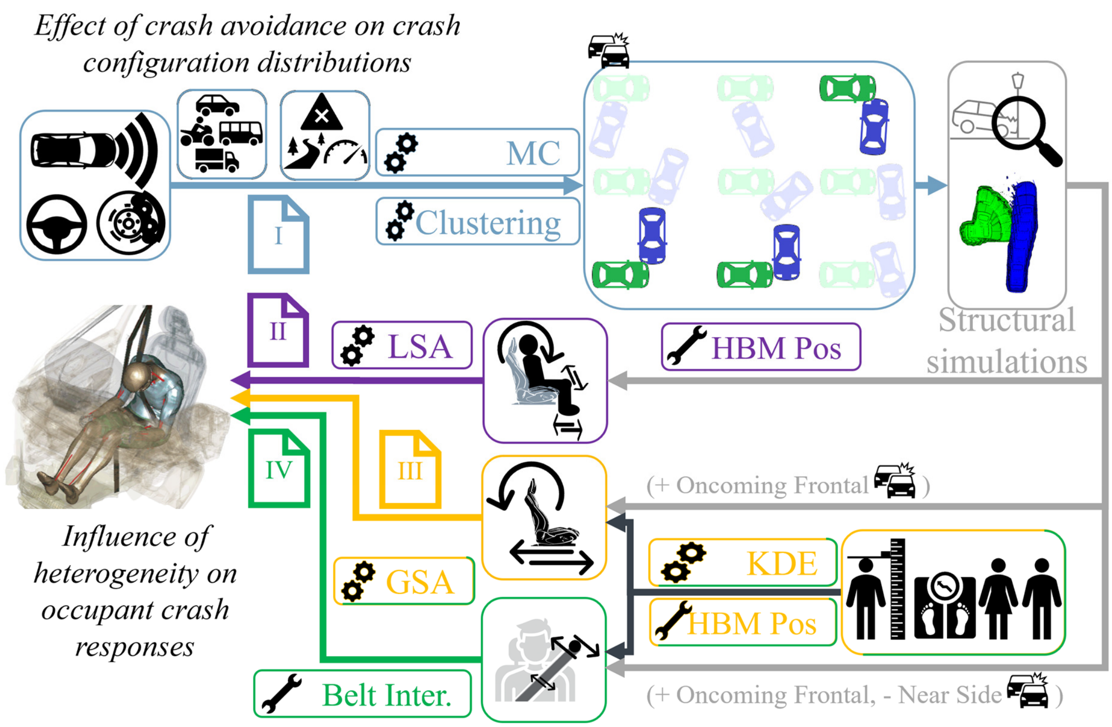

Figure 11. Flowchart depicting the included papers, with unique colours, and how they connect. The main methods and techniques developed and applied are also illustrated.

Paper III expanded the scope by including a crash pulse of an Oncoming Frontal crash, aiming to also capture a more severe crash configuration. This study analysed characteristics of the US population using Kernel Density Analysis (KDE) and morphed HBMs to represent a large portion of this population. The HBMs were positioned using a (semi)automated method, and a Global Sensitivity Analysis (GSA) method was employed to investigate how anthropometric variability and seat adjustments can influence the occupants' kinematic and kinetic responses.

Paper IV is built upon the four crash configurations (excluding the Near-Side crash due to its reduced level of challenge in terms of belt retention), occupant population, and methods used in Paper III. The study delved into individualised restraint system aspects and developed a novel belt interaction quantification method which supports the objective classification of belt interaction.

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4 Methods Background

Computational modelling and simulation offer insights into the responses of complex systems when subjected to diverse input conditions. Central to extracting meaningful knowledge from these behaviours are two pivotal concepts: uncertainty quantification and sensitivity analysis. Uncertainty quantification addresses the challenge of understanding the potential variability in model outcomes due to inherent uncertainties in input parameters. It seeks to provide a perspective on the range and likelihood of potential outcomes. In parallel, sensitivity analysis provides a deeper understanding of which specific inputs have the greatest effect on the system's outputs and how they influence the system's response. This information is valuable for steering the model's response towards desirable outcomes. Methods like Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS) are powerful tools within uncertainty quantification and sensitivity analysis, providing robust mechanisms to explore and quantify the effect of input variability. Sensitivity analysis can be segmented into local sensitivity analysis (LSA), which delves into effects at distinct points within the parameter space, and global sensitivity analysis (GSA), which offers a holistic view of a parameter's effect across its entire range of inputs.

Data, whether derived from databases, experiments, or other sources, are a crucial component for setting up relevant experiments and deriving conclusions. Thus, it is crucial to interpret data correctly. One generalisable way to understand statistical distributions is to use non-parametric techniques like Kernel Density Estimation (KDE). Additionally, clustering techniques can be employed, both in pre-processing—to identify and group similar input scenarios, and in post-processing—to categorise and identify patterns in the simulation outcomes. These techniques, whether applied before or after the main analysis, can provide insights by providing the means to a structured data exploration.

The subsequent subsections elaborate on these techniques, providing background knowledge and a more comprehensive understanding of their roles in the conducted studies.

4.1 Clustering

Clustering is a data analysis method that partitions datasets into subsets, called "clusters", revealing underlying patterns in the dataset (Kaufman et al., 1990). The k-means and k-medoid are two popular clustering algorithms, classified as "partitional" algorithms (Jain et al., 1999).

The k-means algorithm assigns each data point to one of a predetermined number (k) of clusters. These clusters are generated by iteratively minimising the squared distance between the data points within a cluster and that cluster's mean, known as the "centroid".

The k-means clustering algorithm consists of the following steps (Jain et al., 1999):

- **Initialisation**: k initial cluster centres are randomly selected within the dataset bounds.
- **Cluster Assignment**: Every data point is assigned to the cluster corresponding to the nearest cluster centre.
- **Centre Re-computation**: The cluster centres are updated to be the mean (centroid) of all data points assigned to that cluster.
- **Convergence Check**: The current state is evaluated against a convergence (termination) criterion. Common termination criteria are "no reassignment of data points between clusters" or "a threshold in the decrease of squared error". If convergence is not achieved, the process is iterated from the Cluster Assignment step.

While the k-medoid algorithm follows a similar approach, it diverges in the way it determines the cluster centre. Instead of using the mean, the k-medoid identifies the most representative data point within the cluster, called the "medoid" (Reynolds et al., 2006); see Figure 12. By choosing an actual data point as the cluster centre, the k-medoid method tends to be more robust against outliers than the k-means approach, which can be skewed by extreme values (Park et al., 2009). Moreover, the k-medoid is suitable for datasets with categorical variables.

Selecting the optimal number of clusters (k) is pivotal in clustering. An inappropriate choice can lead to clusters that are either too specific or too broad, making it hard to identify patterns. Several methods have been proposed to guide the selection of k. For example, the "Elbow Method" involves plotting the "cost" (defined as the sum of squared distances from each point to its centroid) of different k values. The aim is to find an "elbow point" (a deflection in the graphed cost) where the cost starts to level off, indicating an optimal or near-optimal number of clusters (Thorndike, 1953). However, this point may not always be unambiguous. Another approach is the "Silhouette Method" (Figure 12), which utilises the concepts of "cohesion" and "separation" to determine cluster quality. It involves calculating the silhouette coefficient for each data point, which measures how similar a data point is to its own cluster (cohesion) compared to other clusters (separation). A high average silhouette coefficient across all data points suggests a suitable number of clusters (Rousseeuw, 1987).

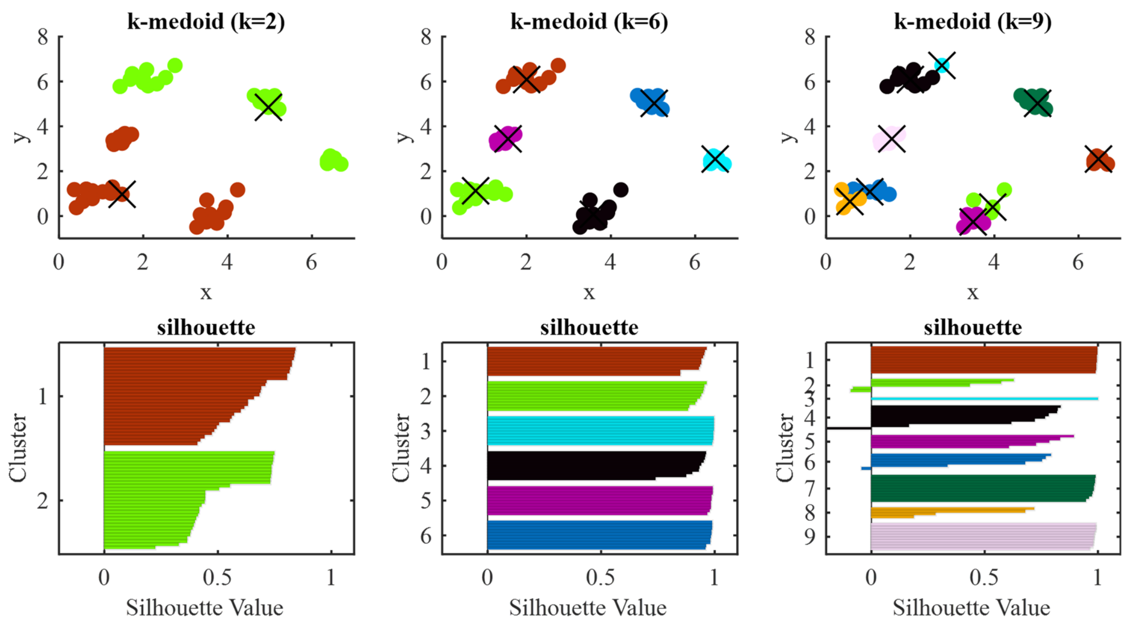

Figure 12. At the top (left to right), an example of clustering applied to a set of randomly generated data using the k-medoid algorithm for two, six, and nine clusters. Each cluster is visualised with a distinct colour, and a black x marks its medoid. At the bottom, the silhouette scores corresponding to each choice of k (number of clusters) are displayed. A high average silhouette score indicates the appropriate k for the dataset, which, in this case, is k = 6.

Method Application: In Paper I, an adapted version of the k-medoid was used to identify representative crash configurations.

4.2 Monte Carlo Simulations—Latin Hypercube Sampling

Monte Carlo Simulations (MCS) are a group of computational algorithms that utilise random sampling to obtain approximate solutions to numerical problems (Fishman, 1996). One of the key applications of MCS is in estimating the average response of a system across varied inputs. Additionally, MCS can be used for uncertainty quantification by estimating the typical range and likelihood of the possible outcomes and demonstrating how uncertainties in input variables can propagate through a system.

Typically, the MCS method consists of the following steps (Fishman, 1996):

- **Define a Domain of Inputs**: Relevant inputs are selected, and their distributions are specified. If the inputs are correlated, their interrelationships are also important for an accurate representation of the parameter space.
- **Generate Random Inputs**: A random population is generated.
- **Perform Computations**: The model is evaluated with the generated random inputs, and outcomes are recorded.
- **Analyse Outcomes**: The distribution of outcomes provides an estimate of the system's probabilistic behaviour.

The mathematical basis of the MCS method is the law of large numbers, which ensures that estimations converge to the true value as the number of independent observations (n) is increased (Kroese et al., 2011). However, the applicability of the MCS method may be limited in the context of computationally expensive models, as it typically requires a large number of samples to achieve a good approximation.

Latin Hypercube Sampling (LHS) is a space-filling algorithm, used primarily to enhance sampling efficiency within probabilistic modelling. LHS is often used instead of a "random" number generator with MCS, primarily to avoid uneven coverage. LHS operates by dividing the probability space into non-overlapping intervals of equal probability. Considering a k-dimensional parameter space (X), in order to guarantee that every part of the distribution for each input variable X_k is represented, the range of each X_k is stratified into N segments, each with an equal marginal probability of 1/N (Figure 13). A single sample from every segment is then generated, denoted as X_{kj}, where k = {1, …, k} and j = {1, …, N}. The components are then systematically combined (McKay et al., 1979). LHS leads to a more representative sampling compared to random sampling and avoids clustering around the mean (Figure 13).

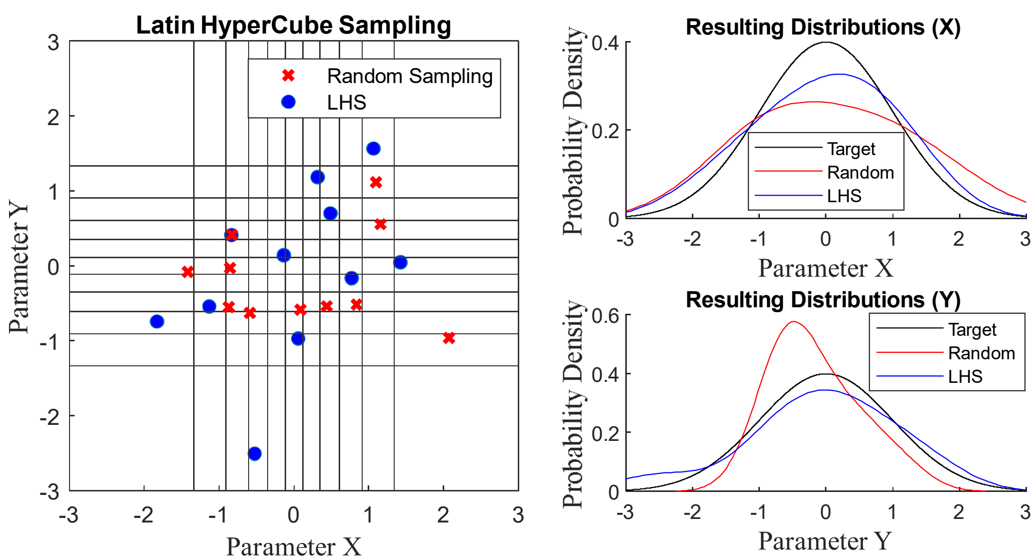

Figure 13. On the left, a parameter space is sampled via random sampling (red x's) and Latin Hypercube Sampling (LHS–blue dots). For the LHS sampling, the x and y dimensions are stratified at intervals of equal probability. On the right, the probability density functions (PDFs), resulting from random (red line) and LHS sampling (blue line), are compared against the target distributions (black line) for the x and y dimensions. These PDFs are estimated via kernel density estimation (see Section 4.4).

Method Application: In Paper I, to account for uncertainties not covered by the crash databases, such as the vehicle's position on the lane or braking behaviour prior to the crash.

4.3 Sensitivity Analysis

Sensitivity Analysis is a set of methods that provides a systematic approach to assessing the influence of variables on a system's response under varied conditions. Applications of sensitivity analysis, as outlined by Saltelli et al. (2007), include:

- **Model Verification:** The model's predictions can be assessed to ensure they are robust and not overly reliant on assumptions.
- **Parameter Space Exploration**: Interesting regions in the parameter space (combinations of factors) that may lead to extreme system responses can be identified.
- **Research Prioritisation**: High-impact factors can be identified, in order to direct the selection of research areas for further studies.
- **Model Simplification**: Non-influential factors can be simplified or held constant without affecting the accuracy of outcomes, leading to simpler models.

Sensitivity Analysis can be categorised as Local Sensitivity Analysis (LSA) or Global Sensitivity Analysis (GSA). LSA methods assess the effect of individual variable changes at specific points within the parameter space, offering insights into each variable's main effect(s). On the other hand, GSA methods examine the cumulative effect of multiple variables throughout the parameter space, investigating how changes in these variables, individually or collectively, influence the overall model response. GSA utilises various approaches, including "Elementary Effects" and "Variance Decomposition" methods.

The Morris Method (Morris, 1991) falls under the "Elementary Effects" category. This method systematically perturbs one parameter while holding others constant to measure its effect on model response. These effects are evaluated at multiple points within the parameter space, so the Morris Method is considered a GSA approach. Elementary Effects methods such as the Morris Method and its subsequent evolutions (e.g., Campolongo et al., 2007) are particularly suitable as screening tools for estimating the importance of parameters for models with many parameters or whose evaluations are expensive, because they require relatively few model evaluations.

In contrast, Variance Decomposition Methods divide the total variance in model outcomes into contributions from individual variables or their combinations (Saltelli et al., 2010). By calculating the variance share for each variable, these methods identify the variables that have the most pronounced influence on the system's response throughout the parameter space.

4.3.1 Design of Experiments in Sensitivity Analysis

Design of Experiments (DoE) is a systematic approach to planning, conducting, and analysing experiments. The experimental design is tightly connected with the sensitivity analysis methods.

LSA methods commonly use One-At-a-Time (OAT) experimental designs (Figure 14). OAT designs change one parameter at a time, enabling them to capture the individual effects of the factors tested; however, they do not identify their interaction effects. In contrast, GSA methods tend to adopt more sophisticated designs, including factorial designs and space-filling designs like LHS (see Section 4.2).

A common type of factorial design is the full factorial design, which investigates both the individual and interaction effects of all factors by rigorously testing every possible combination at a few predefined levels. A widely adopted approach within this design is the 2^k design, which investigates k factors at two levels each, enabling the investigation of interaction effects (Figure 14). The number of runs or conditions in an experiment is determined by 2^k; for example, when there are three factors, there will be 2^3 or 8 experimental runs.

A key aspect of the 2^k design is its assumption of linearity across selected factor levels, which makes it ill-suited to scenarios where non-linear effects are suspected or a more granular understanding is sought (Montgomery, 2013). In such cases, generalised full factorial methods (m^k) are more suitable. For instance, a 3^k design would explore k factors, at three levels. The total number of experimental conditions in such designs is the product of the levels for all the involved factors; thus, these designs can capture non-linear effects in the response function as needed (Figure 14).

While the comprehensiveness of factorial designs enables the clear identification of interaction effects, a challenge arises with the exponential increase in the number of evaluations required as more factors are introduced. Fortunately, lower-cost alternatives are available in the form of Central Composite Design (CCD) and fractional factorial designs. CCDs typically combine a full factorial 2^k design and an OAT design, which enables the calculation of second-order interactions. The CCD designs serve as a practical alternative to the 3^k design, permitting the investigation of interactions and curvatures without mandating the exhaustive number of runs imposed by a 3^k design (Montgomery, 2013). Additionally, when higher-order interaction effects are considered irrelevant, Fractional factorial designs can be utilised to reduce the computational demands. Fractional factorial DoEs utilise only a subset of the full factorial design, but they can still provide estimations of primary effects and some interactions.

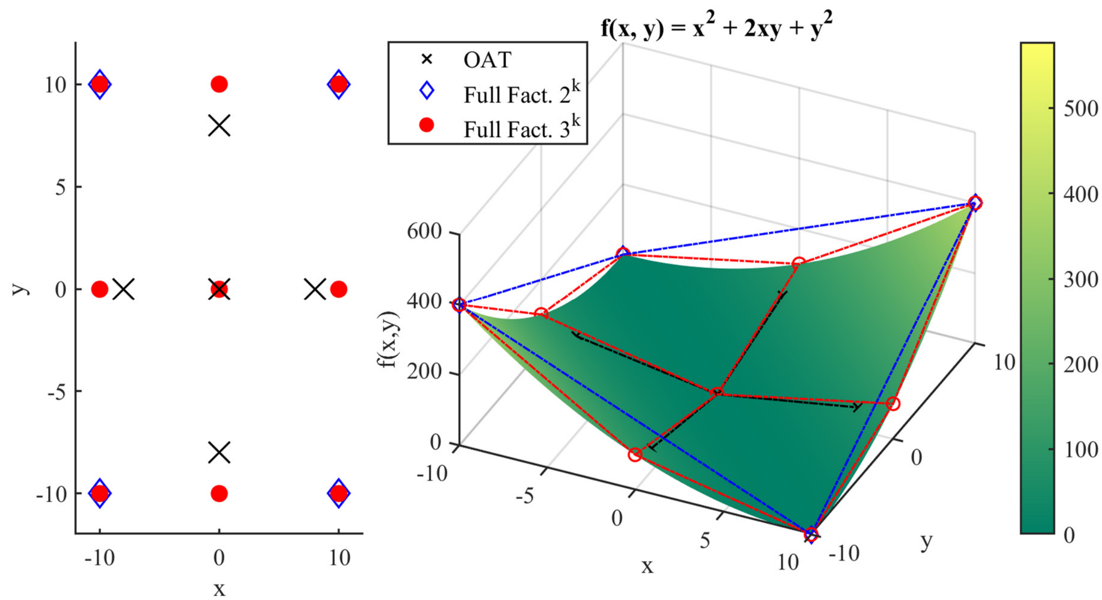

Figure 14. On the left, an example of a One-At-a-Time (marked by black x's) design and two full factorial designs (2^k and 3^k, represented with blue diamonds and red dots, respectively) can be seen. On the right, the response surface of an example function is illustrated with a colour map indicating the function's response. It becomes evident that the OAT design (black lines) overlooks interaction effects between x and y, which are pronounced in this example. Moreover, the 3^k design captures the non-linearities, which the 2^k design fails to reveal.

Method Application:

- **Paper II**: LSA (using an OAT design) investigated the effects of non-nominal occupant postures on occupant responses during a crash.
- **Paper III**: GSA (using a full factorial design) investigated the influence of occupant shape and size, as well as seat adjustments, on occupant responses during a crash.
- **Paper IV**: GSA (using a full factorial design) investigated how the occupant's shape and size, the seat adjustments, and the restraint configuration affect the occupant's interactions with the belt during a crash.

4.4 Kernel Density Estimation

Statistical distributions, commonly used for understanding and describing data, can be categorised as parametric or non-parametric. Parametric distributions, such as the normal distribution or the exponential distribution, are defined by a set of parameters. For instance, the normal distribution is characterised by its mean and standard deviation. A parametric model is particularly appropriate when the data aligns with the model's distribution and can provide a good estimation of the distribution even with a relatively small sample size. However, if the assumptions made by these parametric models about the underlying data are not accurate, any inference or conclusions drawn from the models might be misleading. The true distributions of many datasets can deviate from the typical parametric distributions. For these datasets, non-parametric methods can be used, since they do not assume a specific form for the distribution. As a result, they offer more flexibility and can capture a wider range of data patterns.

Among non-parametric methods, histograms represent the simplest way to visualise and comprehend statistical distributions. However, histograms typically produce "steps", which rarely mirror real-world distributions. Moreover, histograms are sensitive to arbitrarily chosen bin boundaries. On the other hand, KDE is a statistical method, which estimates the Probability Density Function (PDF) of a random variable from observed data. Its value becomes particularly apparent when dealing with distributions that cannot be characterised by parametric models. KDE offers a flexible, non-parametric approach, capturing both the global trends and local effects of the distribution (Silverman, 2018). Mathematically, KDE operates by placing a kernel function at the position of each data point. The kernel functions are then added across the input space, and the summation forms the PDF (Figure 15, left).

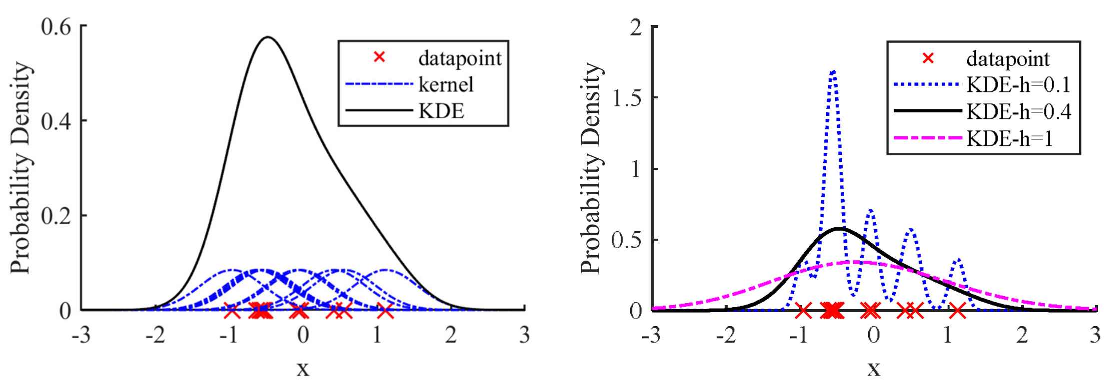

Figure 15. On the left, a random data set is presented along the x-axis (red x's). A kernel (blue dashed lines) is placed at every data point. Summing these kernels generates the kernel density estimation of the PDF (solid black line). On the right, three PDFs derived from the same set of data points, utilising three different bandwidths. A low bandwidth produces a higher resolution (dotted blue line), whereas a higher value leads to a smoother PDF (dashed magenta line). Silverman's method provides a balanced estimate (solid black line).

KDE encompasses a range of parameters, each influencing the characteristics of the resulting PDF estimate. Among these factors, the bandwidth plays a prominent role (Wand et al., 1994). The bandwidth scales the width of the kernel function and significantly shapes the estimation's accuracy and granularity. To optimise KDE, a normal kernel is commonly employed, with the bandwidth being fine-tuned according to the data. Fine-tuning the bandwidth parameter presents challenges, which is where Silverman's rule comes into play. The rule adjusts the bandwidth based on data features, such as the number of samples and the standard deviation (Silverman, 2018). This rule is typically used as the starting point for selecting the bandwidth. Ideally, the bandwidth selection should balance excessive smoothing and too much noise, thereby capturing global and local patterns (Figure 15, right). Note that KDE can be employed for density estimation in multidimensional datasets (Figure 16).

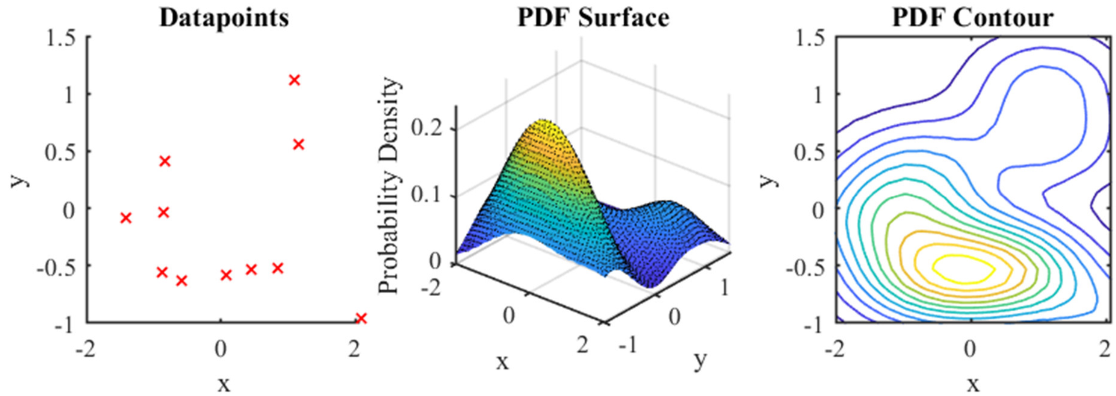

Figure 16. Kernel density estimation applied to a 2D dataset (on the left), with the estimated PDF as a 3D surface (in the centre). A corresponding contour plot (on the right) displays iso-probability lines for equal probability points in the space.

Method Application: In Paper III, KDE was used to identify the PDF of stature and BMI for the male and female populations of the US.

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5 Summary of Appended Papers

5.1 Paper I

Crash avoidance systems have the potential to not only avoid crashes but also mitigate inevitable crashes, potentially changing the crash configuration distribution. With the overall objective of enhancing the assessment of future safety systems, this study developed a method for predicting crash configuration distributions when crash avoidance systems are introduced.

The four-step method (see Figure 17) began with a statistical analysis of a national database to identify traffic challenges in a selected ODD. Following this, a baseline, representing crashes that occurred before the introduction of crash avoidance systems, was established using real-world crash data from in-depth databases. Counterfactual Model-in-the-Loop (MIL) pre-crash simulations were then performed based on this baseline, in order to predict changes in crash configurations as a result of crash avoidance interventions. The final step involved clustering the predicted remaining crashes to identify the most representative configurations using a novel definition based on five parameters.

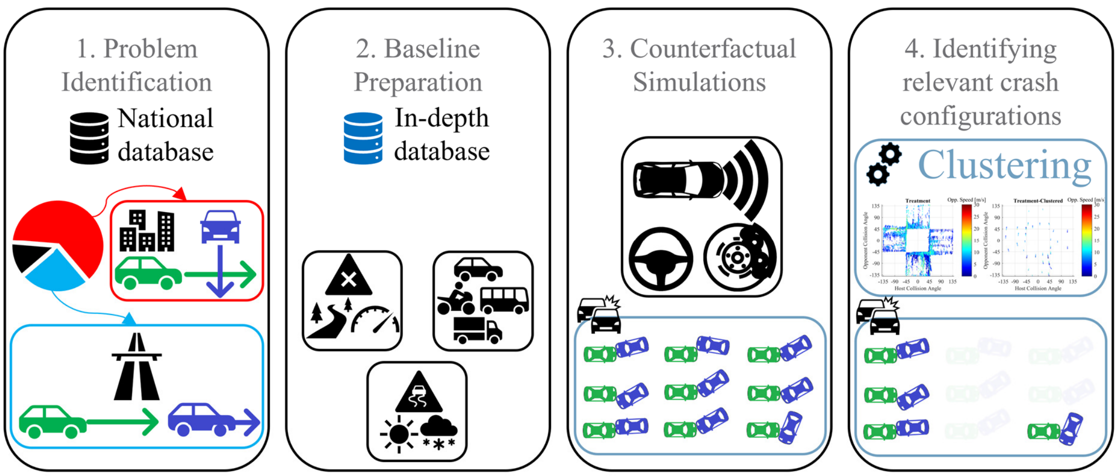

Figure 17. Graphical abstract of Paper I

The developed method was applied using Swedish national and in-depth crash data, using a conceptual AEB system. Based on the analysis of national crash data, two conflict situations were selected for this study: Same Direction—rear-end-frontal (SD—ref), representing 53% of highway vehicle-to-vehicle (v2v) crashes, and Straight Crossing Path (SCP), representing 21% of urban v2v intersection crashes. Pre-crash baselines, for SD—ref (n = 1010) and SCP (n = 4814), were prepared based on the analysis of cases from the in-depth dataset and their variations. Pre-crash simulations identified the crashes not avoided by the conceptual AEB; clustering them revealed 5 representative crash configurations for the highway SD—ref and 52 for the urban intersection SCP conflict situations. These remaining crash configurations can be used in future crashworthiness studies.

The study showed that the introduction of crash avoidance systems could shift the impact points towards the vehicle’s corners. The results demonstrate that the proposed method is feasible for predicting relevant crash configurations for in-crash testing of injury prevention capabilities.

5.2 Paper II

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 driving the vehicle. The anticipated introduction of AVs could allow “drivers” to adopt similar non-nominal postures and be involved in similar activities. Therefore, it is becoming increasingly important to investigate the effects of non-nominal postures during relevant car crash events. This study aimed to investigate the effects of different postures of front-seat passengers on kinematic and kinetic responses during intersection crashes.

An HBM was positioned as a front-seat passenger in 35 postures, with variations to the lower and upper extremities, torso, and head (Figure 18). Three crash configurations, identified in Paper I as representative of predicted urban intersection crashes—a Near-Side, a Far-Side, and an Intersection Frontal impact—were assessed in a simulation study. The occupant kinematics and loading were analysed, and any differences between the nominal and altered posture responses were quantified using cross-correlation of signals in order to highlight the most notable variations.

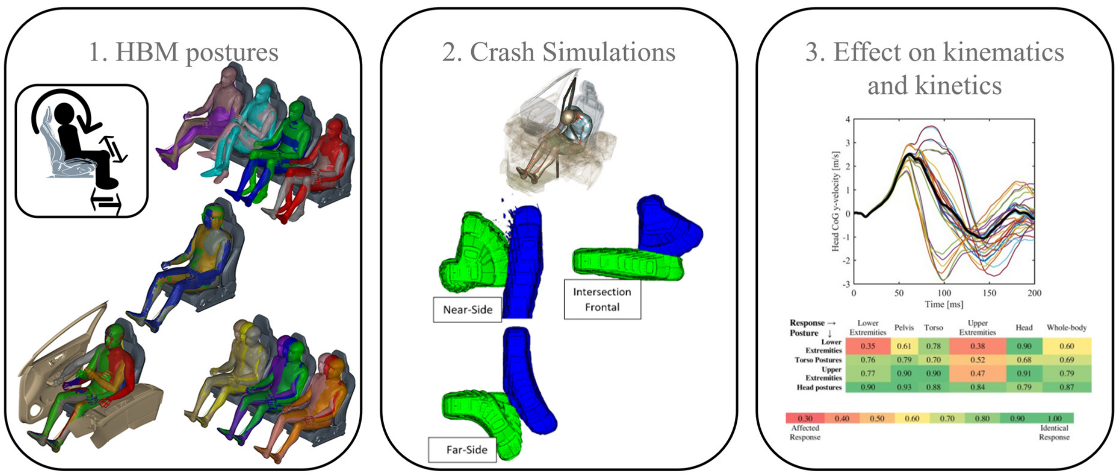

Figure 18. Graphical abstract of Paper II

Changes to the lower extremities’ postures had the greatest overall influence on the kinematic and kinetic responses of the lower extremities, pelvis, and whole-body for all crash configurations. In the frontal impact, crossing the legs led to higher 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 extremities on the centre console resulted in increased torso excursions. Moreover, the upper extremities were consistently 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.

The use of HBMs was instrumental in investigating the effect of non-nominal occupant postures. Their postures may be adopted by choice or as a consequence of pre-crash manoeuvres. Given that pre-crash manoeuvres are expected to become more common, it becomes increasingly important to consider such postures in the design of safety systems for future vehicles.

5.3 Paper III

Past studies have indicated that variations in occupant anthropometry and seat adjustments can affect the occupant's response and the potential risk of injury in vehicle crashes. This study aimed to investigate, quantify, and rank the effects of variations in occupant anthropometry and seat adjustment on the occupants' kinematic and kinetic responses.

Utilising the HBM from Paper II, a set of morphed HBMs was created to represent a broad spectrum of US male and female adult body shapes and sizes. This cohort of 22 morphed HBMs underwent a set of crash simulations with various seat adjustments, as illustrated in Figure 19. The models occupied the front passenger seat of the interior model used in Paper II. There were 12 seat configurations, differing in fore-aft position and backrest inclination. Four distinct crash scenarios were examined: Near-Side, Far-Side, Intersection Frontal impacts from Paper I, and an additional Oncoming Frontal impact. A full factorial DoE was implemented, resulting in a total of 944 simulations.

The analysis of occupant responses was conducted in two phases. Initially, cross-correlation techniques were used to quantify and rank the impact of various parameters on each body region. Subsequently, GSA identified the dominant kinematic and kinetic patterns across the scenarios.

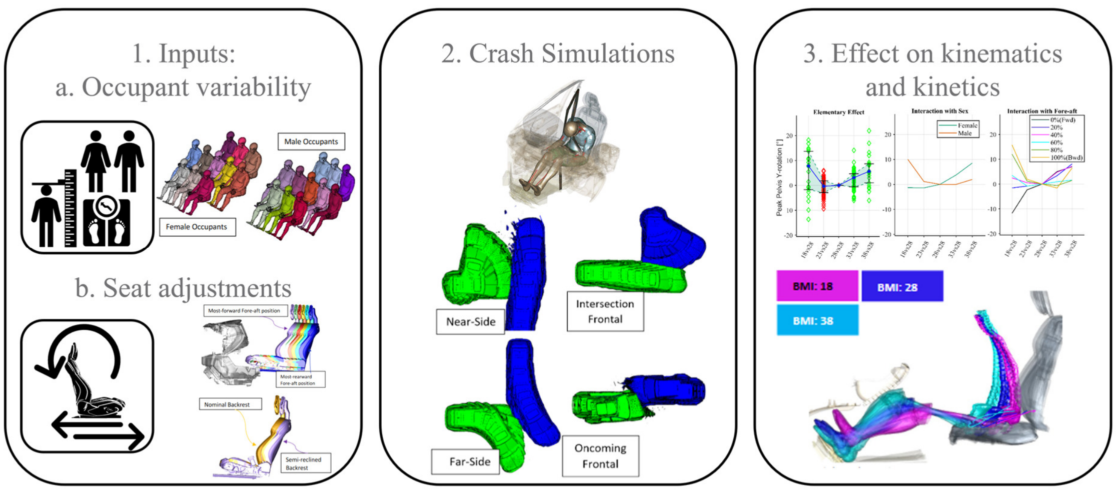

Figure 19. Graphical abstract of Paper III

A consistent correlation emerged across the crash configurations between HBMs with high BMI and increased lower extremity loading. Likewise, taller occupants consistently experienced increased lower extremity loading. Fore-aft seat adjustments influenced head and torso velocities relative to the vehicle's interior. Particularly noteworthy was the effect of seat positioning during Oncoming Frontal impacts; altered knee-to-dashboard contact shifted occupant load distribution. Rearward seat adjustments led to increased loading on the pelvic and lumbar regions while reducing forces on the lower extremities. Conversely, forward seat positions had the opposite effect.

Through a large set of simulations, this study went beyond standardised testing protocols to offer a thorough evaluation of diverse frontal and side-impact crashes. The sensitivity analysis provided valuable insights into occupant protection strategies, illuminating challenges and trade-offs, such as altered occupant loading due to seat adjustments. These findings underscore the importance of accounting for the wide spectrum of occupant anthropometry and seat adjustment variability to proactively understand occupant protection challenges.

5.4 Paper IV

This study aimed to investigate the influence of individualised shoulder belt positioning on seat belt interaction and occupant kinematics, taking into account the variability in occupant anthropometry, seat position, and sitting posture.

A series of simulations was conducted using 22 morphed HBMs from Paper III, representing a diverse range of occupant shapes and sizes. These HBMs were positioned in the front passenger seat of the interior model from Papers II and III. Each simulation involved a specific setup, combining three elements: an HBM with distinct occupant anthropometry, a selected seat adjustment, and an occupant posture. The simulations explored two seat fore-aft adjustment configurations and three different sitting postures. For each setup of HBM, seat adjustment, and posture, two belt configurations were tested: the traditional shoulder belt and an Individualised Shoulder Belt Position (ISBP), which aimed to provide ideal mid-shoulder belt placement (Figure 20). Each combination of simulation setup and belt configuration was then subjected to three crash configurations (the Far-Side, Intersection Frontal, and Oncoming Frontal impacts from Paper III), resulting in a total of 792 crash simulations. To identify patterns in the occupant's kinematic responses and seat belt interaction across the varied parameters, the GSA method from Paper III was employed, augmented with a technique to quantify and classify belt interactions.

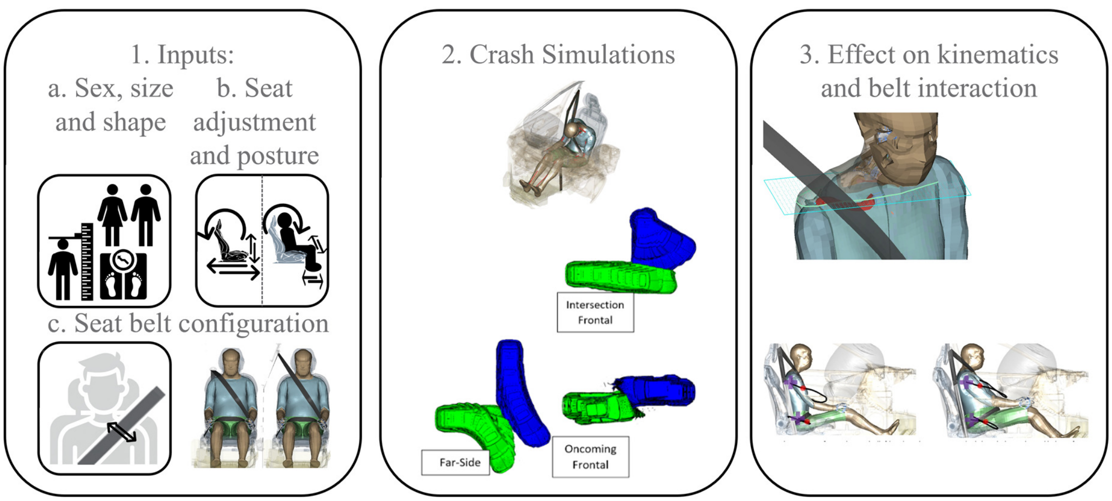

Figure 20. Graphical abstract of Paper IV

The initial shoulder belt placement was influential for the occupant's interaction with the belt and the occupant's kinematics. However, this parameter alone did not invariably lead to an overall improved seat belt interaction. Occupants' seat belt interactions depended on their anthropometry. Tall occupants with low BMI were predisposed to sliding out of the shoulder belt, while shorter occupants with low BMI were more prone to submarining. The two mechanisms underlying these challenges were identified as the balance between torso and pelvis retention and the axial rotation of the torso. Furthermore, the occupant's posture played an important role in shoulder belt interaction, with inboard or forward-leaning occupants posing challenges for torso retention.

This study examined seat belt interaction across diverse occupant characteristics and postures, as well as seat adjustments. Besides highlighting potential seat belt interaction challenges, the occupant-to-belt interaction analysis technique demonstrated the feasibility of evaluating restraint system modifications towards the development of individualised occupant protection systems.

6 Discussion

The goal of this thesis was to incorporate additional aspects of heterogeneity into the occupant protection assessment to guide the development of future vehicle safety systems. To achieve this, prospective methods were developed and applied.

The developed methods, which are discussed in the subsequent section, offer insights into crash exposure and the influence of real-world heterogeneity on occupant safety, thereby contributing to the identification of occupant protection challenges. This discussion then focuses on the implementation of the methods in large-scale simulations and their main findings. Addressing these challenges through the development of vehicle safety systems and occupant protection countermeasures can lead to safer vehicles under a broader spectrum of real-world conditions.

6.1 Methods Incorporating Crash Heterogeneity

In this thesis, methods and techniques were developed and/or combined to: predict the effect of crash avoidance systems on crash configurations; investigate crash heterogeneity factors, such as occupant posture and anthropometry, seat adjustment, and restraint configurations; and conduct simulations with HBMs. Additionally, the experimental designs were selected based on their suitability for the specific research aims.

6.1.1 Design of Experiments

In the study predicting the crash configurations (Paper I), LHS (Section 4.2) was used to generate synthetic crashes, which accounted for uncertainties in the real-world crash database, encompassing factors such as travelling speed, braking behaviour, and lane positioning. These synthetic crashes were subsequently simulated to predict the effect of crash avoidance on a large population of crashes, accounting for uncertainties. Potential correlations among the input variables (uncertainties) were not explicitly known. To partially address those potential correlations, a set of empirical rules was implemented (as detailed in the Appendix of Paper I). These rules systematically excluded improbable variable combinations, such as early braking and high deceleration levels, and ensured the generation of synthetic crashes representative of the original distribution.

The One-at-a-Time (OAT) method (Section 4.3.1) was employed to investigate the influence of different occupant postures (Paper II) on the occupant's crash response, by manipulating isolated body regions. This enables the estimation of main effects at a relatively low computational cost. In addition, combinations of torso and upper extremity postures were investigated, providing insights into the interaction effects of different body region postures.

Papers III–IV utilised a full factorial DoE (Section 4.3.1) to investigate multiple factors: occupant stature, BMI, and sex; seat adjustment; and restraint configuration. Full factorial designs were used to evaluate all combinations of input factors, thereby revealing not only the main effect of each factor but also the interaction effects among them on the occupant's crash response across the input parameter space.

Large-scale studies probing the effect of variability due to occupant, vehicle or restraint system factors, typically prefer LHS or other space-filling algorithm variants, as evidenced by numerous studies (see Hu et al., 2019; Perez-Rapela et al., 2020; Joodaki et al., 2021a, 2021b; Miller et al., 2021; Ressi et al., 2022; Schneider et al., 2022). While some studies (see Hu et al., 2017; Rawska et al., 2019; Boyle et al., 2020) utilise a full factorial approach, they are often limited by the sample size due to the approach's computational demands. Computational efficiency is an important driver behind the preference for space-filling algorithms. As aptly noted by (Joodaki et al., 2021a), a study encompassing 15 restraint parameters with only two values each, would require a staggering 32,768 simulations for a full factorial analysis.

Moreover, merely choosing points at vast distances within the parameter space might not reveal the phenomena occurring between these points. Considering the computational demands of FE simulations, which can offer detailed insights into complex physical interactions and material behaviours, undertaking such a large number of simulations would be challenging.

Despite this challenge, a carefully designed full factorial DoE has advantages. When interaction effects might be present, a full factorial design is recommended because misleading conclusions can be avoided: factor effects can be estimated across multiple levels, providing findings that hold across diverse experimental conditions, as articulated by Montgomery (2013).

Full factorial design can also play a role in addressing the challenges that arise when conducting large-scale FE occupant safety simulations, particularly with occupants of varied sizes. Such studies mandate additional geometric modifications to the models, such as "deforming" the vehicle model to accommodate the occupant and routing the seat belt appropriately. These subsequent adjustments add layers of complexity; under these circumstances, a full factorial design can be advantageous. For instance, generating morphed models using a structured grid of HBMs, as in Papers III–IV, allows for a more in-depth quality control of the models. While automation offers a solution to those challenges, it is not without limitations. As Perez-Rapela et al. (2020) cautioned, identifying faulty model setups is paramount for successfully deploying automated processes.

In summary, the choices of experimental design in the studies were driven by their relevance to the research objectives. LHS was particularly useful in generating synthetic crashes representative of real-world scenarios while accommodating the inherent uncertainties. Meanwhile, the OAT method in Paper II provided insights into the main effects of various postures. The full factorial DoE in Papers III–IV, on the other hand, enabled a comprehensive analysis (including interaction effects) across a broad parameter space, deepening the understanding of the influence of these investigated parameters on occupant responses.

6.1.2 Predicting Crash Configurations

Pre-crash systems can potentially avoid or mitigate crashes, changing the exposure of both equipped vehicles and other vehicles on the road. This thesis crafted a method to predict the influence of crash avoidance interventions on the expected crash configuration distribution. The method utilises real-world data, counterfactual simulations, numerical models, and analysis methods to predict remaining crash configurations. These insights into the anticipated changes in crash exposure can be used to guide the future development and assessment of in-crash safety systems.

The foundation of the counterfactual simulations conducted In Paper I was real-world data from crash databases. While national databases, like STRADA, capture trends across large regions, they might lack details in specific ODDs or inadequately represent individual car brands with distinct designs. Additionally, databases that filter crashes by occupant injury severity or vehicle damage might remove lower-severity crashes. However, with the potential emergence of new vehicle use cases, such as extreme leaning postures in AVs, lower-severity crashes could become relevant, as these use cases could present unique occupant protection challenges. To achieve a balance between capturing overarching trends and detailed crash scenarios, Paper I made use of the broad scope of the National Crash Database (STRADA) and the detailed information of the in-depth dataset (VCTAD), leveraging the distinct strengths of each.

Among the method's strengths is its modular nature, permitting seamless integration with numerical models of varying fidelity or with entirely different simulation strategies, such as multi-agent traffic simulations (Kitajima et al., 2019). The modularity of the method presented in Paper I has allowed it to find applications in the analysis of other RTCs. For example, parts of the methods were used in pedestrian-AEB systems assessments (Gruber et al., 2019).

The counterfactual simulations of critical events are valuable for estimating the effect of crash avoidance systems on crash characteristics. However, critical events are rare occurrences relative to the time spent in "normal driving". ADASs and AVs can be active during the normal driving phase, preventing critical situations entirely. Consequently, relying solely on counterfactual simulations of critical events may not fully capture the capabilities of ADASs and AVs. Therefore, evaluating the safety performance of vehicle(s) that include ADASs or AVs might require different simulation strategies.

Additionally, counterfactual simulations, when combined with Monte Carlo methods (see Section 4.2), can address some of the traffic environment variability, such as different road conditions or road users' behaviour. However, counterfactual crash simulations may be insufficient for exploring other aspects like legislation and infrastructure design. Different approaches, such as multi-agent simulations, might better suit those investigations.

A simplified AEB system, similar to that employed in Östling et al. (2019a), was used in Paper I. While simplified models offer a glimpse into potential conflict scenarios in future vehicles, they might not fully capture the logic and effectiveness of the vehicle systems intended for production. Thus, the modular method presented in Paper I was designed to use Model-in-the-Loop pre-crash simulations, enabling the assessment of pre-crash systems intended for real-traffic deployment.

The use of counterfactual simulations in Paper I also necessitates highlighting the importance of driver models. Previous research, such as the study by Bärgman et al. (2017), underscores how the selection of a driver model can substantially alter safety benefit estimations. In Paper I, synthetic crash variants were generated during the pre-crash simulations to capture uncertainties linked to driver behaviour and other road users' actions. Yet, interventions during the pre-crash phase can introduce additional uncertainty by potentially altering drivers' reactions prior to a crash. Thus, future studies could also integrate driver reaction models, such as those of Svärd et al. (2021), to improve prediction accuracy.

This thesis demonstrated a crash configuration definition, which was initially presented by Wågström et al. (2019). The definition efficiently captures essential crash details, enabling accurate replication during testing with a limited set of variables. Additionally, a clustering technique was developed to identify a representative subset of crash configurations that take into account the multifaceted nature of real-world crashes while also considering the computational time constraints for in-crash safety evaluations. Unlike studies which rely on conventional clustering algorithms (Östling et al., 2019a; Putter et al., 2023), Paper I developed a clustering method that classifies crash configurations as "similar" based on thresholds chosen by the user, allowing the structural robustness of the evaluated vehicle to be taken into account. This is crucial, as even small changes in impact location can considerably alter the vehicle's structural engagement, leading to different occupant compartment deformations (Simon et al., 2019) and/or crash pulse. The ability to fine-tune the clustering behaviour is vital to avoid compromising the representativeness of the clusters.

Furthermore, interventions during the pre-crash phase can alter vehicle kinematics, potentially influencing the occupant's position and state (Östh et al., 2013). The impact of pre-crash interventions has been studied in simulations with HBMs with active musculature; the muscle activation was found to be important for capturing occupant pre-crash motion. Additionally, muscle activation might also be important for more accurate injury prediction during the in-crash phase (Östh et al., 2022). In this thesis, the focus was on expanding the evaluation of various crash configurations, occupant postures, and anthropometries. Therefore, expected crash configurations after pre-crash interventions were combined with occupant postures that could result from pre-crash vehicle kinematics. This approach was prioritised over evaluations with whole-sequence active HBM simulations, partly due to the substantially longer duration and increased computational demands of pre-crash compared to in-crash events. This decision aligns with the thesis's overall goal of exploring a wider range of scenarios, albeit with the limitation of not incorporating dynamic pre-crash postures induced by pre-crash interventions in favour of including occupant postures representing the outcome of those interventions.

Future research could encode vehicle pre-crash kinematics and include them as part of the crash configurations, as exemplified for a highway rear-end crash by Dobberstein et al. (2019). The pre-crash vehicle motion could either be parametrised or encoded using more advanced numerical methods, such as eigenvector analysis, which has previously been used to characterise crash pulses (Iraeus et al., 2021). Including the pre-crash kinematics information as part of the crash configuration would pave the way for identifying the whole-sequence crash scenarios to be further investigated with active HBMs. Active HBMs could then predict the dynamic pre-crash postures induced by pre-crash interventions during the whole-sequence safety assessment.

6.1.3 Incorporating In-Crash Heterogeneity Aspects

A set of methods focusing on investigating in-crash variables and their influence on occupant protection was developed. The variables include occupant posture, anthropometry, seat adjustments, and restraint configurations. The methods employed numerical models and analytical techniques to provide insights into the variables' effect on the occupant's responses and their complex interactions. An examination of these factors offers a comprehensive view of how occupant and vehicle attributes can alter the effectiveness of protection systems. A better understanding of the diversity encountered in real-world crashes can spotlight potential safety challenges. When challenging situations are identified, previously unknown occupant protection needs can be addressed, and more effective countermeasures can be designed.

Numerical Models

Finite Element (FE) HBMs played a crucial role in the conducted studies. These models were chosen for their detailed and accurate representation of human anatomy, which potentially offer greater biofidelity compared to ATDs (Wismans et al., 2005). Moreover, the omnidirectional nature of HBMs enables the evaluation of complex crash configurations (when the occupant is subjected to loading from multiple directions), which cannot be accurately simulated with ATDs predominantly designed for a single direction. Similarly, the tested occupant postures could not have been investigated with ATDs. As discussed by Hu et al. (2012), HBMs can serve as a platform to integrate the accumulated knowledge about occupant responses during a crash. Using these models is thus the logical way to benefit from this knowledge; they are also important for a more comprehensive assessment of occupant safety. A broader range of scenarios can be explored when FE HBMs are used, bringing the assessment one step closer to the full range of real-world conditions.

For the investigations carried out in Paper II, the SAFER HBM v9 (Östh et al., 2020) was used. Uniformity and comparability were maintained across the different studies through the use of the v9 for the studies from Papers II–IV, although SAFER HBM v10 became available during the timeframe of Papers III–IV. During the hundreds of simulations conducted for Papers III–IV, the SAFER HBM v9 was found to be robust, which is an important attribute for deploying HBMs in large-scale studies.

The selection of a detailed FE vehicle interior model was not arbitrary. Prior studies have illustrated that the choice of boundary conditions, such as a detailed interior model or a simplified sled environment, can considerably influence the simulation outcome (Gierczycka et al., 2021). Furthermore, the development of vehicle safety countermeasures often mandates the utilisation of detailed models. Thus, a detailed model was deemed appropriate for the studies to ensure the accuracy of the results and the practical feasibility of the proposed methods.

However, using detailed models comes at the cost of potentially limiting generalisability with respect to the vehicle fleet.

The in-crash occupant simulations in this thesis were conducted with the intention of investigating occupant kinematics and kinetics, since desirable occupant kinematics are a requirement for effective occupant protection. A natural continuation of this project would be to investigate further how some of the tested parameters can alter the occupant's injury risk.

Papers II–IV encompassed simulations with various occupant postures and anthropometries, seat adjustments, and seat belt configurations. The overarching objective was to investigate how these parameters influence the occupant's response during an impact. Papers II and III focused on occupant kinematics and kinetics, whereas Paper IV delved into the occupant's interaction with the restraints. The combination of cross-correlation and GSA was beneficial in the analysis. Cross-correlation quantified the extent of the change in the occupant's response across the entire time sequence, providing a systematic assessment of the investigated parameters' influence on the occupant's response. GSA assessed and ranked the parameters' effects on the occupant's response, providing valuable insights into the relative importance of each parameter in shaping the overall response of the occupant—while also enabling the investigation of interactions among parameters. A systematic analysis of the occupant's kinematics, kinetics, and interactions with restraints, as performed in these studies, can enhance our comprehension of the factors that drive occupant responses during crashes.

HBMs have the potential to use tissue-level injury predictors, which could provide better injury prediction than global criteria. However, at the time of these studies, their predictive accuracy had yet to be thoroughly validated with the morphed models. For instance, although morphed HBMs aligned better with kinematics from PMHS experiments, this agreement did not translate to improved accuracy in predicting individual rib fracture risk (Larsson K.J. et al., 2019). Additionally, a recent simulation study has presented evidence that morphological variations in the inner skull can alter the impact response of brain tissue (Liu et al., 2022). Yet, the connection between these morphological variations and brain injury risk remains to be fully understood.

It is important to be cautious in relying on apparent trends when analysing occupant kinetic because the absence of observable kinetic trends does not necessarily imply an absence of injury risk, especially considering the potential presence of altered injury tolerance in certain anthropometries. For instance, the lack of considerable differences in lumbar compression forces between shorter-than-normal and normal-stature occupants could hint at increased injury risk for the former, given their potentially smaller vertebral structures and consequently reduced force tolerance. Scaling techniques have been adopted by previous studies to account for body size variations. However, as Hu et al. (2019) pointed out, relying on "simple linear functions of geometry" is almost certainly inadequate for capturing the variation in tolerance with body size.

As HBMs are further developed, and their injury-predicting capabilities are enhanced, they could be used in future studies to replicate the findings of the present studies and expand them to include injury trends, which could then be compared with real-world trends.

Occupant Anthropometry

Contemporary adult-size ATDs and HBMs predominantly consist of three distinct occupant sizes: a small-sized female, an average-sized male, and a large-sized male, typically referred to as the "5th F", "50th M", and "95th M", respectively. The foundation for those anthropomorphic measurements most often stems from a study by the University of Michigan Transport Research Institute (Schneider et al., 1983). This study offered guidelines on ATD anthropometry to represent the demographics of the US population at that time; the 50th M was designed to have the median weight and stature of the male population in the United States (as recorded between 1971 and 1974 in the 1974 HANES survey), representing the "average person" anthropometry.

However, percentiles in a multivariate environment are not always straightforward. A combination of the 5th percentile for stature with the 5th percentile for weight results in an individual relatively rare in the population, as also acknowledged by Schneider et al. (1983). Moreover, as seen in Figure 21, the 5th and 95th percentiles cannot effectively bracket 90% of the population. This lack of adequate representation could become even more pronounced when additional dimensions in which humans exhibit variations are included. Daniels et al. (1952) underscored this point by demonstrating that among approximately 4000 US Air Force personnel, no "average man" could be identified when ten anthropometric measurements were considered. To address this multidimensionality, Paper II turned to KDE (Section 4.1) to estimate the distribution of anthropometric characteristics across the population.

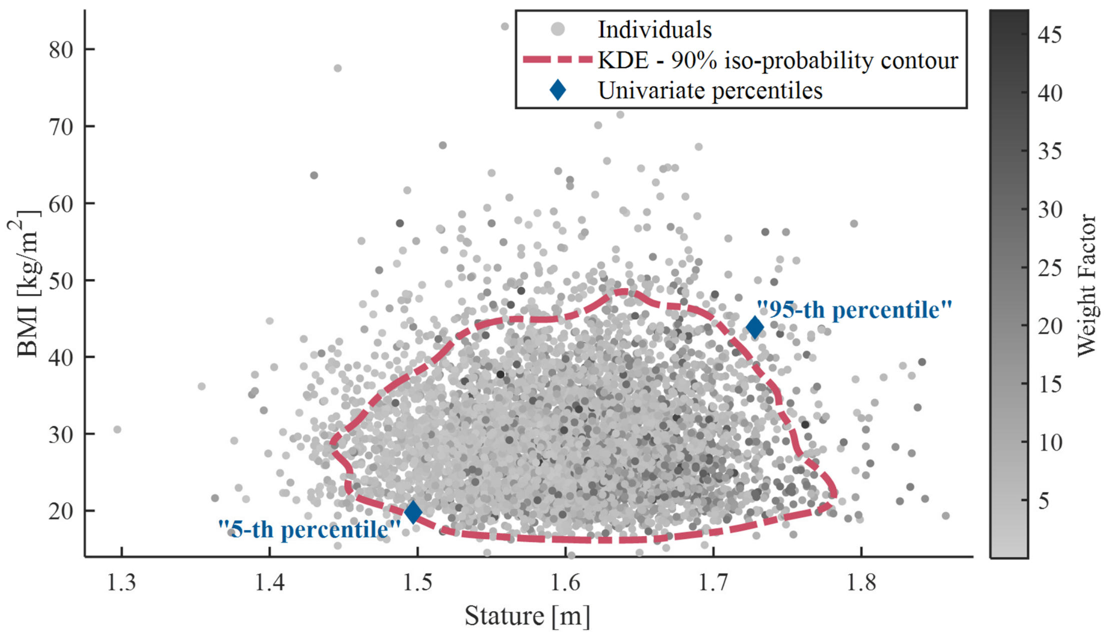

Figure 21. Bivariate distribution of stature and BMI for the female US population. Individuals are depicted with grey dots, and the intensity reflects the weight of the data point to make it representative of the US population. An iso-probability contour line in red, generated using KDE, brackets 90% of the population. The 5th and 95th percentile females (using univariate analysis on the same population) are represented with blue diamonds.

To align with the human shape data used for HBM morphing, the target anthropometric population in this study was selected based on data from the US. The average stature (NCD Risk Factor Collaboration, 2016a) and BMI (NCD Risk Factor Collaboration, 2016b) are known to vary across different regions/countries worldwide. Notable examples include the Netherlands, with an average male height of 182 cm and female height of 171 cm, and China, where the average male height is 167 cm. Regarding BMI, India's male population has an average of 22 kg/m², compared to the US average of 28 kg/m², underscoring the broad spectrum of anthropometric profiles worldwide. While the 90th percentile iso-probability line of the US population might cover the average stature and BMI of other regions, certain anthropometric dimensions may still be underrepresented. Variability also exists in measurements not solely defined by BMI and stature. For example, differences in the sitting-to-standing height ratio between Chinese and US males suggest a proportionally taller upper body region in the former (Li et al., 2020). Consequently, future studies could consider including a broader range of populations to enhance the global representativeness of HBMs.

The occupant sizes selected for evaluation were intended to represent as broad a range of the population as possible. Past studies using morphed HBM have predominantly focused on the implications of obesity for occupant injury risks (for example, Joodaki et al., 2021b). This focus is well-motivated, given the growing global obesity epidemic and its associated health risks. Additionally, obesity has been flagged as a potential risk factor in motor vehicle injuries, as indicated in a meta-analysis by Hoebee et al. (2022). However, there are indications that underweight occupants might also face an increased risk of injury compared to normal BMI occupants (Zhu et al., 2010; Rice et al., 2014; Dubois et al., 2018). Despite these findings, the lower end of the BMI range has received less attention, potentially leaving gaps in our understanding of injury mechanisms for these individuals. Given the importance of addressing the entire BMI spectrum, this research sought to cover a larger part of the population.

It should be recognised that, beyond the aggregate occupant characteristics that were used, occupant diversity encompasses much more than can be captured by these measurements. Individual anthropometric variability, which encompasses variations in the mechanical and geometrical properties of the skeleton and soft-tissue (Section 1.1.3), can influence occupant responses. While the thesis did not specifically delve into individual anthropometric variability, it is worth noting that this area of research is gaining increasing attention in the scientific community (Section 1.3.3). The importance of understanding and accounting for the individual variations in biomechanical properties, in order to accurately predict and assess injury risk during crashes, is increasingly recognised. The methods presented in this thesis, while demonstrated with aggregate anthropometric variability, are adaptable and scalable for future research. For instance, future investigations using HBMs could be expanded to include individual variability in both geometrical and mechanical properties. This inclusion has the potential to deepen our understanding of occupant responses, better reflecting the diverse range of human anatomy. Such advancements would allow for a more comprehensive and accurate assessment of safety measures across a broader spectrum of the population.

6.1.4 Streamlining the Setup and Analysis of HBM Simulations

The increased detail of HBMs, notably the presence of multiple articulable joints and malleable soft-tissue that adapts to the vehicle's interior, makes setting up numerical experiments more complex. To address these complexities, a range of techniques was developed in Papers II–IV, which enable accurate, consistent configuration of the simulation environment across a vast array of crash scenarios. The techniques standardise the simulation framework and utilise (semi)automation, improving the reproducibility and comparability of HBM simulations, thereby forming a solid base for reliable analyses of occupant responses during crash events. Furthermore, the (semi)automation boosts the number of experiments that can be prepared in a set time frame, enhancing the statistical robustness through larger sample sizes.

In this thesis, the HBM positioning was accomplished with a version of the "marionette method" (Poulard et al., 2015a), specifically modified to respect the geometric constraints of a vehicle's interior. While FE simulation-based HBM positioning has been used in previous studies (e.g., Hu et al., 2019; Perez-Rapela et al., 2020; Miller et al., 2021), the method used in Papers II–IV differs by utilising the vehicle interior geometry to define the target posture. The posture of the positioned HBMs can then be compared with data from volunteer studies, such as the one by Reed et al. (2002). The motive was to avoid unrealistic postures due to incompatibilities between laboratory mock-ups of generic vehicle interiors and the specific vehicle interior investigated. These incompatibilities could result in gaps between the occupant and the seat or the floor. The method uses valuable data about occupant postures while at the same time respecting the geometrical constraints of the vehicle. The term "seat squashing" refers to the process that adjusts the form of the seat to represent the compression caused by the occupant's weight. In Papers II–IV, this process was integrated into the occupant positioning, allowing for better control of the equilibrium requirements, and thereby enhancing the quality of the subsequent simulations.

However, FE positioning methods are computationally expensive. An alternative is morphing-based strategies (for example, Beillas et al., 2017), which can drastically reduce the resources required. Unfortunately, these strategies typically overlook HBM material properties, which can lead to unphysical postures or reduced model element quality (Beillas et al., 2017). As a result, issues like negative-volume elements may make such models unfit for direct simulations (Grébonval et al., 2021). Metamodelling techniques have been proposed, leveraging a set of positioning simulations to generate new HBM postures. However, those techniques do not necessarily avoid the pitfalls of poor element quality. Additionally, it is pivotal to ensure that the metamodels preserve the realism of the positioned models without extrapolating (Bacquaert et al., 2020). It is also important to note that past studies (Boakye-Yiadom et al., 2018) indicated that the occupant's initial stress state can affect their kinematics and kinetics. In Papers II–IV, the stresses from the occupant positioning stage were not retained due to a lack of data on the neutral body posture, which could be subject to further variability (Mount et al., 2003).

During the occupant morphing stage, the resulting element quality influenced the selection of the target population. Challenges arise when addressing extremes in BMI and stature distributions due to the substantial adjustments to the element mesh that are required. For smaller individuals, the soft-tissue around the pelvis shrank even though the number of element layers remained unchanged, which led to difficulties in maintaining the desired element quality. In contrast, larger individuals experienced an increase in soft-tissue volume, leading to pronounced distortions in the element mesh, especially in the abdominal area. The anthropometries addressed in this thesis account for approximately 90% of the sample population (US from NHANES 2013-2016), as seen in Figure 21. Maintaining the current morphing method and extending beyond the investigated anthropometric range may prove challenging, mainly because of the extensive adjustments required to the element mesh.

Recent studies have proposed alternative morphing techniques that could improve element quality—by, for example, adding or removing layers of elements (Zouzias et al., 2023). Different techniques have focused on personalising HBMs based on data from individuals using image registration (Li et al., 2023). Such techniques could prove advantageous for morphing HBMs to more "extreme" body sizes. For example, morphed HBMs based on individual anatomical data could better model the abdominal folds observed in obese occupants (Lebarbé et al., 2020). Additionally, it is important to investigate whether an average person of a specific population can represent larger portions of the population—in other words, whether a model tailored for an average individual is generalisable to a broader demographic.

In addition to HBM positioning techniques and target population definition, an analysis technique for seat belt interactions was also demonstrated (Paper IV). The interaction between the occupant and the seat belt was quantified using HBM numerical simulations, leveraging their inherent advantages. As the effective function of the seat belt relies on its proper placement over strong load-bearing bones, such as the pelvic bone, ribcage, and clavicle, the ability to measure the interaction between the seat belt and the landmarks associated with the bones is crucial for assessing the effectiveness of the seat belt. In numerical simulations, it is possible to measure the distances between landmarks, which may not be visible in physical tests and may not be as accurately represented in ATDs (due to their lower level of detail). To benefit from the possibilities of the HBM's detailed anatomy and simulation approach, the "belt score" (Reed et al., 2009), which is a metric formulated to assess the belt fit on the occupant, was extended to function during the dynamic phase of the crash. Automating those measurements enabled a systematic and consistent quantification of belt interaction, providing insights into the belt's positioning during the crash. This information was used to auto-classify belt interactions for events such as submarining or sliding out of the shoulder belt, enhancing our understanding of the seat belt's interaction with the occupant during the impact and allowing the belt's effectiveness at restraining the occupant to be quantitatively evaluated.

6.2 Simulation Findings

Vehicle crashes are complex events affected by factors during the pre-crash and the in-crash phases. This subsection discusses the main findings of the efforts to predict the remaining crash configurations considering pre-crash systems (Paper I), as well as examining the factors influencing the occupants' response during the in-crash phase—such as their sex, shape, and size; the seat position; and the design of restraint systems (Papers II–IV). This thesis demonstrates findings that can be employed to identify key areas for improvement in vehicle safety systems.

6.2.1 Crash Configurations Predictions

Valuable insights into the distributions of the crash configurations expected after crash avoidance interventions can be obtained when the method from Paper I is applied with appropriate prospective assessment techniques. The method's general applicability was demonstrated by using a simplified, publicly available AEB system (Wimmer et al., 2019) across two ODDs of varying complexity (urban intersections and highway driving). While this approach does not encompass all crash scenarios, it offers a glimpse of the heterogeneity of real-world crash configurations. This heterogeneity cannot be adequately represented in current standardised tests (Figure 22).

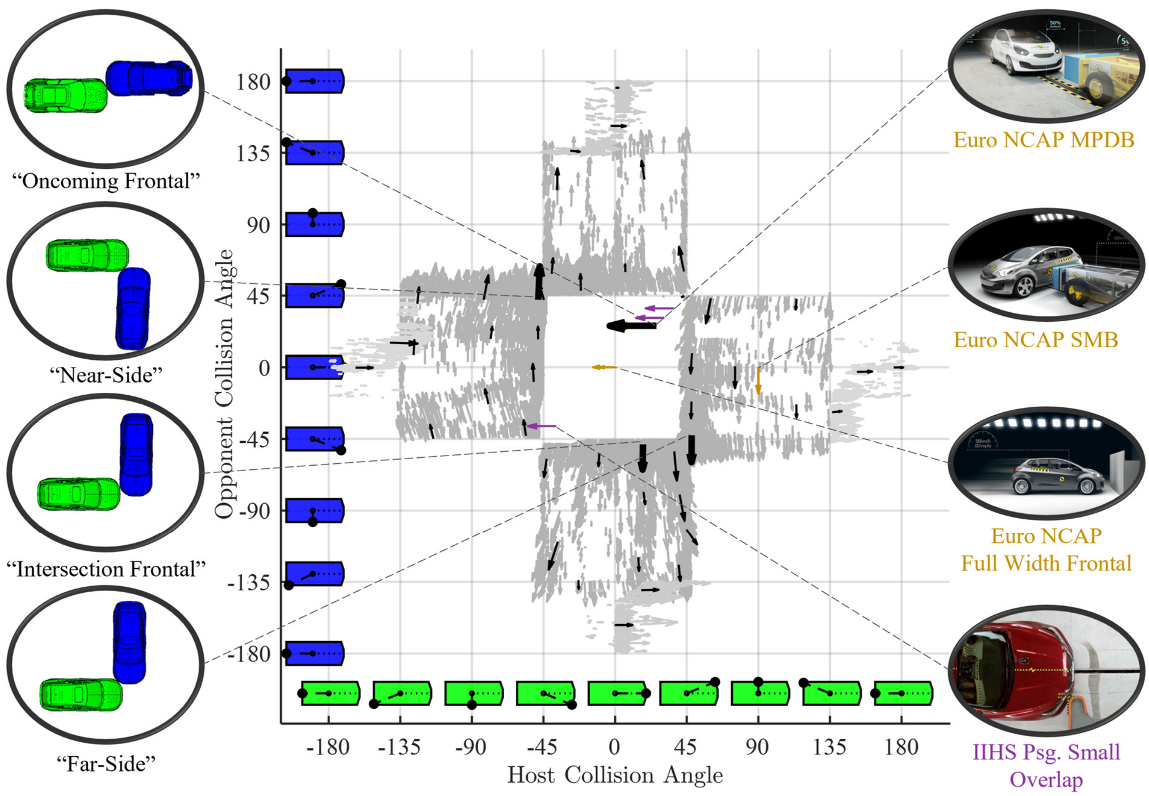

Figure 22. A "crash configuration map" depicting the expected crash scenarios after pre-crash interventions within SCP at urban intersections and SD—ref on highways. Crash configurations are shown as arrows, indicating the impact location by their origin and the relative movement direction of the involved vehicles. The arrow length corresponds to the closing speed. Grey arrows show all predicted configurations after the AEB intervention in Paper I; black arrows denote the representative subset (selected through clustering). The configurations analysed in Papers II–IV are detailed on the left and juxtaposed with standardised crash configurations from Euro NCAP and IIHS on the right. [source: adapted from euroncap.com and iihs.org]

The crash avoidance rates obtained from simulations align with findings from other studies, although they may appear optimistic compared to results obtained from retrospective studies, since the simulations are based on a futuristic concept AEB system with idealised sensors unaffected by environmental conditions. The results are comparable to other prospective studies, like the one by Sander et al. (2018), which underscore the potential benefits of crash avoidance systems. These studies suggest that widespread implementation of advanced AEB systems could drastically reduce crash occurrences.

The pre-crash assessment from Paper I supplements the typical data on avoidance rates and reductions in impact velocity (e.g. Rosén, 2013) with impact location and angles, providing a comprehensive overview of the anticipated crash characteristics. Particularly in urban intersections, pre-crash braking interventions (from Paper I) lead to a relatively more frequent occurrence of impacts near the vehicle corners, offering valuable insights into expected crash configurations for future protection needs. These results align with findings from a concurrent study that examined data from the German GIDAS database (Östling et al., 2019a). Due to the simplified models of crash avoidance systems and the limited number of ODDs, the predicted crash configurations cannot replace the crash configurations used in the existing regulatory or consumer information tests. However, the ability to predict changes in crash configuration distributions can improve the effectiveness of crash avoidance systems by enabling the proactive development of complementary systems that address potential occupant protection challenges.

The crash configurations predicted in Paper I were based on two ODDs using data from a single country, Sweden. Future studies could assess more ODDs to provide a more comprehensive understanding of the expected crash configurations. Different conflict types—which refer to the different kinematic sequences leading to potential collisions—are typically analysed separately during the pre-crash phase, as different countermeasures might apply to different types. However, the predicted crash configurations from multiple conflict types could be jointly clustered, as the conflict type is no longer relevant for assessing occupant protection. Furthermore, databases from more regions could be used, since differences (such as infrastructure characteristics and fleet composition) could exist. Additionally, during the pre-crash intervention, the vehicle's pre-crash motion could be encoded for inclusion as an additional parameter in the crash configurations.

Even after applying the clustering method, the number of identified crash configurations may still be too large to be applicable for in-crash assessments. Therefore, a subset of crash configurations was further selected for detailed investigation using the developed clustering method. Three crash configurations were selected based on their shares of the distribution: a Near-Side, a Far-Side, and an Intersection Frontal impact. Priority was given to crashes with the highest severity, based on factors such as the highest opponent speed for Near-Side and Far-Side impacts and the highest host vehicle speed for Frontal impacts. Structural simulations informed the selection process.

The distribution of predicted crash configurations offers a comprehensive view of the diverse range of real-world crashes that could exist even with the implementation of crash avoidance systems. By investigating occupant protection in these anticipated crash scenarios (as seen in Papers II–IV), the thesis demonstrates a tool chain that enables the proactive identification of occupant protection challenges. This thesis thus contributes to the development and refinement of future safety systems, taking into account a broad spectrum of relevant real-world situations.

6.2.2 Effects of In-Crash Heterogeneity

The findings in Paper I indicate that crash avoidance manoeuvres will precede most future crashes. Even if the occupant is in the "nominal" posture before a pre-crash event—a situation that does not always occur—these manoeuvres could change their initial posture. Therefore, considering posture variability in the design of restraint systems and vehicle safety measures is important. HBMs are valuable tools for including posture variations and enabling the assessment of whole-sequence scenarios (Section 1.3.2). Those assessments can support the development of systems that incorporate posture prediction algorithms and posture control countermeasures, ultimately contributing to improved occupant protection and a reduced risk of injury during unavoidable crashes.

Occupant posture variations, based on naturalistic data (Reed et al., 2020b), were assessed for their influence on the occupant's kinematic response during crashes. Although muscle activations could potentially influence injury outcomes during the in-crash phase, their effect on crash kinematics have been shown to be limited in whole-sequence simulations (Östh et al., 2022). Therefore, the selected torso postures for this study reflect positions commonly assumed during cornering (Bohman et al., 2020) and braking events (Ólafsdóttir et al., 2013), and could be indicative of the occupant's kinematic response to pre-crash manoeuvres. It is essential, however, to acknowledge that the occupant posture at the crash onset matched the response of the "average" occupant and doesn't capture the variability in pre-crash occupant kinematics, which be affected by a wide array of other factors (Larsson E., 2023).

Paper II highlighted the important role of the torso's posture in determining the torso and head's responses during side impacts. For instance, when occupants leaned away from the incoming impact, the relative velocity between their head and the vehicle was drastically increased. Leaning forward might also present additional challenges due to the torso's increased sensitivity to lateral movements as a result of the reduced support from the seat. In contrast, occupants in a semi-reclined position were better supported by the seat side bolsters and less sensitive to such lateral movements. The importance of the torso's posture was also seen in Paper IV: if it was leaning inboard or forward, it was more prone to sliding out of the shoulder belt in frontal and side impacts. Although sliding out of the belt is not necessarily accompanied by substantial increases in torso excursions, it is neither robust nor desirable for occupant retention.

Furthermore, the posture of the lower extremities, such as sitting cross-legged, greatly influenced the whole-body response across all tested crash configurations, primarily due to the interaction between the lower extremities and the vehicle interior. Changes to this interaction also caused differences in the pelvis kinematics and the lap-belt-to-pelvis interaction. The altered pelvis motion affected the occupant's torso and propagated to all other body regions. This sequence of events underscores the importance of accurately predicting pelvis motion during assessments and ensuring it is effectively controlled during a crash. Paper III further explored this event sequence, revealing a correlation between the occupant's BMI and the pelvis kinematics and loading: greater BMI occupants resulted in larger pelvic movements.

Regarding the obese occupant, the simulation results indicated increased loading in the lower extremities. This might partially explain the increased lower extremity risks observed for obese occupants compared to occupants with normal BMI (Hoebee et al., 2022). The increased loading is likely attributable to a combination of increased kinetic energy and earlier contact between the knees and the dashboard.

The influence of seat adjustment on occupant response was also described in Paper III. When seats were adjusted rearward, increased pelvic and lumbar spine loading was observed. This effect was attributed to the diminished role of the lower extremities, through the interaction between the knees and the knee restraint, in regulating the occupant's pelvic motion. This finding indicates a delicate balance based on seat position between the pelvis and lumbar spine loading and the forces acting on the lower extremities. Moreover, this finding supports previous research, which found that a larger distance between the occupant and the knee bolster increased the risk of submarining (Rawska et al., 2019). In a real-world context, since approximately 50% of occupants in a naturalistic driving study maintained the seat position as they found it prior to the trip (Reed et al., 2020b), many occupants might be potentially exposed to increased injury risk in certain crashes.

Since belt fit varies across occupants (Section 1.1.3), individualised restraint systems could potentially lead to improved occupant retention. Therefore, Paper IV focuses on individualised restraint configurations, including occupant and seat adjustment variability. While important, the initial placement of the seat belt over an occupant's shoulder was not sufficient to predict the interaction between the occupant and the shoulder belt during an impact. Differences in shoulder belt routing in frontal impacts altered the torso-to-pelvis retention balance, pelvis motion, and lap belt interaction. Thus, in addition to obese occupants, who pose particular protection challenges, underweight occupants might also require special attention. This finding suggests that specific demographic groups, such as those who are underweight, might benefit further from individualised restraint systems.

As noted, individualising the initial shoulder belt placement did not necessarily result in better occupant kinematics or belt interaction. Especially for underweight occupants, additional restraint system modifications might be needed in conjunction with individualising the initial shoulder belt placement, in order to avoid submarining, which was observed on backward-adjusted seats. Similarly, in a simulation study by Rawska et al. (2019), smaller body sizes were found to be more prone to submarining than larger sizes.

Analysing the occupant-to-belt interactions across diverse setups and occupant characteristics (Paper IV) revealed specific challenges for certain population groups and identified their source mechanisms. Thus, using morphed HBMs and diverse setups can highlight protection challenges and ultimately lead to the development of more robust, effective restraint systems.

In the simulation setups of Paper IV, the seat belt was routed along the shortest path, which resulted in a belt fit that was generally comparable with measurements from a static vehicle test (Jones et al., 2017). However, during real-world driving, obese occupants might be at a higher risk of suboptimal belt placement (Makris et al., 2023); these alternative placements were not considered in Papers III–IV. Furthermore, state-of-the-art HBMs are limited in their ability to capture the interaction between the lap belt and the pelvis, as well as the pelvis kinematics (Gepner et al., 2022). Also, as mentioned, the morphing technique employed did not account for the abdominal fold frequently present in obese occupants (Lebarbé et al., 2020). These aspects should all be considered regarding the submarining trends reported.

Future research on occupant protection should focus on including individual anatomical variability and injury risk prediction. This work will obviously require extensive model development and will probably require data that do not exist at the moment. Including injury risk prediction will likely add to the complexity of the safety assessment, as parameters that might not influence the occupant kinematics might be essential for injury risk prediction. For example, in a sensitivity analysis conducted by Larsson K.J. et al. (2023), differences in rib cortical bone thickness, cross-sectional width, and material properties were found to considerably influence the predictions from HBM simulations regarding the likelihood of an occupant sustaining two or more fractured ribs in frontal and near-side impacts.

While investigating which aspects of individual variability are influential and should be further investigated, one should remember that the results might depend on the boundary conditions used.

6.3 Application of Methods and Findings

The thesis primarily focuses on supporting the advancement of safer vehicles for the future, but it can also be used to understand safety challenges in existing cars. To support the development of safer vehicles, a set of methods was developed and applied to incorporate aspects of crash heterogeneity. These methods and the concomitant findings can identify relevant, challenging setups early in the development stage of vehicle safety systems. By developing and illustrating the practical applications of methods tailored for analysing road traffic safety challenges, this thesis deepens our understanding of the diverse protection needs of occupants, considering various body shapes, sizes, and postures, as well as seat adjustments, and the interactions of these factors.

Compared to past crash avoidance evaluations (Yue et al., 2018), which focused on crash avoidance percentages or impact velocity reduction estimations, Paper I takes one step further by examining how pre-crash interventions can change other crash configuration characteristics (such as impact locations). Examining these changes is especially useful in the event of mitigated crashes, as predicting the injury risk of the occupant requires considering variables beyond the reduced speed. Knowledge of the expected crash configuration distributions can inform the development of in-crash safety systems, by proactively accounting for their specific challenges (Wågström et al., 2013a).

Coupling the assessment of crash avoidance and in-crash safety systems makes it possible to evaluate future protection strategies considering both the pre-crash and in-crash phases. The emergence of vehicle-interior-sensing systems on the market creates new opportunities to implement new occupant retention strategies, such as adapting seat belt characteristics to the protection needs of specific individual occupants in the event of a crash. However, implementing these new strategies requires knowledge of how occupants respond to diverse conditions, which is challenging due to the large number and wide diversity of variables involved. The thesis contributes to this challenge by developing methods that support the assessment of occupant responses under various conditions. These methods not only improve our current understanding, but also lay the groundwork for targeting occupant protection challenges and developing safer future vehicles.

The methods employed in Papers III and IV specifically focus on capturing interaction effects between the investigated parameters. The simulation results justify this approach, as the presence of interaction effects considerably impacted the conclusions drawn from the studies. For example, in tests of an individualised shoulder belt position, variations of the "average" anthropometry in stature or BMI alone were not very influential for seat belt interaction (as detailed in Paper IV); however, changes to stature and BMI together revealed potential occupant protection challenges. This finding underscores the thesis's aim to identify these challenges—and concomitantly, populations at higher risk. Different population groups and situations may require tailored countermeasures; this demonstrates the potential of targeted strategies to further improve safety for everyone.

When considering the broader applications of this research, one note is that the computational cost of the methods and simulations used in this thesis might limit their immediate application in standardised tests. However, their utilisation provides insights into the complex dynamics of occupant protection, and thus has the potential to inform the development of more representative safety assessments. The findings emphasise that what may be insignificant for one group of occupants could be highly influential for another. This understanding underscores the need for comprehensive research that considers the diverse characteristics and interactions among different factors in occupant protection. When these interactions and their consequences are examined, protection strategies and countermeasures can be refined to better address the needs of different population groups.

6.4 Limitations and Recommendations for Future Studies

This thesis presents studies of car occupant safety, an important concern in traffic safety worldwide. While the thesis focuses on car occupants—who account for about half of the fatalities in Sweden, Europe, and the USA (World Health Organization, 2023)—it needs to be acknowledged that globally, unprotected road users, like pedestrians, cyclists and those on power two-wheelers are more prevalent (World Health Organization, 2023). Thus, it is important to expand future research beyond car occupants.

Specific ODDs like urban intersections and highway driving were drawn from Swedish data. These ODDs do not encompass the full spectrum of potential crash types (in Sweden or elsewhere). Notably, the focus on car-to-car crashes omitted crash types like single-vehicle crashes and multiple events, which also contribute considerably to injuries and fatalities and thus should be examined in future research.

The research primarily focused on front-seat passengers, excluding drivers and rear-seat passengers. Due to differences in the vehicle interior between the front-seat passenger and driver, there might be different challenges for those occupants, which were not seen in this thesis. Additionally, while both near- and far-side impacts were included, those crash pulses were not symmetric. This asymmetry, along with the differences in vehicle interiors and possibly occupant postures, implies that the findings of the thesis may not fully apply to drivers.

Only simulations of belted occupant models were included in the studies despite the fact that belt usage rates globally have been reported to be below 100%. For instance, the front-seat occupant usage rate is around 96% in Sweden (Hurtig et al., 2022) but only around 40% in parts of Asia (Kargar et al., 2023). Furthermore, specific population groups, such as obese individuals (Schlundt et al., 2007), may exhibit lower seat belt usage rates. Thus, the real-world potential of safety measures like individualised restraint systems could be lessened for some population groups.

The studies aimed to assess occupant kinematics as this is the first step in the evaluation of restraint systems' effectiveness. As HBMs are further developed with enhanced injury risk prediction capabilities, a logical progression would be to incorporate injury risk into occupant safety assessments.

Investigating crash heterogeneity solely through real-world data poses considerable challenges. Databases often lack details, particularly at lower severity levels, making the task of correlating injury risks with specific contributing factors impracticable. Therefore, the results obtained in this thesis have not been compared to field data. Although this comparison would be challenging, it would also be very valuable.

In conclusion, this thesis has contributed methods and findings about occupant responses in simulated crashes that can provide valuable insights into car occupant safety. Nevertheless, there remains a pressing need for further studies that encompass a broader range of crash types, occupant seating positions, and regional variability. Given that traffic safety continues to be a major health problem, effectively addressing it likely requires more than just advancements in vehicle safety countermeasures.

7 Conclusions

This thesis has advanced the understanding of real-world occupant protection needs with the overall goal of reducing occupant injuries in vehicle crashes. Methods were developed and applied, incorporating various aspects of real-world crash heterogeneity not typically included in current safety assessments, to support the development of safety systems.

Specifically, this thesis has:

- Predicted the change in crash configurations by developing a method which simulates crash avoidance interventions and uses a novel crash configuration definition. The predicted crash configurations can be used for developing relevant in-crash countermeasures.
- Quantified the effect of crash heterogeneity factors on occupant crash responses and identified protection challenges for diverse populations, using methods that also capture interaction effects.
- Implemented techniques, such as (semi)automated positioning and seat belt interaction quantification, to streamline the setup and analysis of large-scale numerical experiments with HBMs.

Through large-scale simulation studies, this thesis has also provided insights into the effects of crash heterogeneity, such as:

- Changes in vehicle crash exposure after an intervention of an autonomous emergency braking system at urban intersections, indicating a higher relative likelihood of crashes at vehicle corners.
- Challenges in occupant protection, encompassing non-nominal postures, non-standardised seat adjustments, and varied anthropometry. The challenges include:
  - Sensitivity of forward-leaning occupants to lateral motions, with increased excursions in side impacts for those leaning away from the struck side.
  - Sensitivity of the torso’s lateral movements during side impacts to upper extremity interactions with the vehicle’s centre console.
  - Increased pelvic movement in frontal collisions due to non-nominal lower extremity postures, such as sitting cross-legged.
  - Altered occupant load path in frontal impacts resulting from seat adjustments: A rearward-adjusted seat increased pelvic and lumbar spine loading but reduced lower extremity loading as the balance of the lap belt and interaction force was altered; forward seat adjustment reversed these effects.
  - Correlations between greater BMI or greater stature and increased lower extremity loading, due to increased kinetic energy and earlier interaction with the instrument panel.

In addition, an analysis technique used to investigate aspects of individualised restraint systems was showcased. The analysis was demonstrated by individualising the shoulder belt placement, without changing additional belt parameters. The simulations demonstrated that different body types interact with the restraint systems in varied ways, suggesting that the protection challenges differ for different body types. This finding underscores the importance of considering individual characteristics in the design of occupant restraint systems in order to enhance safety for all.

The methods, developed in this thesis, were employed in large-scale simulation studies to investigate the effect of crash heterogeneity aspects. Incorporating additional aspects of crash heterogeneity has the potential to further enhance safety systems for future vehicles, for a broader population, in more real-world representative situations.

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