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in

Machine and Vehicle Systems

Structural Safety Design for Real-World Situations

Using Computer Aided Engineering for Robust Passenger Car Crashworthiness

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Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Basic model of how traffic environment affects the vehicle and human occupants in crashes (left), and simulation setup for oblique crashes described in Paper III (right).

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You miss 100% of the shots you don't take.

- Wayne Gretzky

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Abstract

Road traffic continues to cause more than a million fatalities worldwide every year. Although many steps have been taken to improve occupant protection in car crashes, challenges still remain for car designers.

In the present study, real-world data derived from frontal crashes has been used as a base for identifying crash situations where occupants are severely or fatally injured in cars despite them having been awarded top-ratings in crashworthiness evaluation tests. One situation identified is small overlap crashes, where injuries are commonly related to intrusion. Another is large overlap situations, where injuries are not directly linked to intrusion but rather to vehicle deceleration and interaction with restraint systems.

The aim of the studies constituting this thesis was to develop design methods for robust crashworthiness of future passenger cars and propose solutions to mitigate injuries in large overlap situations. Research was performed using simulation models ranging from simple mass-spring elements to detailed Finite Element (FE) models of contemporary passenger cars.

A newly developed methodology has been proposed as a main contribution based on the research undertaken, in order to provide a comprehensive way of simulating and visualising structural robustness in car-to-car frontal crashes. The methodology was applied to identify worst-case scenarios both regarding intrusion (oblique small overlap scenarios) and deceleration (large, but not full, overlap scenarios). Further development of this methodology has been proposed in order to address issues of crash compatibility, as well as a tool for securing robustness in future mass reduction scenarios.

Another contribution is the proposal of an adaptive front structure to reduce passenger compartment deceleration levels by actively decoupling the front subframe on a contemporary passenger car in a range of frontal car-to-car crash scenarios. Results suggest a deceleration reduction potential equivalent to reducing the velocity change in a frontal crash by up to 44%.

The findings of the present study are compared to previous work and future applications are suggested.

Keywords: passive safety, crash simulation, structural robustness, frontal crashes, structural adaptivity, crash compatibility, small overlap crashes

List of appended papers

Paper I

Wågström, L., Thomson, R., Pipkorn, B. (2004) *"Structural adaptivity for acceleration level reduction in passenger car frontal collisions"* International Journal of Crashworthiness 9 (2), 121-127.

Paper II

Wågström, L., Thomson, R., Pipkorn, B. (2005) *"Structural adaptivity in frontal collisions: implications on crash pulse characteristics"* International Journal of Crashworthiness 10 (4), 371-378.

Paper III

Wågström, L., Kling, A., Norin, H., Fagerlind, H. (2013) *"A methodology for improving structural robustness in frontal car-to-car crash scenarios"* International Journal of Crashworthiness, International Journal of Crashworthiness 18 (4), 385-396.

Paper IV

Wågström, L., Kling, A., Norin, H., Fagerlind, H. (2012) *"A Correlation Study for Oblique Frontal Impacts with Focus on Small Overlap Situations"* In: Proceedings of the International Crashworthiness Conference (ICRASH), Milan, Italy.

Paper V

Wågström, L., Kling, A., Berge, S., Norin, H., Fagerlind, H. (2013) *"Adaptive structure concept for reduced crash pulse severity in frontal collisions"* International Journal of Crashworthiness (published online).

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for planning the aim and scope of the papers, carrying out the numerical simulations, analysing the results, and stating the conclusions.

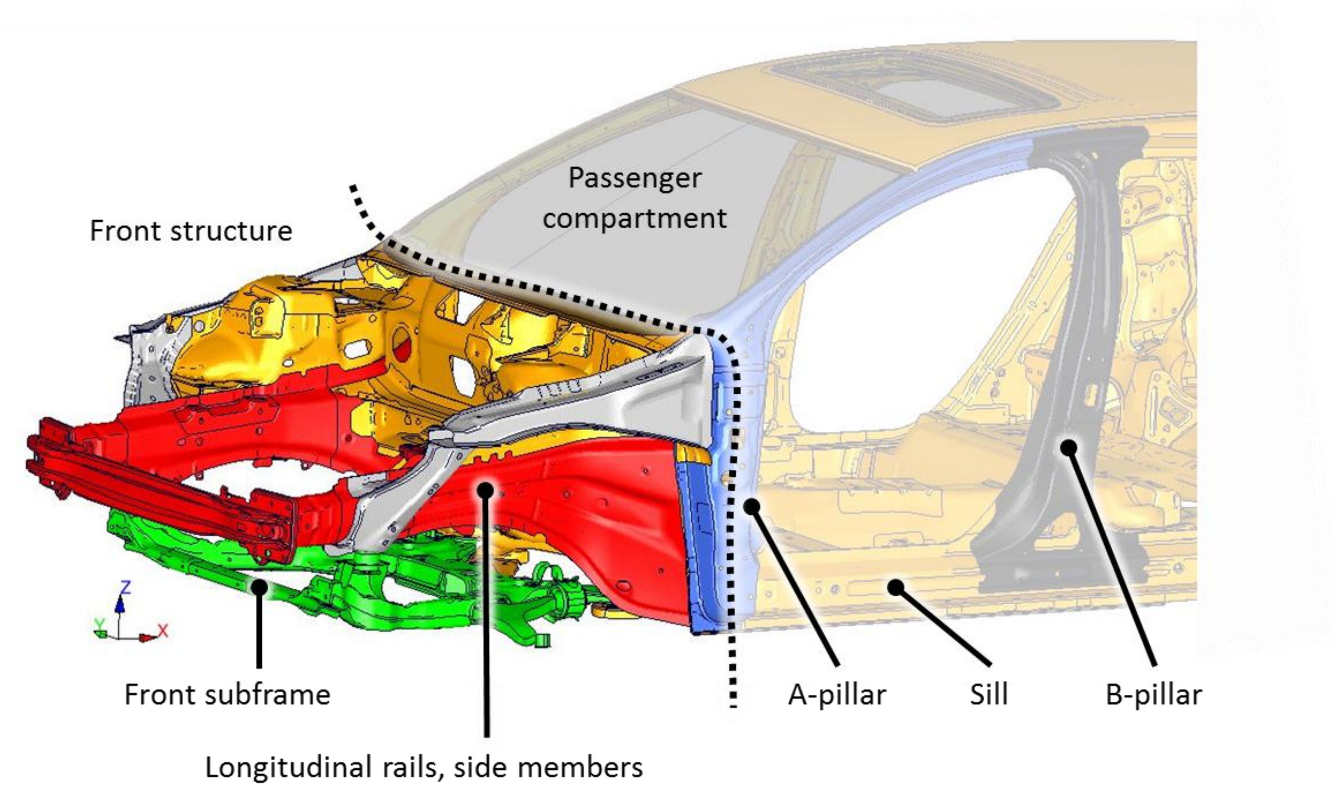
Table of contents

Definitions and abbreviations

Active safety	Measures taken to avoid or mitigate crashes
Aggressivity	Measured for a subject vehicle in terms of fatality or injury risk for occupants in opponent vehicles involved in the same crash
AHOF	Average Height of Force
AIS	Abbreviated Injury Scale
A-pillar	Vehicle structure connecting floor and roof, in front of front doors
B-pillar	Vehicle structure connecting floor and roof, rear of front doors
CAE	Computer Aided Engineering
CCIS	Cooperative Crash Injury Study
Crash	Dissipation of vehicle kinetic energy by structural deformation
Crash compatibility	Combination of self and partner protection in crashes
Crash pulse	Vehicle deceleration time history
ELVA	Advanced Electric Vehicle Architectures, research project acronym
Euro-NCAP	European New Car Assessment Programme
EVCR	Equivalent Velocity Change Reduction
EVERSAFE	Everyday Safety for Electric Vehicles, research project acronym
FE	Finite Element
FIMCAR	Frontal Impact and Compatibility Assessment Research, research project acronym
Frontal stiffness	Relationship between force and displacement during crush of frontal structures
FWDB	Full-width Deformable Barrier
FWRB	Full-width Rigid Barrier
GIDAS	German In-Depth Accident Study
HIII	Hybrid III crash test dummy
HOF	Height of Force
IIHS	Insurance Institute for Highway Safety
KW400	Work stiffness over the first 400 mm of vehicle front crush
LS-DYNA	Finite element solver used for crash simulations

MAIS	Maximum Abbreviated Injury Scale
MPDB	Moving Progressive Deformable Barrier
NHTSA	National Highway Traffic Safety Administration
ODB	Offset Deformable Barrier
OLC	Occupant Load Criterion
Partner protection	A vehicle's ability to indirectly protect occupants in opponent vehicles against injuries in car-to-car crashes (i.e., reduction in aggressivity)
Passive safety	Measures taken to reduce consequences of crashes
PDB	Progressive Deformable Barrier
Restraint system	Interior vehicle system designed to mitigate injuries in crashes, e.g., seatbelts, airbags and seats
Self-protection	A vehicle's ability to protect own occupants against injuries in crashes
SUV	Sport Utility Vehicle
Vehicle structure	Structural element of vehicle, e.g., body structure or front subframe
Vision Zero	Long-term aim for eliminating fatalities and serious injuries in road traffic
VPI	Volvo Pulse Index
WHO	World Health Organization

Visualisation of vehicle structures



Preface

The work presented in this thesis was carried out at Chalmers University of Technology in Gothenburg, Sweden and was divided into two periods.

The first work period was carried out at the Crash Safety Division of the Department of Machine and Vehicle Systems from 2002 to 2004 under the supervision of Dr. Robert Thomson and Dr. Bengt Pipkorn and was sponsored by Autoliv Research.

The second work period was carried out at the Division of Vehicle Safety of the Department of Applied Mechanics from 2011 to 2013 under the supervision of Dr. Hans Norin, Helen Fagerlind and Anders Kling. All studies during the second period were sponsored by Volvo Cars and conducted as a part of the Volvo Cars Industrial PhD Programme (VIPP) in association with SAFER – Vehicle and Traffic Safety Centre at Chalmers, Sweden.

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The creation of this thesis would not have been possible without the support of numerous colleagues and family members. I would like to mention the people that have played the most important roles and at the same time apologize to anyone that I may have failed to mention:

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All my colleagues at Chalmers University of Technology, especially associate Professor Dr. **Karin Brolin** for assistance with Paper III that needed two major revisions before finally being accepted for publication, Professor **Jac Wismans** for collaboration in ELVA, and assistant Professor Dr. **Johan Davidsson** for assistance regarding teaching.

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Finally, the **Wågström** clan: my parents **Ingrid** and **Sören**; my sister **Linda** and brother **Pär-Johan** with families. Thanks for everything since day one.

My dear family **Arezo**, **Jonathan**, **Elias** and **Alicia**. This is for you.

Göteborg, September 30, 2013

1 Introduction

The World Health Organization (WHO) estimates annual road fatalities to more than 1.2 million globally (World Health Organization 2013), making traffic injuries the leading cause of death among young people aged between 15 and 29. The WHO reported data from 2006 amounting to more than 100,000 fatalities in India, close to 90,000 in China and more than 40,000 in the United States. Furthermore, the WHO stated in the same report that “while road traffic death rates in many high-income countries have stabilised or declined in recent decades, data suggest that in most regions of the world the global epidemic of traffic injuries is still increasing”.

In the European Union, road transportation claims more than 30,000 lives annually as reported by the European Commission (2013). Approximately half of the European road fatalities represent occupants in passenger cars (DaCoTA 2011). The design of passenger cars must therefore constantly be reviewed to investigate whether there are further steps that can be taken in order to reduce the number of road fatalities.

A number of countries and organisations have adopted visions for eliminating fatalities and serious injuries in road traffic, often referred to as Vision Zero (Tingvall and Haworth 1999, Johansson 2009). It has been identified that countermeasures may be feasible both by protecting occupants in the event of a crash (passive safety) and by avoiding or mitigating a crash (active safety) as described by Eugensson et al. (2011).

1.1 Basic model for occupant protection in passenger car crashes

This thesis is focused on passive safety of passenger cars and uses a basic model of how car occupants interact with the traffic environment via the vehicle in crashes as illustrated in Figure 1. In the first layer of this model, the outcome for the occupants in a crash is defined by how they can be protected from crash loads by the vehicle structure and restraint systems. Restraint systems and vehicle structures are dependent on each other, i.e., without a stable structural response the restraint systems may not be sufficient to protect occupants against injuries. Vice versa, the detailed structural response may be less important if occupants are not restrained to the vehicle in a crash. Therefore, occupant protection is considered to be based on equivalent shares of structural response and restraint system performance.

In the next layer, the basic model describes vehicle interaction with the crash environment as illustrated in Figure 1. The crash environment is divided into three categories: crash opponent, crash scenario and crash energy, all affecting vehicle response in a crash and defined as follows:

- <u>Crash opponent</u> are all types of objects that a car may collide with, e.g., trees, poles, roadside barriers, animals, trucks, cars or other vehicles.
- <u>Crash scenario</u> is a description of how a car interacts with its crash opponent, e.g., offset frontal crashes, oblique side crashes, etc.
- <u>Crash energy</u> describes, for a situation defined by crash opponent and scenario, the initial velocity and mass of vehicles and objects involved in the crash.

Any combination of these three crash environment parameters will hereafter be referred to as a crash situation.

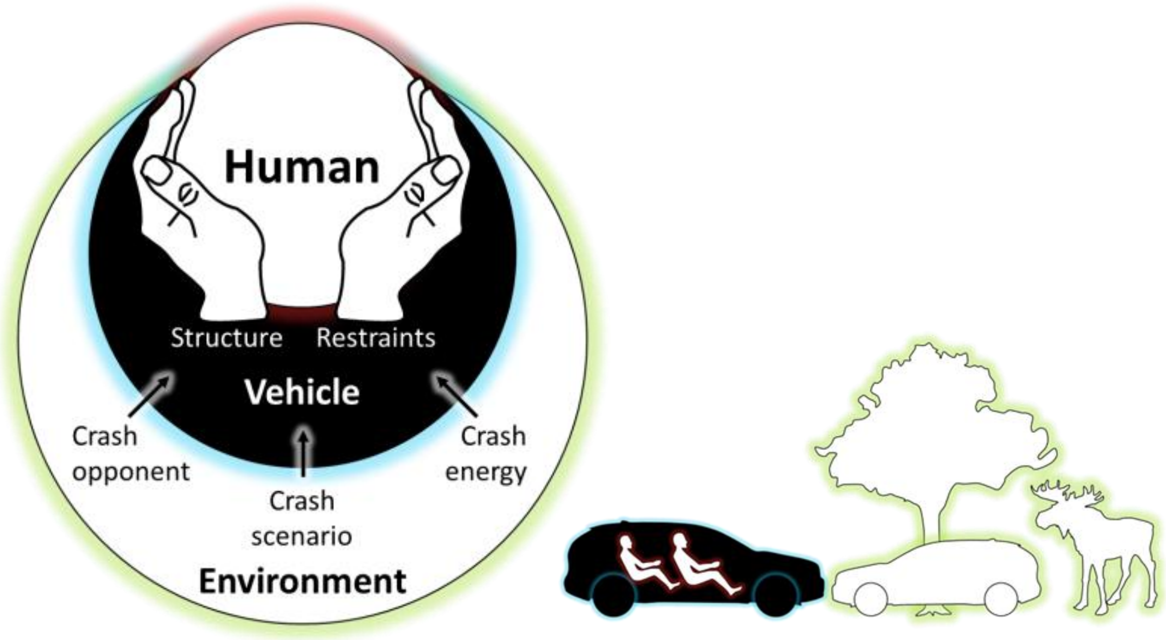


Figure 1. *Basic model of how traffic environment affects the vehicle and human occupants in crashes.*

The objective when designing passenger cars for safety should be that any crash loads transmitted to the occupant from the traffic environment via the vehicle should be within human tolerance limits. This objective should ideally be realised for all crash situations, i.e. combinations of crash opponent, scenario and energy, which the car may be subjected to during its lifetime. If this cannot be achieved, the most relevant crash situations should be considered based on the real-world occurrence and corresponding injury risk for each type of situation. In order to visualise the described traffic environment parameters, they can be plotted in separate dimensions creating a crashworthiness design volume as illustrated in Figure 2. This design volume can then be considered to contain all the crash situations that a passenger car needs to be designed for in terms of structural response, as well as restraint system performance.

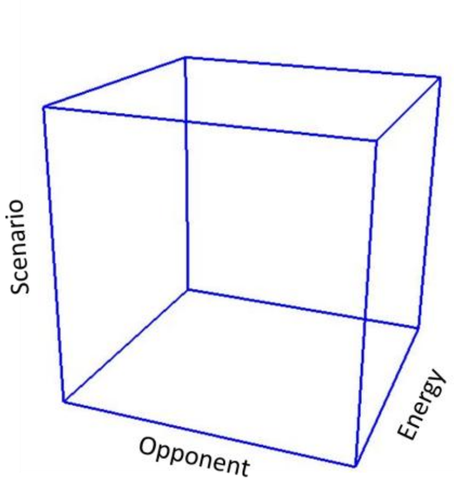


Figure 2. *Visualisation of crashworthiness design volume, i.e., three dimensions of traffic environment parameters: opponent, scenario and energy.*

The total number of crash situations is inarguably immense and considering every situation when designing a passenger car is simply not feasible. Therefore, a number of regulatory and consumer rating load cases have been developed over the years to represent the most relevant situations. These load cases, or crash setups, are evaluated by means of Computer Aided Engineering (CAE), i.e., crash simulation, in all phases of product development and by crash tests later in the development process. If these load cases are selected in an optimal way, all situations that are relevant in terms of occupant protection for a car's real-world crash performance are covered. Feedback on the actual crash performance will be provided during the car's life cycle, thus showing strengths and weaknesses in terms of real-world crash safety performance years after the car model was first introduced on the market. Any design changes that may be prompted by the real-world crash performance are thus limited to be implemented late in the product's life cycle, or to be passed down to the next generation of vehicles by which time design conditions may have changed.

An alternative approach to awaiting real-world crash data to become available is to use simulation models to predict real-world crash performance. By using crash simulation, which is a faster and less expensive method than crash testing, a large number of situations in the design volume illustrated in Figure 2 can be evaluated. However, this approach relies on model validity, i.e., if the simulation models cannot be shown to be valid for the complete evaluation range, results may be inaccurate. Therefore, increased simulation capability for assessment of real-world crash performance depends largely on improved modelling techniques such as model refinement and advanced material models including failure predictions.

Another advantage of using simulation models is that they are well suited for parameter studies. In this way, individual effects of crash scenario, opponent and energy levels can be studied. Such relationships may be harder to find in real-world crash data since many combinations of crash opponent, scenario and energy occur, and confounding factors are inevitable. Using crash testing to find such relationships is challenging in terms of time and resources. Furthermore, reconstructing and thoroughly analysing a wide range of real-world situations by crash testing often requires extraordinary crash laboratory specifications, including a full range of available crash angles and possibilities to capture film sequences from underneath vehicles.

1.2 General aim and scope

The general aim of this thesis is to contribute to passenger vehicle design methods and solutions towards eliminating road fatalities and serious injuries as described by Vision Zero (Tingvall and Haworth 1999, Johansson 2009). This contribution was attempted by using computer simulation models for use in the design process of passenger cars for improved real-world crashworthiness. As both structural response and restraint system performance represent extensive research areas, this thesis is delimited to the design and response of vehicle structures. Special focus has been directed towards robust structural response, i.e., a vehicle's ability to manage a wide range of crash situations without sudden changes of structural performance.

Furthermore, the studies that comprise this thesis have been delimited to front-to-front car-to-car crashes at initial oblique angles from -45° to +45° relative to the target vehicle heading angle in the horizontal plane as illustrated in Figure 3.

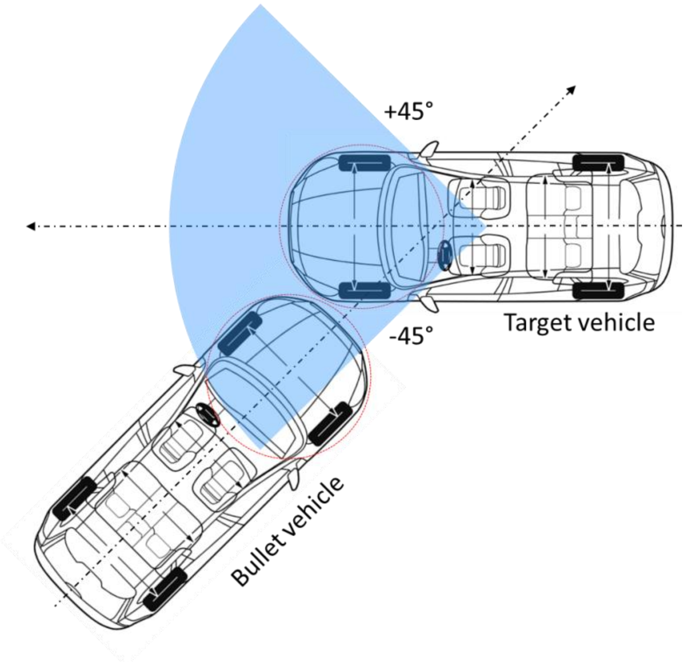


Figure 3. Definition of thesis scope with respect to oblique angle in car-to-car crashes.

The delimitation to structural aspects of passive safety is further illustrated in Table 1, where the scope of this thesis is related to crash scenarios and safety systems.

Part of the aim was to develop methods that are general in their application, i.e., they should be extendable to a wider scenario range such as side and rear crashes as outlined in Table 1. Another part of the objective was that methods should be able to support the development of restraint systems and future decisions on the balance between passive and active safety systems.

Table 1. Overview of crash scenarios and safety systems describing thesis scope limited to methods and solutions for vehicle structures and frontal crashes.

		Frontal crashes	Rear crashes	Side crashes	Rollover, run-off-road	Pedestrian protection	...
Passive safety systems	Structures	Methods Solutions					
	Restraints						
Active safety systems	Mitigation						
	Avoidance						

In order to study and discuss different degrees of horizontal overlap, a definition is needed. Since passenger cars are designed in various ways, connecting degrees of overlap to a percentage of vehicle width may not represent structural engagement. Furthermore, when oblique angles exist, measuring horizontal overlap is subjective and this measurement may vary during a crash sequence. In this thesis, the extent of engaged structures are therefore used to define horizontal overlap as illustrated in Figure 4.

- Small overlap scenarios are defined as when the frontal structures designed for energy absorption, such as longitudinal rails (also called side members) or front subframe, are not engaged.
- Moderate overlap scenarios are defined as when the frontal structures designed for energy absorption on one side of the vehicle are engaged.
- Large overlap scenarios are defined as when the frontal structures designed for energy absorption on both sides of the vehicle are at least partly engaged. If the entire front of the vehicle is engaged, this is referred to as a full-width scenario.

When analysing real-world crashes as well as crash simulations, it may be difficult to draw precise borderlines between the different categories as indicated by the gradient shading in Figure 4.

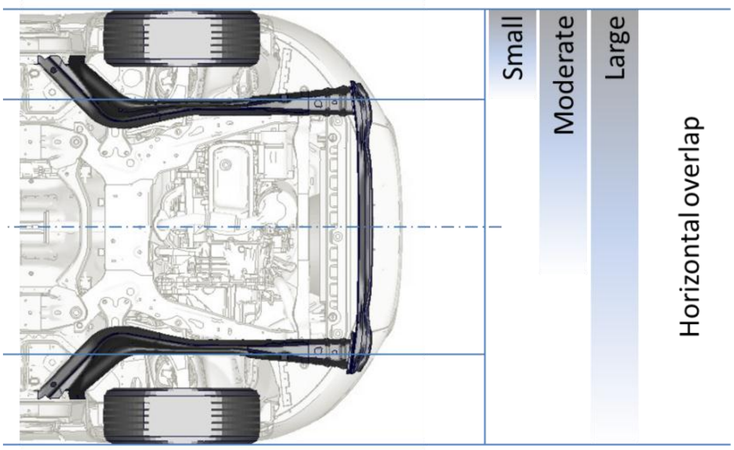


Figure 4. Definitions of small, moderate and large horizontal overlap in car-to-car frontal crashes.

1.3 Thesis outline

This thesis is structured into separate parts as illustrated in Figure 5. The first part serves as an introduction to the research area and describes the delimitations made in order to move from the general area of crash safety to the specific area of simulations of frontal car-to-car crashes. The following part describes a literature review that was conducted in order to provide an overview of previous work in the area of structural design of passenger vehicles focused on frontal car-to-car crashes. The literature review also identifies areas of priority and corresponding research gaps, leading to the objectives of this thesis. In the next part, the five appended research papers are summarised, focusing on methods and results on the specific level of simulations of frontal car-to-car crashes (Paper II applies rigid barriers to estimate energy absorption in frontal crashes). The last part of the thesis discusses the derived methods and results, and relates them to previous work, as well as possible future applications and research questions.

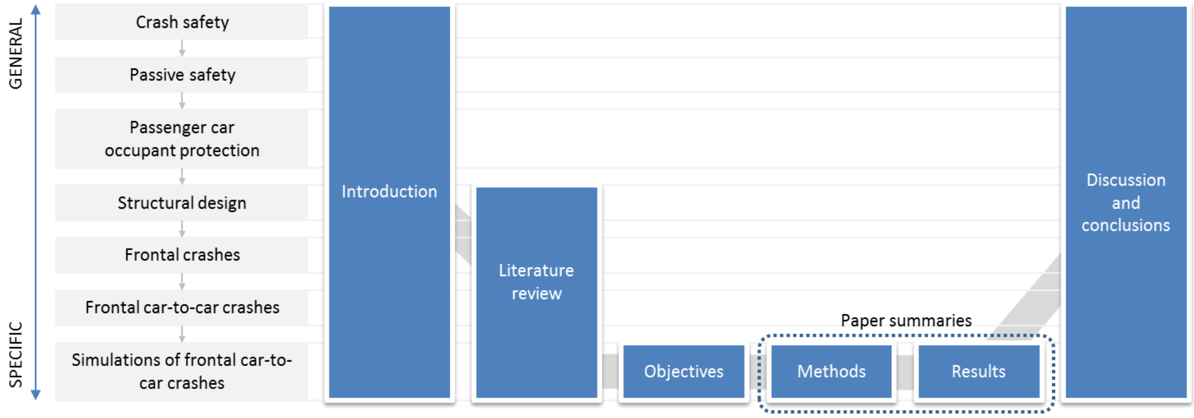


Figure 5. Thesis outline.

2 Literature review

2.1 Current status of passenger car structural design for frontal crashes

Analysing crash statistics in further detail, it is estimated that approximately half of the fatal accidents involving car occupants in Sweden occur in frontal crashes (Lindman 2012). Additional studies show the importance of frontal crashes among situations with severe and fatal injuries. Over the years 1979 to 2007, NHTSA estimated frontal crashes to account for 44% to 51% of US occupant fatalities (NHTSA 2009). The European FP7 project FIMCAR reported that frontal crashes represented 57% of UK occupant fatalities 2008-2010 and 32% of German occupant fatalities 2005-2007 (FIMCAR 2011b).

Regarding frontal crashes, the overall safety level in modern vehicles has been improved since offset deformable barrier (ODB) tests were introduced. Real-world data show that good performance in ODB rating tests correlates with reduced injury risk in traffic accidents (Farmer 2005, Kullgren et al. 2010). However, there are still situations where improvements can be made which will be described in the following sections.

A specific subset of frontal crashes is frontal car-to-car crashes. In these situations, the crash performance of frontal structures is tested in real-world situations versus other designs. European data from frontal car-to-car crashes suggests that the share of occupant fatalities occurring in frontal car-to-car crashes is 12% in Germany and 23% in the UK (FIMCAR 2011b), illustrated in Figure 6. By assuming that approximately 15% of car occupant road fatalities occur in frontal car-to-car crashes, this type of situation is estimated to account for more than 2,000 European road fatalities annually.

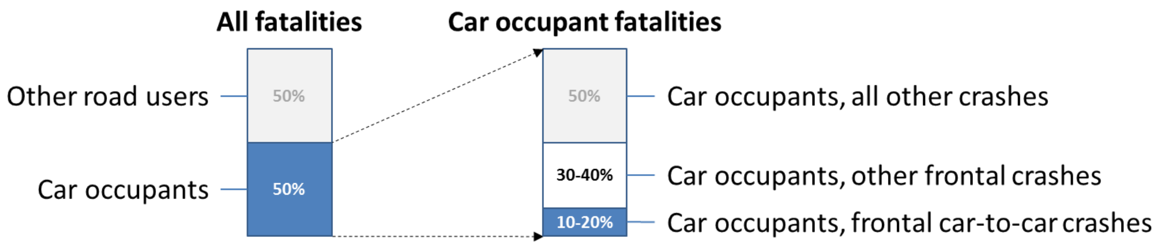


Figure 6. Approximate distribution of EU road fatalities, data from FIMCAR (2011b).

Severe injuries to occupants in frontal crashes, as defined by a Maximum Abbreviated Injury Scale (MAIS) score of three or higher (Sherwood 2009) have been shown to be strongly linked to passenger compartment intrusion. Furthermore, similar correlation with intrusion has been found for Injury Severity Scores (ISS) above 25 (Conroy et al. 2008). These findings support the need for improved car structural integrity, i.e., minimising intrusion into the passenger compartment. When structural integrity is compromised, injury risk for car occupants increase both from direct contact with intruding structures, as well as by influencing the effect of available restraint systems (Brumbelow and Zuby 2009). These findings from real-world situations propose structural integrity as a crucial performance measurement for passive safety of passenger cars.

2.2 Crashworthiness and robustness

In order to ensure that the vehicle structural response will support the occupant restraint systems in all relevant situations in the design volume outlined in Figure 2, some measurement of structural response is needed. Whether it is deceleration, intrusion or another measure, this measurement should be possible to record and visualise over the entire design volume in order to compare design options. Therefore, definitions of optimised design compared to robust design used in this thesis are required.

Consider a system where one output variable describes the system performance as a function of one input variable as illustrated in Figure 7. The objective of the system is to minimise the output variable, e.g., passenger compartment intrusion or deceleration which must be achieved for all input variable settings, e.g., horizontal overlap, within its lower and upper bounds as illustrated in Figure 7. Furthermore, all input settings must yield output below the maximum allowable response indicated by the horizontal line in Figure 7

In this example, the definition of optimal input is the input leading to minimum output. However, if this optima is associated with a small range of input variable settings, a large output variation may be the result of a minor input variation as described in further detail by Lee and Park (2001). Therefore, a more desirable input may be one resulting in a higher minimum performance but lower performance variation.

The definition of a robust solution is a solution where large variations in input result in small variations in output, as illustrated in Figure 7. If the input is considered an adjustable variable, the input should be controlled towards an optimal or robust solution. If the input variable is to be considered a random variable to be handled by the system, the design should be made in such a way that no input variable settings result in unacceptable performance as illustrated in Figure 7. In order to address the problem of robustness and unacceptable performance, a proposal for a modified design is given by the dashed curve in Figure 7. On the one hand, this design provides a higher minimum performance. On the other hand, the modified design provides a more robust system, i.e., smaller variations in the output variable when the input variable is changing. In addition, the modified design does not violate the maximum allowable response limit as indicated in Figure 7.

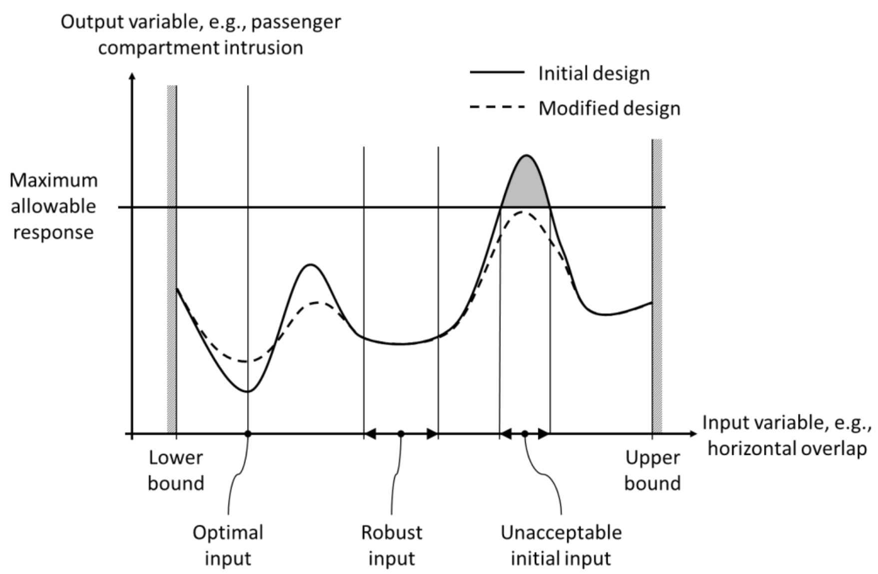


Figure 7. Schematic figure showing principles of optimisation and robustness.

As described in previously published work on this subject (Marklund and Nilsson 2001, Craig et al. 2005, Lönn et al. 2009, Lönn et al. 2010, Lönn et al. 2011), studying both structural optimisation, as well as robustness requires well-defined measurements of performance. The performance is often called response values (one output variable) or response surfaces (two or more output variables). In crashworthiness, injury mechanisms are related to passenger compartment intrusion, intrusion velocity and/or deceleration (Conroy et al. 2008, Sherwood 2009). Therefore optimisation or robustness response surfaces could possibly be based on these measurements. However, since car-to-car frontal crashes can be described as highly non-linear systems, optimisation was not attempted within in the scope of this thesis. The input variables in car-to-car crashes may be regarded as random to some extent; an appropriate objective for structural design could be the robustness of the intrusion and deceleration response of vehicles involved. This means, designing vehicle structures that exhibit small variations in structural response although variations in input as described by parameters such as oblique angle and horizontal overlap may exist.

2.3 Crash compatibility

Aiming at a robust structural response, an important aspect of occupant protection in passenger car frontal car-to-car crashes is the opponent encountered. This topic, called crash compatibility, has been thoroughly studied in various research initiatives over the years. The main findings of this work are presented in the present section, giving an outline of the complexity of the subject.

Crash compatibility is considered a combination of both self and partner protection, i.e., protecting occupants in the own vehicle as well as occupants in opponent vehicles (FIMCAR 2011a). This definition is needed since protection of occupants in one vehicle should not be achieved by reducing occupant protection in opponent vehicles.

Compatibility was considered a prioritised research area in the late 1990s and early 2000s. It was shown that light truck vehicles were over-represented in US car-to-car opponent fatality statistics and the concept of vehicle aggressivity or partner protection was commonly used to describe the problem (Gabler and Hollowell 2000, Austin 2005, Huang et al. 2011). This means that some vehicles cause a disproportionately large number of severe injuries or fatalities in opponent vehicles in car-to-car frontal crashes. Crash incompatibility and aggressivity issues were observed also in UK data (Edwards et al. 2001), French data (Delannoy and Diboine 2001), Canadian data (Fredette et al. 2008) and Japanese data (Mizuno and Kajzer 1999).

Moreover, the compatibility issue was also found in Swedish accident statistics and attempts were made to separate the effects of mass and structure by observing police reported two-car crashes (Kullgren et al. 2001). Kullgren et al. found SUVs to be considerably more aggressive than the average car. Multibody simulation models were developed as an approach to compatibility research for estimating effects of fleet changes. (Buzeman-Jewkes et al. 1999, Buzeman-Jewkes et al. 2000). Similar approaches were later attempted that underlined the usability of such simplified vehicles in order to perform a large number of simulations to provide a basic understanding of the complex system of a large car fleet (Jenefeldt and Thomson 2004, van der Zweep et al. 2005, Watanabe et al. 2005). Other researchers used FE models and crash testing to develop front structure concepts with multiple load paths in order to address compatibility issues (Fujii et al. 2003, Saito et al. 2003). Attempts were also made to make car consumers increasingly aware of the safety issues related to vehicle crashes between vehicles of different size and weight (The Insurance Institute for Highway Safety 2005, The Insurance Institute for Highway Safety 2009)

Starting in 2003, a European consortium consisting of safety research institutes, authorities and vehicle manufacturers joined forces in the project VC-Compat to find solutions to crash compatibility issues. In the final VC-Compat technical report (VC-Compat 2007), it was estimated that approximately 1,000 lives could be saved annually on European roads by improved crash compatibility. It was identified that structural interaction and compartment strength are key issues to be addressed in order to improve crash compatibility. However, no consensus could be reached on standardised test procedures in order to introduce legislative or consumer rating tests for enhanced crash compatibility.

In order to advance further towards better crash compatibility in frontal car-to-car crashes, VC-Compat was followed by the 2010-2012 research programme, Frontal Impact and Compatibility Research (FIMCAR). The starting point of FIMCAR was that crash compatibility consists of both self and partner protection and the consortium finally reached a recommendation to introduce a full-width test procedure for Europe based on priority of structural interaction and restraint system performance (FIMCAR 2011e).

The importance of structural interaction appears to be a common conclusion in many of the studies conducted on crash compatibility. In the United States, a voluntary agreement was initiated by the Alliance of Automobile Manufacturers in 2003 (Barbat 2005). This agreement was based on placing frontal energy absorbing structures in a common interaction zone at 16 to 20 inches above ground level. Later studies from NHTSA (Greenwell 2012) and IIHS (Baker et al. 2008, Teoh and Nolan 2012) all indicate improvements to crash compatibility after the agreement on alignment of vehicle front structures had come into effect.

The results so far from the voluntary agreement suggest that a relatively simple target of a common interaction zone has been effective in addressing crash incompatibility. However, developing test procedures using crash barriers to objectively measure appropriate structural interaction frontal force levels has proved to be difficult.

One approach to measuring structural interaction properties of a vehicle front structure is to measure the height of force (HOF) time history from a full-width barrier. Alternatively, the average height of force (AHOF) has been proposed as an average over a certain evaluation period in time. The applicability of HOF and AHOF were investigated thoroughly by researchers from the United States (Verma et al. 2004, Subramaniam et al. 2007, Nusholtz et al. 2009, Brewer et al. 2011) as well as Japan (Mizuno et al. 2005, Watanabe et al. 2005, Hirayama et al. 2007, Uwai et al. 2007, Yonezawa et al. 2008). Some criticism was raised regarding the reproducibility of AHOF and possible velocity dependence. Regardless of evaluation method, the height at which forces are transmitted appears to be of great importance to car-to-car crash compatibility. Vertical misalignment has been shown to be unbeneficial for energy absorption and deformation modes which may increase injury risk to occupants in both vehicles involved in frontal car-to-car crashes (Baker et al. 2008, Mizuno and Arai 2010).

A second approach suggested is to use the deformation pattern of offset deformable barriers to assess structural interaction. Aiming at increasing the test severity for small vehicles and avoiding bottoming-out of the deformable barrier honeycomb block, the Progressive Deformable Barrier (PDB) was developed for offset crash tests (Delannoy and Diboine 2001, Delannoy et al. 2005, Delannoy et al. 2007). Additional studies were conducted regarding the feasibility of attaching the PDB to a trolley, creating a so-called Moving Deformable Barrier or MPDB (Schram and Versmissen 2007, Versmissen et al. 2007). The MPDB has the potential to further increase the crash severity for light cars which leads to discussions regarding the initial velocity and trolley mass setup for this specific load case. If a MPDB test is always run with a fixed trolley mass and initial velocities as proposed by FIMCAR (FIMCAR 2011d), this test method could potentially decrease the self-protection of heavier vehicles since the crash severity will be reduced for this type of cars. The PDB was further studied by NHTSA (Meyerson et al. 2009) where the PDB was once more proposed as a tool for assessing partner protection. The PDB has been proposed to be introduced into regulation as an update to the UNECE R94 regulation (Chauvel et al. 2011). The crash compatibility assessment potential of the PDB was recognised by FIMCAR, but could not be recommended for regulatory testing since barrier evaluation metrics were identified to require further development and validation (FIMCAR 2011c).

A third approach is a full-width deformable barrier (FWDB) that could potentially replace a full-width rigid barrier (FWRB) in tests for high deceleration response (Edwards et al. 2003a, Edwards et al. 2003b, Edwards et al. 2007, Edwards 2009). By assessing the barrier face deformation, structural interaction may also be assessed. Additional studies were performed by Arai et al. (2007) which supported the FWDB as a tool for assessing structural interaction. Similarly to the PDB, FIMCAR found that although the FWDB could potentially be used for assessment of structural interaction, these assessment metrics needed further development (FIMCAR 2011e). FIMCAR however recommended the FWDB to replace the FWRB in regulatory testing mainly based on indications that the FWDB yields an occupant compartment deceleration response more representative of real-world situations in the initial stage of the crash compared to the FWRB (FIMCAR 2011e).

Once structural interaction is improved, the next level of improved crash compatibility is believed to be stiffness matching, i.e., harmonising frontal force levels for dissimilar vehicle mass categories. One approach to this could be to base frontal force levels on average vehicle mass rather than the actual vehicle mass. Based on FE simulations of frontal car-to-car crashes, it has been suggested that matching the stiffness of a lighter vehicle up to the level of a 30% heavier car may only have minor effects on the crash pulse shape (Volvo Car Corporation et al. 2010). It has been shown however, that when stiffness of a lighter vehicle is matched to a heavier crash opponent, dummy injury values in car-to-barrier tests are increased significantly (Watanabe et al. 2005).

Matching the frontal stiffness of a heavier vehicle down to the level of a lighter vehicle requires extended front structure deformation length to maintain energy absorption for self-protection in the heavier vehicle. Without structure extension, such a design change could reduce intrusion in the opponent car below a certain impact velocity, but increase intrusion at higher impact velocities (Hirayama et al. 2007). Subramaniam et al. (2007) explored the effect of modifying the initial stiffness of a light truck vehicle to match that of a car crash opponent, and increasing the stiffness in the later phases of crush to compensate for the lost energy absorption. The result of this modification was a deteriorated car-to-barrier performance in terms of intrusion as well as deceleration and dummy response. It was recommended that a wide range of crashes should be evaluated for effects on occupant protection before any stiffness matching regulations are implemented.

A concrete proposal on how to implement stiffness matching of frontal structures in passenger vehicles was presented by NHTSA and called KW400 (Patel et al. 2007). This metric was established as an attempt to measure the frontal stiffness during the first 400 mm of deformation in a FWRB crash, and was used for stiffness matching studies (Hirayama et al. 2007, Subramaniam et al. 2007, Nusholtz et al. 2009). One important issue that was raised was the sensitivity of KW400 to the starting time of the signals (also known as time zero). Since KW400 is calculated from the barrier force starting at 25 mm of vehicle displacement, the initial vehicle-to-barrier contact becomes an important parameter, rewarding a low initial barrier force response.

It has been noted that improved passenger compartment integrity does not necessarily mean higher stiffness of the front structure (Lund and Nolan 2003). Overall, the studies performed on stiffness matching underline the balance between self-protection and partner protection. Given the available front deformation distance, it appears inevitable to match frontal force levels of frontal structures without affecting this balance.

Adding to the complexity of the subject, real-world data suggest that incompatibility in frontal crashes can exist even if vehicles are identical. In FIMCAR (2011a), an example of this from the Great Britain Cooperative Crash Injury Study (CCIS) was given. In this case, two vehicles of the same make and model were involved in a head-on crash at approximately 50% overlap. As illustrated in Table 2, the two cars exhibited significantly different structural responses, with up to seven times greater dashboard intrusion in one of the cars which was also reflected in the injuries sustained by the drivers.

Table 2. Overview of the outcome in a head-on crash involving two cars of same model. Adapted from FIMCAR (2011a).

		
Model year	2002	2001
Kerb mass	1,423 kg	1,384 kg
Overlap	51%	50%
Equivalent test speed based on deformation	26 km/h	46 km/h
Dashboard intrusion	190 mm	900 mm
Footwell intrusion	170 mm	1,180 mm
Driver injury level	MAIS 2	MAIS 5

The conclusion from studies of previous work within the research area of crash compatibility between passenger vehicles in frontal crashes is that there is a range of factors that affect structural response and thereby occupant injury risk. Looking solely at real-world crash data appears to be incomprehensive for understanding the mechanisms that affect structural integrity and robustness. Crash simulation could be one tool to isolate unbalance from crash scenario, as attempted using modified public domain models (Thomson et al. 2008).

In line with this, detailed efforts to describe crash incompatibility in the case of dissimilar vehicles will not be attempted in this thesis. Instead the incompatibility that arises from the crash scenario will be explored. In order to protect occupants in frontal crashes, vehicles should be developed to provide a robust and predictable structural response in frontal crashes independent of crash opponent.

2.4 Small overlap situations

Another key issue for the design of vehicle structures for real-world crashworthiness in frontal crashes are situations where structures intended for energy absorption are not engaged. One such situation occurs when the front of a vehicle is loaded outboard of the front structure, often called severe frontal collision with partial overlap (Planath et al. 1993) or simply small overlap crash (Lindquist et al. 2004), as illustrated in Figure 4.

The real-world significance of small overlap crashes is not a new phenomenon. The importance of designing vehicles for this load case was described by Planath et al. (1993) where a test method with 20 to 40% horizontal overlap against a fixed rigid barrier at initial velocities up to 65 km/h was proposed. Accident data from the early 1990s suggested that the percentage of moderately and severely injured drivers was higher in crashes with an overlap below 30% than in crashes with an overlap of more than 30%. (Kullgren and Ydenius 1998). Further indications of the importance of small overlap crashes was presented by Lindquist et al. (2004), where small overlap crashes accounted for 48% of the fatalities to belted occupants in a data set of frontal crashes in Sweden.

Small overlap situations were given renewed focus when the IIHS highlighted this type of situation in the early 2010s. When observing real-world frontal crashes involving vehicles awarded with good ratings in the IIHS test programme for frontal crash protection (Brumbelow and Zuby 2009), small overlap crashes was one type of scenario where occupants sustained severe injuries. The strong link between occupant compartment intrusion and injury severity in small overlap crashes was presented in a later study by the IIHS (Sherwood 2009). This lead to the development of an IIHS small overlap rigid barrier load case, described in detail by Sherwood et al. (2013). The IIHS also demonstrated that the test method shows acceptable repeatability, indicating that vehicles with poor structural performance in this load case show the largest test-to-test variations in terms of intrusion (Mueller et al. 2013).

NHTSA also suggested that small overlap crashes should be a priority area for future research (Rudd et al. 2009), followed by an additional study where it was demonstrated that small overlap crashes frequently produce oblique kinematics, and the interaction along the side of the struck vehicle increases the risk for injuries from outboard components such as the door and A-pillar (Rudd et al. 2011).

Several studies have thus indicated that these situations are critical for reducing severe and fatal injuries. There are, however, studies suggesting that “the small overlap is at worst a moderately dangerous crash in the overall scheme of frontal crashes” (Scullion et al. 2010). In a later study (Kühn et al. 2013), the German Insurers Accident Research supported the IIHS finding that approximately 25% of frontal crashes can be characterised as small overlap situations. In this German dataset, small overlap crashes were found to represent a small number of fatalities but a large number of serious (AIS2+) injuries to the lower extremities.

Although the representativeness of the IIHS small overlap barrier crash test appears to be a subject for debate, real-world data suggest that small overlap situations should not be neglected when striving for a vision of zero fatalities and serious injuries. Further support for a small overlap barrier load case to represent small overlap car-to-car scenarios was given by Jakobsson et al. (2013a) combined with an overview of vehicle design changes for small overlap situations (Jakobsson et al. 2013b).

2.5 Large overlap situations

In addition to crash compatibility issues and small overlap crashes, there appears to be issues related to the crash pulse or restraint system in frontal crashes with modern cars. In a US study on the types of frontal crashes that cause serious injuries and fatalities to belted front-seat occupants in passenger cars, a considerable portion of serious injuries occur in frontal crashes despite good structural integrity (Brumbelow and Zuby 2009). In that study of cars that had been awarded good ratings in the IIHS frontal moderate (40%) overlap test, it was shown that many belted occupants still sustain severe injuries in frontal crashes without significant vehicle passenger compartment intrusion. This means that even without intrusion, occupants may be injured from contact with restraint systems or car interior, i.e., injury mechanisms are related to the crash pulse rather than intrusion.

Similar findings were presented in the European research project FIMCAR (2011a), where datasets of frontal crashes involving R94-compliant vehicles from Great Britain (Cooperative Crash Injury Study, CCIS) and Germany (German In-Depth Accident Study, GIDAS) were analysed. The study showed that approximately 40% of MAIS 2+ injuries and 30% of fatal injuries suffered by occupants occurred in crashes with more than 75% frontal overlap (compare to Figure 4), and it was suggested that compartment intrusion may not be the direct cause of injury. Besides improving the functionality and robustness of restraint systems, injuries related to the crash pulse can potentially be addressed by the vehicle front structural response.

Current vehicle structures may exhibit stiffer response in frontal crashes compared to older vehicles, especially in the late phases of the crash pulse as a direct effect of improvements in terms of intrusion (Nolan and Lund 2001, Samaha et al. 2010). It is therefore important to balance high-deceleration load cases with offset load cases with significantly different crash pulse shapes and structural loading (FIMCAR 2011a).

2.6 Adaptive structures

Adaptive structures could be one way to optimise the structural response in the wide range of crash scenarios that passenger vehicles encounter. In frontal crashes, it has been suggested that adaptive structures can be used in order to affect the deceleration response. Witteman and Kriens (2001) followed by Witteman (2005) suggested "high-low-high" deceleration pulses to be optimal based on occupant response simulations of crashes with velocity change of 56 km/h or greater. These deceleration pulses were proposed to be accomplished by friction forces applied to steel cables that had the additional benefit of being able to transfer loads from the struck side of a vehicle to the non-struck side.

An alternative approach to achieving "high-low-high" deceleration pulses in a passenger car has been proposed (Motozawa and Kamei 2000, Motozawa et al. 2003), where axial buckling is followed by bending of the main energy absorbing members. A practical solution for the required operational volume for such a system was, however, not presented.

Pipkorn et al. (2005) recommended implementing variable crush force in passenger cars by pressurising vehicle longitudinal frontal members. Since the additional volume required for the pressurised frontal members to function may be minor, this solution may be more efficient in terms of packaging space than the concept proposed by Motozawa et al. (2003). Any solution as to how the Pipkorn et al. proposal would be applied to production vehicles was not presented, although the mass-reducing potential based on increased force levels from pressure in such members was highlighted. In a subsequent study, Pipkorn and Kullgren (2009) again showed that pressurising thin-walled tubular structures can significantly increase the crush force and energy absorption and considerably reduce occupant injury risk as measured by HIII dummy readings. Furthermore, a comprehensive review on adaptive vehicle structures was made by TRL (Thompson et al. 2007), where altering the frontal force level was identified as one of the key principles for adaptive structures.

Other applications of adaptive structures were proposed by Pipkorn et al. (2007) such as attaching an external inflatable airbag to the front structure of an SUV. This was demonstrated to increase structural interaction by creating a lower load path into the sill of a passenger car in side crashes where the SUV is the bullet vehicle. Two types of adaptive front structures, fixed and extendable, were investigated using simplified, two-dimensional, simulation models by Elmarakbi and Zu (2006). The study predicted that improvements, in terms of injury risk, related to both intrusion and deceleration could be accomplished by adaptive front structures.

Pyrotechnically controlling the stiffness of load-carrying front structures of passenger cars in front-to-side crashes were investigated by Ostrowski (2007). In that study, an adaptive structure was shown to decrease the front-end crash stiffness of the bullet vehicle and to extend the crushing distance when needed. Another thorough review on adaptive structures for improved crashworthiness was made by Khattab (2011), where extendable add-on energy absorbers were also suggested. Additionally, Pipkorn et al. (2011) suggested further applications of adaptive structures in passenger cars. In that study, the balance between forward vision and A-pillar load capacity was suggested to be improved by introducing expandable A-pillars.

3 Objectives

The general aim of this thesis is, as previously described, to investigate novel methods based on computer simulation models that can be used in the design process of passenger cars for robust real-world crashworthiness. Supporting Vision Zero through vehicle design requires a holistic view on safety, beyond the load cases defined by legal requirements and consumer rating programmes. Given the level of reliability that crash simulation models have reached through constant development over several decades, these models today represent valuable tools for understanding and proposing countermeasures for the structural challenges seen in real-world crash situations.

One specific objective of this thesis was therefore to develop tools for engineering of safe future passenger vehicles. These tools should be applicable for addressing crash compatibility, small overlap situations and large overlap situations with focus on robust structural response. A second specific objective of this thesis was that the developed tools should be used to explore the applicability of adaptive front structures for crash severity reduction in frontal car-to-car crashes.

4 Paper summaries

The individual papers are linked by their connection to real-world data as illustrated in Figure 8. All five appended papers are summarised in the following section and their relative coherence is explained here.

Two major crashworthiness issues were found in literature regarding real-world frontal car-to-car scenarios where injuries occur in modern vehicles. The first issue concerns small overlap situations, where intrusion appears to be the main cause of injuries. The second concerns large overlap scenarios where intrusion is not necessarily the major cause of injuries but rather the deceleration of the passenger compartment.

Based on these two problems seen in real-world crash data, the work was divided into two paths – one for large overlap situations and one for small overlap situations. Paper I served as an initial study of structural adaptivity in frontal crashes and Paper II followed up on those findings by exploring effects on the crash pulse with a public domain FE model. Paper III laid a foundation for a methodology to be used for structural robustness in frontal crashes regardless of scenario. Paper IV used the methodology from Paper III to examine and classify small overlap situations by validating the FE model against full-scale crash tests. To finally bring both halves of the thesis together, Paper V used parts of the methodology from Paper III to set up a large number of crash simulations to explore a specific concept for structural adaptivity, a detachable front subframe.

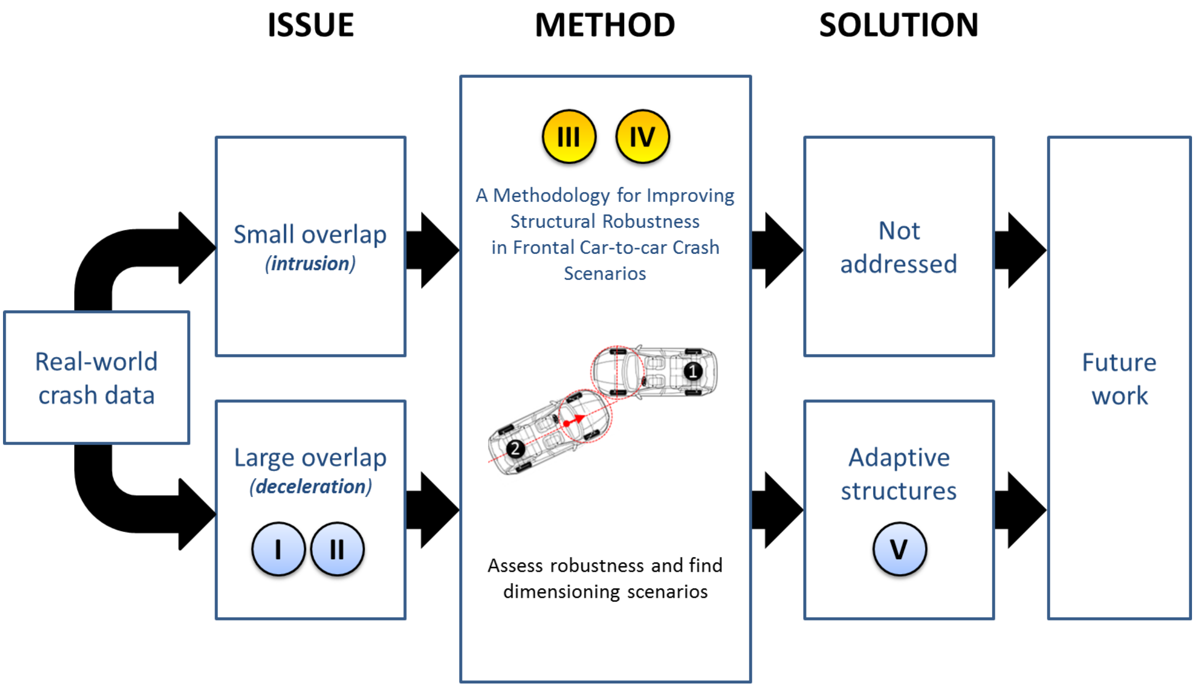


Figure 8. Overview of study coherency with appended papers in roman numerals.

The studies conducted were divided according to the respective issue seen in real-world crash data and their nature, i.e., being a method or a proposed solution. For small overlap scenarios, any specific solutions to address the issues seen in real-world crashes were not proposed. However, for the issues with larger overlap, i.e., deceleration-related injuries, adaptive frontal structures were proposed as a possible solution that could potentially address this type of situation.

All five papers can be related to the crashworthiness design volume in Figure 2. This is illustrated in Figure 9 where each point represents a crash situation evaluated by means of simulation. Figure 9 shows that only Paper I attempts to assess the effect of the crash opponent, whereas Papers II to V are focused on crash scenario or crash energy. Paper II applies rigid barrier simulations for estimation of energy absorption relevant to car-to-car crashes with satisfactory structural interaction.

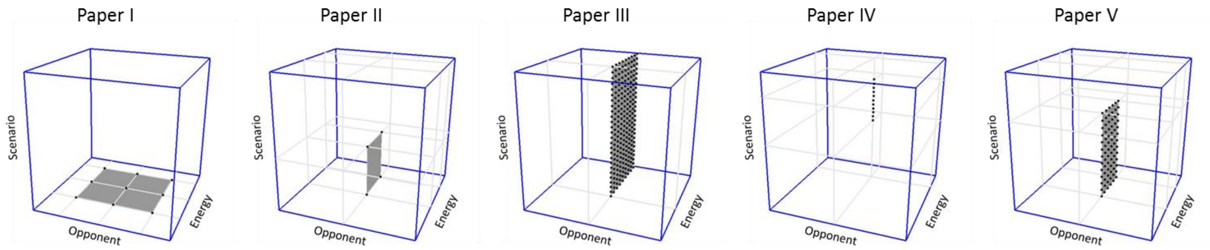


Figure 9. *Overview of which crash environment parameters were addressed in the appended papers. Each point represents an evaluated crash situation.*

A central concept in Papers III to V is crash pulse severity metrics. These are based on acceleration signals of the sill structures close to the B-pillars. These signals were used to estimate the crash pulse severity based on two simplified models, the Volvo Pulse Index, VPI (ISO 2012) and the Occupant Load Criterion, OLC (Stein et al. 2011). Both models are attempts of generically measuring the restraint forces that the driver is subjected to during a crash, based on deceleration only. Each model uses the occupant displacement relative to the vehicle in the longitudinal direction. Furthermore, both models assume an initial phase of free-flying motion without any occupant deceleration at relative displacement less than 30 mm for VPI and 65 mm for OLC, as illustrated in Figure 10. However, the model responses following the initial slack represent fundamentally different assumptions. VPI assumes a linearly increasing occupant deceleration of 0.25 g/mm of relative displacement, without any limitation on occupant deceleration or relative displacement. The OLC instead assumes a maximum relative displacement of 300 mm and a constant occupant deceleration up to this point. This means that the OLC model assumes a perfectly adaptive restraint system that will always utilise the available interior distance. The VPI model, on the other hand, simulates a non-adaptive restraint system based on chest decelerations measured in crash test dummies in physical tests.

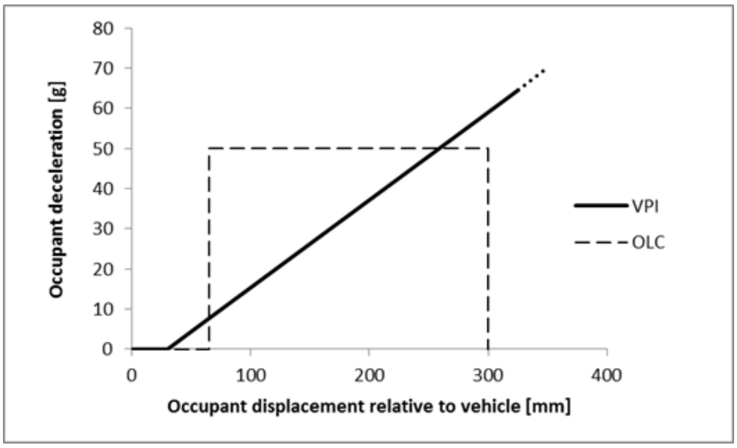
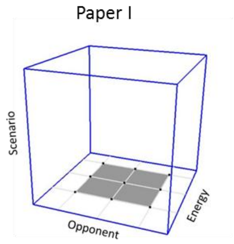


Figure 10. *Characteristics of the crash severity indicators VPI and OLC.*
Occupant deceleration plotted vs. occupant displacement relative to vehicle.



4.1 Summary of Paper I

4.1.1 Introduction

In-depth studies of crash pulses from real-world frontal crashes have shown a correlation between acceleration levels and injury risk, indicating that high vehicle acceleration during frontal crashes increases the risk of long-term consequences for the occupants. The only way for a vehicle manufacturer to affect the crash pulse is to change the characteristics of the energy absorbing parts of the car. Consumer tests such as Euro-NCAP have prompted car manufacturers to design vehicles with high intrusion resistance. However, in low severity crashes, these structures could potentially subject car occupants to higher accelerations than what would be possible if the stiffness could be adapted to crash severity. Suggestions to design adaptable frontal structures have been found in the literature. This study has sought to find guidelines of how to select deformation characteristics that lead to less harmful acceleration pulses during low-speed crashes while maintaining intrusion resistance at higher crash velocities in frontal crashes.

4.1.2 Method

Car-to-car crashes were simulated using mass-spring models assuming linear frontal stiffness. Typical values for vehicle frontal stiffness were chosen after separating the car fleet into two categories, where one category consisted of cars with a test weight below 2000 kg and the other category consisted of cars with a test weight above 2000 kg. Crash test data was used to approximate frontal stiffness.

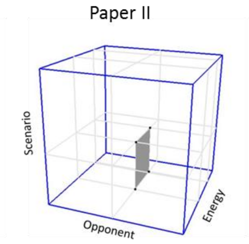
To simulate full-frontal crashes between cars of dissimilar mass or frontal stiffness, three vehicle classes were defined. Using all combinations of car classes and three closing velocities ranging from 40 to 120 km/h resulted in a total of eighteen simulations that were run with the baseline configuration, i.e., constant stiffness. The results of these simulations in terms of maximum deceleration were then compared to the results using an adaptive deformation system, where the frontal stiffness was minimised for each level of kinetic energy.

4.1.3 Results

All peak acceleration values were decreased as a result of the adaptive system. Peak deceleration values were on average reduced by 14% at the highest closing velocity of 120 km/h. When the closing velocity was decreased to 80 km/h, the corresponding reduction was 43% and at 40 km/h, the average peak value was reduced by as much as 73%. It was observed that at the lowest closing velocity, the calculated adaptive stiffness was less than 10% of the original value.

4.1.4 Discussion

Systems including an adaptive frontal stiffness could require pre-crash sensors that can provide information both regarding the state of the own vehicle, as well as the collision object. Structural adaptivity could be accomplished by decreasing or increasing the internal force levels of the deforming vehicle parts. This should be executed in a manner that vehicle occupants are guaranteed an acceptable level of protection in case of undesired system response. It was suggested that a fully-developed adaptive system would have the potential to decrease deceleration levels in low severity accidents, as well as increasing the deformation energy absorption in high velocity crashes.



4.2 Summary of Paper II

4.2.1 Introduction

In passenger-car crashes, frontal crashes are the most frequent accident type. Modern cars are able to maintain structural integrity even in high velocity crashes and thereby reducing the risk of severe and fatal injuries. Indications of safer cars were found in crash statistics in terms of lower injury risk to all body regions, with one alarming exception: injuries to the neck. Studies of crash pulse recorder data have suggested mean deceleration as a candidate crash-severity measure for AIS1 neck injuries.

It has been suggested that greater passenger compartment integrity may have made vehicles less forgiving in terms of deceleration-related injuries such as long-term neck injuries. To reduce harmful crash pulses caused by stiff frontal structures, it is suggested that the optimal frontal structure stiffness should be adapted to the crash situation. The logical approach to achieve lower deceleration is to weaken the engaged structural members. By altering the structural deformation characteristics in suitable locations of a passenger car front, the response could be made sufficiently supple for a low-velocity crash while the front-end stiffness is maintained or increased in a high-velocity crash.

4.2.2 Method

A public domain full-vehicle LS-DYNA FE model of the passenger car model Geo Metro was used to simulate full-width crash and offset crash with a rigid barrier that covered 40% of the maximum vehicle width. In four preliminary simulations, the longitudinal rails were identified to represent the largest portion of absorbed internal energy for impact velocities of both 32 km/h and 56 km/h.

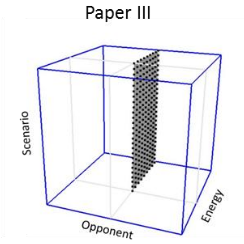
To study the effect on crash pulse characteristics and the possible implications of structures with alternating structural strength, the material of the longitudinal rails was given three levels in subsequent simulations at a range of initial velocities chosen from 16, 32, 48 and 64 km/h. The passenger compartment was modelled in two variants, a rigid compartment and the original deformable compartment.

4.2.3 Results

Minimising passenger compartment intrusion, assessed by a rigid compartment model, will potentially reduce the crash pulse duration and thus increase mean deceleration. The effect of front longitudinal members crush strength on the crash pulse depends largely on the geometric constraints in the engine compartment and the kinetic energy to be absorbed in a crash. Reducing the yield stress of longitudinal members can only reduce the peak deceleration if this peak is associated with structural deformation and not engine contact with a stiff passenger compartment.

4.2.4 Discussion

To design adaptive frontal structures that have a significant effect on the crash pulse, strategies for affecting the global load paths must be investigated. This study suggests that changing the strength of the most significant energy absorbing structural members would only affect the crash pulse to a limited extent.



4.3 Summary of Paper III

4.3.1 Introduction

From data collected in real-world frontal crashes involving new vehicles, it has been suggested that consumer rating crash tests have encouraged improvements to passenger vehicle structural crashworthiness. However, there still seems to be room for further improvement in so-called small overlap conditions, i.e., where vehicles are involved in frontal crashes without engaging the main frontal crash absorbing structures.

It has also been shown that the available coding standards for crush damage in passenger vehicle crashes do not always capture differences in crash configuration, making detailed parameter analyses of car-to-car crash configurations a difficult task. Additional approaches such as computer simulation are therefore needed for understanding how different crash scenarios are linked to vehicle structural performance and possibly occupant injury risk.

Based on these findings from previous studies and real-world crash data, it is suggested that improved crash simulation techniques should be developed in order to better understand the structural mechanisms that lead to large passenger compartment intrusion or deceleration in frontal car-to-car crash scenarios. The aim of this particular study was therefore to develop a methodology for identifying dimensioning frontal car-to-car crash scenarios by assessing crash configuration parameters that influence structural response.

4.3.2 Method

A full-vehicle FE model was validated in terms of intrusion and deceleration response in frontal crashes and used to establish a car-to-car crash simulation model with two identical passenger cars. The car-to-car FE model was employed for a parameter study including 378 simulations on how the crash setup affects passenger compartment intrusion and deceleration. Based on this output, a set of scenarios with outstanding properties in terms of structural response were defined and considered candidates for crash scenarios that should be used for dimensioning of car structures.

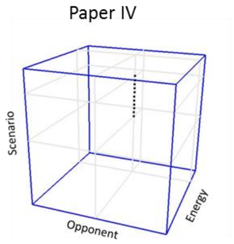
Since the FE model used for the parameter study cannot be validated by physical testing in all of the scenarios defined by the simulation matrix, a few of the most noteworthy crash setups have been selected for further validation work as they fell outside the scope of the study. By improving numerical robustness and validity of FE models, the methodology would be suitable for comprising part of a comprehensive toolbox for ensuring robust response of vehicle structures.

4.3.3 Results

The intrusion area that displayed the best correlation with other intrusion areas was the central A-pillar intrusion which was therefore suggested to represent the overall intrusion levels in each car. At 15° oblique angle and 1,200 mm lateral offset scenarios, this intrusion was more than three times greater in one of the identical cars. The greatest crash pulse severity was found at scenarios around 300 mm lateral offset and 0 or 5° oblique angle.

4.3.4 Discussion

The purpose of the methodology presented in this study was to establish a tool for structural robustness in the development process of passenger vehicles. The proposed compatibility domain lends itself to visualising structural differences in car-to-car crashes regardless of the vehicles involved. In an extended application, this methodology could be used to compare the relative importance of different aspects of incompatibility, e.g., studying when a structural advantage is cancelled by an unbeneficial car-to-car crash scenario.



4.4 Summary of Paper IV

4.4.1 Introduction

It is estimated that approximately half of the European Union road transportation fatalities are occupants in passenger cars, and that about half of these occur in head-on crashes. Consumer rating programmes using ODBs performed in both Europe and the United States have encouraged car designs with improved passenger compartment integrity in order to increase self-protection. However, fatalities and severe injuries still occur and it is therefore important to study these types of crashes. Data from Europe as well as the United States suggest situations were defined as situations where front structures designed for energy absorption are not engaged as major load paths, often called small overlap frontal crashes.

In addition to designing vehicles for self-protection, consideration should also be made for partner protection. Incompatibility in two-vehicle frontal crashes is characterised by differences in injury risk to occupants in one vehicle compared to the other vehicle. These differences can be caused by both occupant and vehicle dissimilarities, but are normally discussed in terms of vehicle mass, geometry and stiffness. Incompatibility has typically not been used to describe crash situations in cases where both vehicles and occupants are identical. In Paper III, scenarios with large differences in terms of passenger compartment intrusion in one car compared to the other were found around 15° oblique impact angle combined with small overlap of car front ends. These results needed to be validated and it was therefore decided that model validation by comparing to physical crash tests was required.

4.4.2 Method

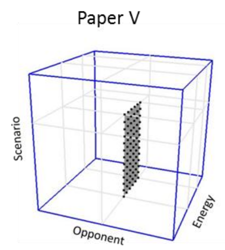
Two full-scale crash tests were performed in order to validate the crash simulation model, a 15° oblique angle car-to-car setup, and a rigid barrier test overlapping 25% of the car. During the analysis of these two crash tests in comparison to simulation results, three major areas were identified where modelling improvements were required for increased model validity: front subframe bushings, rim failure and tyre separation. A parameter study was then performed in order to describe oblique small overlap car-to-car crashes.

4.4.3 Results

Five separate crash categories were distinguished in the simulations. Category A was defined by at least one of the frontal structures being deformed and thus contributing to energy absorption in the crash. Category B refers to the set of crashes where the wheels overlap each other, creating a locking phenomenon which leads to substantial deformations of one of the identical car models. Categories C and D included situations where the wheel of one car becomes detached and is pushed along the sill of the same car, leading to un-robust response in terms of intrusion. Category E comprised sideswipe situations, with a minimal influence on the struck vehicle front structure and A-pillar. The combination of large intrusions and large lateral velocity change was only found for the Category B crashes.

4.4.4 Discussion

Predicting rim failure proved to be difficult since a substantial degree of variation is involved in the physical tests and the borderlines between crash categories do therefore not represent exact limits. If detachment of the front wheels cannot be achieved in a predictable way, intrusion may vary substantially. Previous studies have identified that severe injuries often occur in situations without significant intrusion, suggesting that further development of restraint systems in combination with improving the deformation modes of frontal structures may be needed.



4.5 Summary of Paper V

4.5.1 Introduction

Studies in Europe as well as the United States into the real-world performance of vehicles have shown that many belted occupants still sustain severe injuries in frontal crashes without significant vehicle passenger compartment intrusion. Besides improving the functionality and robustness of restraint systems, injuries related to the crash pulse can potentially be addressed by the vehicle front structural response. It has been suggested that adaptive structures can be used in order to affect the deceleration response in frontal crashes. The front engine subframe has been identified as a major load path in frontal crashes, important both for self-protection and crash compatibility. Equipping vehicles with an adaptive detachable front subframe has the potential to benefit the overall real-world crash performance. The aim of this study was therefore to quantify the effect an adaptive detachable front subframe has on occupant loading in car-to-car frontal crashes in a range of lateral offset distances and closing velocity levels.

4.5.2 Method

A full vehicle model was simplified by removing the majority of the structural components from a plane rear of the A-pillars in order to perform a large number of simulations. It was shown that the deceleration response of the simplified model was similar to the original simulation model at both full overlap and approximately 50% overlap with identical vehicles. The simplified crash model was also shown to represent the crash pulse shape of vehicles with similar stopping distance in physical crash tests. A simulation matrix was established to study the effect of the vehicle deceleration pulse on two simplified crash severity indicators called Volvo Pulse Index (VPI) and Occupant Load Criterion (OLC).

4.5.3 Results

A high level of correlation was found between longitudinal velocity change and both crash severity indicators, VPI and OLC, for lateral offset up to and including 1,000 mm. Using this relationship, an equivalent velocity change reduction (EVCR) was calculated, indicating the required velocity change reduction in order to achieve the same reduction in crash severity indicators in the base, passive model, as was achieved by actively detaching the subframe. The greatest reduction in crash severity gained by releasing the subframe was predicted to be equivalent to a 44% ΔV_x reduction for the VPI model, and 31% for the OLC model. As an average of the considered crash scenarios, the results based on the VPI model suggest 28% relative EVCR compared to 18% for the OLC model.

4.5.4 Discussion

The simplification of the vehicle model resulted in a small influence on the crash pulse shape and it was therefore considered an adequate substitute for the original model. If the subframe cannot be detached by both vehicles as assumed in this study, the effect on the stopping distance will be reduced for both vehicles. The VPI and OLC models represent fundamentally different assumptions on the restraint system characteristics. OLC assumes a perfectly adaptive restraint system whereas VPI assumes a linearly increasing deceleration without any limitation on relative displacement. A typical restraint system may therefore be considered as a combination of the two models and the real-world effect of an adaptive subframe is most likely within the range given by the VPI and OLC models. Using the front subframe for structural adaptivity was demonstrated to have a considerable effect on the full-vehicle crash pulse shape. Benefits over previously proposed solutions were seen, since additional packaging space or modifications to the frontal longitudinal members would not be required and the concept may be implementable in an already existing vehicle structure.

5 General discussion

Although passenger car crashworthiness has improved tremendously over the years, there are still issues that should be considered in order to preserve the positive development in the reduction of the number of fatal and severe injuries in passenger car crashes. Improved CAE modelling techniques bring new possibilities for predicting the real-world crashworthiness before vehicles are produced. The methodology presented in this thesis is one such approach towards vehicle designs that can constitute one of the enablers for reaching a common vision of zero fatalities and severe injuries in road traffic. The methods and solutions in this thesis are not expected to be directly applicable to all aspects of robust crashworthiness in passenger cars. Nevertheless, the suggested approaches adopted in the present thesis are intended as inspiration to utilise the power of state-of-the art simulation technology to chart future safety strategies.

Model validity is an issue that always needs to be addressed when findings based on FE simulation results are discussed. During development of the methodology presented in Paper III, it became obvious that model updates were needed in order to obtain realistic model response in terms of separation of non-structural parts, such as wheels and wheel suspension. Judging by crash tests in small overlap situations with rigid barriers or other cars, the structural response can differ remarkably compared to standardised barrier crash tests with deformable honeycomb elements or full-width rigid barriers. Therefore a first step towards better simulation models was taken and presented in Paper IV. Additional modelling improvements are expected to be required in order to advance with the proposed methodology. This is in line with the general trend that can be seen in CAE, since shorter development time and fewer physical tests during the design phase of passenger cars require greater confidence in simulation models. Improved reliability of CAE models must, however, be combined with an appropriate set of load cases that guarantees robust structural behaviour in real-world situations.

5.1 Discussion of results with respect to crash opponent

The compatibility domain established in Paper III was used to provide an overview of how different crash scenarios compare to each other in terms of intrusion or deceleration in two identical passenger cars, as illustrated in Figure 11. It is suggested that the usage of the compatibility domain could be extended to assess factors such as vehicle mass, size, stiffness in relation to crash configuration factors, such as oblique angle and horizontal or vertical misalignment. In Paper III, a specific area was used to represent the overall passenger compartment intrusion levels. For other vehicle designs, such a representative intrusion area may be more difficult to establish, which would require additional intrusion areas to be monitored in order to compare intrusion response in a set of crash situations. This will introduce a more complex comparison of crash situations and may lead to conflicting results, i.e., one situation leading to large intrusions in one measurement area but small intrusions in another area, and vice versa for a different situation.

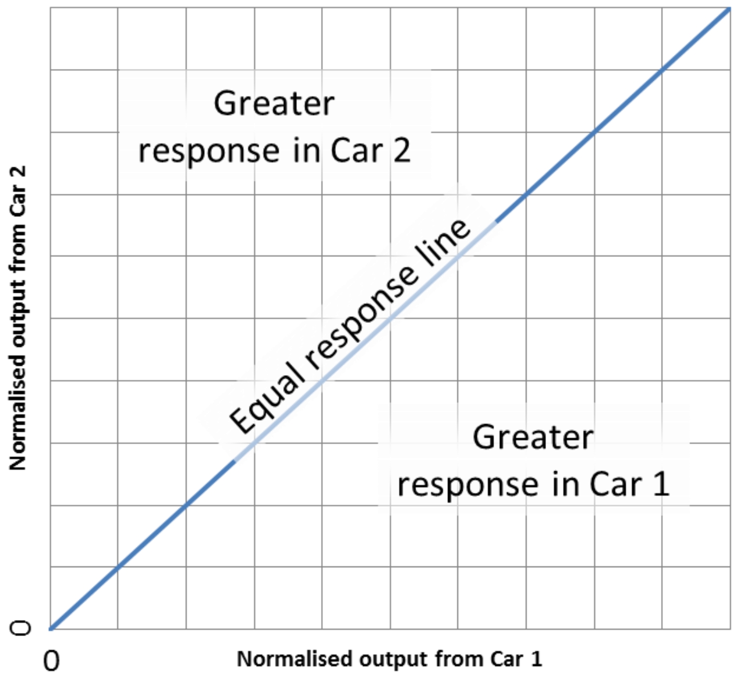


Figure 11. Compatibility domain described in Paper III.

The preliminary findings based on the current state of FE models support previous work on the significance of small overlap situations (Eichberger et al. 2007, Brumbelow and Zuby 2009). In relation to all the crash scenarios evaluated in Paper III, small overlap situations stand out as extreme in terms of passenger compartment intrusion. Whether the same tendencies would be found for a different car design is unknown, however, the methodology should be readily applicable for this type of studies. Furthermore, there are many combinations of car designs that could be investigated in terms of car-to-car crash response. The wheels and wheel suspension components have been identified as important load paths for small overlap crashes. The design and strength of these components are therefore likely to have a considerable effect on the structural response and consequently the categorisation into sub-types of small overlap crashes described in Paper IV.

5.2 Discussion of results with respect to crash scenario

As previously identified, robust structural behaviour constitutes a foundation for restraint system functionality. Further, optimising passenger car structures towards a limited set of crash load cases may introduce sub-optimisation in a wider perspective on crashworthiness. The concepts behind robust structural response should therefore be applicable to other crash scenarios, such as side and rear crashes. The compatibility domain suggested in Paper III may not be directly applicable in front-to-side crashes since injury risk is normally significantly higher in the struck vehicle than the striking vehicle in a front-to-side crash (Summers et al. 2003). For front-to-rear crashes, passenger compartment intrusion in the striking vehicle could be plotted versus relevant intrusion measurements in the struck vehicle. In this way, the compatibility domain may be employed to compare different structural concepts in order to ultimately balance injury risk in both the striking and the struck vehicle.

For the car-to-car simulations performed in Paper III, a rough probability distribution of oblique angles from Eichberger et al. (2007) were taken into account when setting up a simulation matrix. This indicated that most crashes occur at an oblique angle below 10° although the number of cases considered in that study was limited to twenty cases. Therefore, in order to obtain a comprehensive view on frontal crashes, it was decided to cover the complete range of oblique angles between 0 and 45°.

All studies in this thesis were focused on horizontal alignment in frontal car-to-car crashes; vertical misalignment was not addressed at all. Based on previous work, there appears to be agreement that vertical misalignment increases the risk of under riding and increased intrusion (Baker et al. 2008, Mizuno and Arai 2010). This is obviously an important factor to consider when striving for improved compatibility in car-to-car crashes. In terms of methodology development however, it was decided not to attempt to incorporate vertical misalignment as well.

When considering dimensioning crash scenarios for car structural design, road infrastructure design also plays an important role. An example of this is lane separation actions as pointed out by Eugensson et al. (2011). This type of road safety countermeasure can be used in order to avoid head-on collisions on roads with speed limits above a certain level and thereby reducing the crashworthiness design volume described in Figure 2.

Small overlap scenarios stand out as particularly demanding for car structures in terms of passenger compartment intrusion. Crash scenarios combining small horizontal structural overlap and oblique angles between 10° and 20° are suggested as dimensioning for intrusion in frontal car-to-car crashes. This finding should be confirmed with alternative vehicle designs using the methodology described in Paper III. Further, structural countermeasures for small overlap situations were not suggested or within the scope of this thesis. However, to prevent opposing front wheels to lock, it has been proposed to actively turn the front wheel toe-in in order to create a sliding plane from which the crash opponent could be diverted (Winkler et al. 2001). This action may require a substantial wheel rotation angle before achieving a positive effect. Such action must also be well balanced with the risk of a second impact in cases where turning of the wheels is successful in avoiding a first impact.

5.3 Discussion of results with respect to crash energy

For the studies conducted in this thesis, energy levels were estimated and probability distributions were not taken into account. For all studied scenarios, exposing the vehicle structure to increased energy resulted in either higher accelerations, larger intrusions, or both. From a car designer's perspective, the crash energy should be regarded as a framework for which structural integrity must be ensured. Again, road infrastructure can contribute significantly to Vision Zero, by setting speed limits to appropriate levels in order to keep crash energy levels within the crashworthiness design volume.

During the process of active safety systems becoming increasingly efficient in terms of avoiding and mitigating crashes, virtual tools will be essential in order to ensure that occupants will be protected in any crashes that still occur. These active safety systems will thus reduce the crashworthiness design volume as illustrated in Figure 12 which means reducing the energy level that passive safety systems need to be designed for. In a future without crashes, passive safety systems would consequently become obsolete.

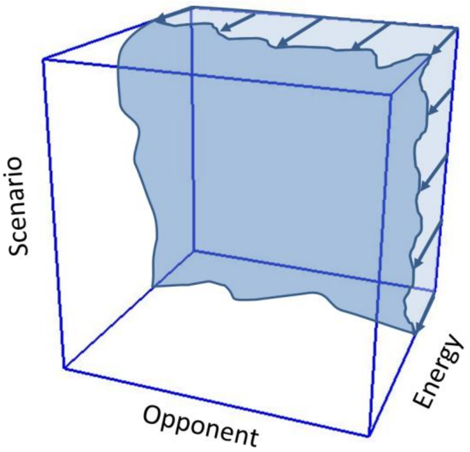


Figure 12. Visualisation of crashworthiness design volume, and how the number of design situations for passive safety can be reduced by active safety systems.

When investigating an adaptive front subframe in Paper V, it was found that such a solution could not be recommended at a closing velocity above 100 km/h for identical vehicles. This recommendation was based on intrusions being increased above the level of the base model with a non-releasing subframe. Furthermore, this result indicates that an adaptively detaching subframe may not be able to reduce fatalities and severe injuries at closing velocities above 100 km/h. An alternative approach to address these high-speed large overlap situations may be to increase the frontal structural force, e.g., by pressurised structures as proposed by Pipkorn and Håland (2005). In this way, it would be possible to change a stiff response in the end of the crash from the integrity of the passenger compartment to a more even deceleration over the same distance. However, there is undoubtedly an upper limit of velocity change that can be tolerated by the average car occupant without sustaining severe or fatal injuries. It was concluded in another study by Pipkorn et al. (2005) that occupant protection in frontal crashes up to 80 km/h is feasible but may require extended distances available for absorption of occupant kinetic energy.

The initial studies reported in Paper I and II were directed towards the applicability of adaptive front structures for reducing the risk of AIS1 neck injuries in frontal crashes. Although indications of harmful crash pulse characteristics were found in literature (Kullgren et al. 2000, Jakobsson 2004), no clear guidelines towards safer crash pulses with regards to AIS1 neck injuries were found. Therefore, no further studies were conducted within the scope of this thesis in order to use adaptive structures for this specific purpose. It is expected, however, that when crash pulse shape recommendations for reduced AIS1 neck injury risk can be given, adaptive structures may be one way to realise such crash pulses.

6 Conclusions

The following conclusions were drawn:

I. Structural adaptivity can reduce deceleration levels significantly in frontal crashes. This, however, requires that the available front structure crush length is not exceeded.

II. In order to achieve efficient structural adaptivity, global load paths need to be modified. When the material strength of the most significant energy-absorbing frontal structures were changed by ±50%, only moderate changes to the passenger compartment deceleration were observed.

III. A methodology for assessing structural robustness based on FE simulation models was proposed. This methodology points out large overlap situations as extreme in terms of occupant deceleration loading, whereas oblique small overlap situations were predicted to be extreme in terms of passenger compartment intrusion.

IV. The results obtained with an updated model based on validation against physical crash tests exhibited large variations in intrusion response as a function of the input variables lateral offset and oblique angle. Car-to-car front crash situations where the front wheels lock up were suggested as critical for occupant safety since this type of situation combined large intrusion with high crash longitudinal crash pulse severity and large lateral velocity change.

V. In the last study, the methodology in Paper III was used as a starting point for addressing the possibility of structural adaptivity to reduce crash pulse severity. It was shown that a detachable front subframe could be used at closing velocities below 100 km/h. Detaching the front subframe was suggested to reduce the crash severity equivalent to a velocity change reduction of up to 44%.

6.1 Lessons learned

Some experiences related to the number of crash simulations performed with the standard models in Paper III as opposed to the updated, more detailed models in Paper IV were gained. When searching for dimensioning scenarios, it would have been beneficial to use a fixed set of initial velocities to save simulation effort in the first stage. The car-to-car model validation work conducted in Paper IV provided several important insights into how details of the models (Centeno G. 2009, Dharwadkar 2011) affect the structural response. Therefore, a larger number of simulations could have been based on the updated Paper IV models to scan the crash configuration domain, also denoted crash scenario matrix.

The detail level of the FE model used for Paper II (16,000 elements) appears to be a limiting factor when compared to the model used for Paper III and IV (>2,000,000 elements). Element size has a direct effect on a model’s ability to capture buckling modes of structural components; a coarse model can simply not capture some deformation modes that a finer model can. Nevertheless, usage of simplified or coarse models should not be disregarded since using these can be an effective way of sorting between high-level decisions. For instance, the studies on adaptive front longitudinal rails, or side members, in Paper II indicated that significant load paths would need to be affected in order to considerably affect the vehicle crash pulse. This was later supported when the concept of an adaptive subframe, which is a major load path in frontal crashes, was demonstrated in Paper V.

Important strategic decisions should be made regarding on how to spend simulation resources. On the one hand, crash models can be made increasingly detailed in order to predict crash performance with higher precision in a constant number of load cases, corresponding to moving right on the horizontal axis in Figure 13. On the other hand, as was demonstrated in Paper III, the number of load cases can be increased with a constant or even reduced model detail level, corresponding to moving up on the vertical axis in Figure 13. Based on studies conducted for this thesis, it is not obvious which choice is more effective in terms of designing for real-world crashworthiness. A trade-off is needed between increasing the model detail level and the number of situations to evaluate. When a new computer system generation becomes available, as illustrated in Figure 13, which enables a larger number of computations to be performed, this trade-off needs to be considered. It is expected that this balance will be affected by which part of the development process that is considered, i.e., at earlier phases of development a lower model detail level may be preferable while exploring a larger number of situations.

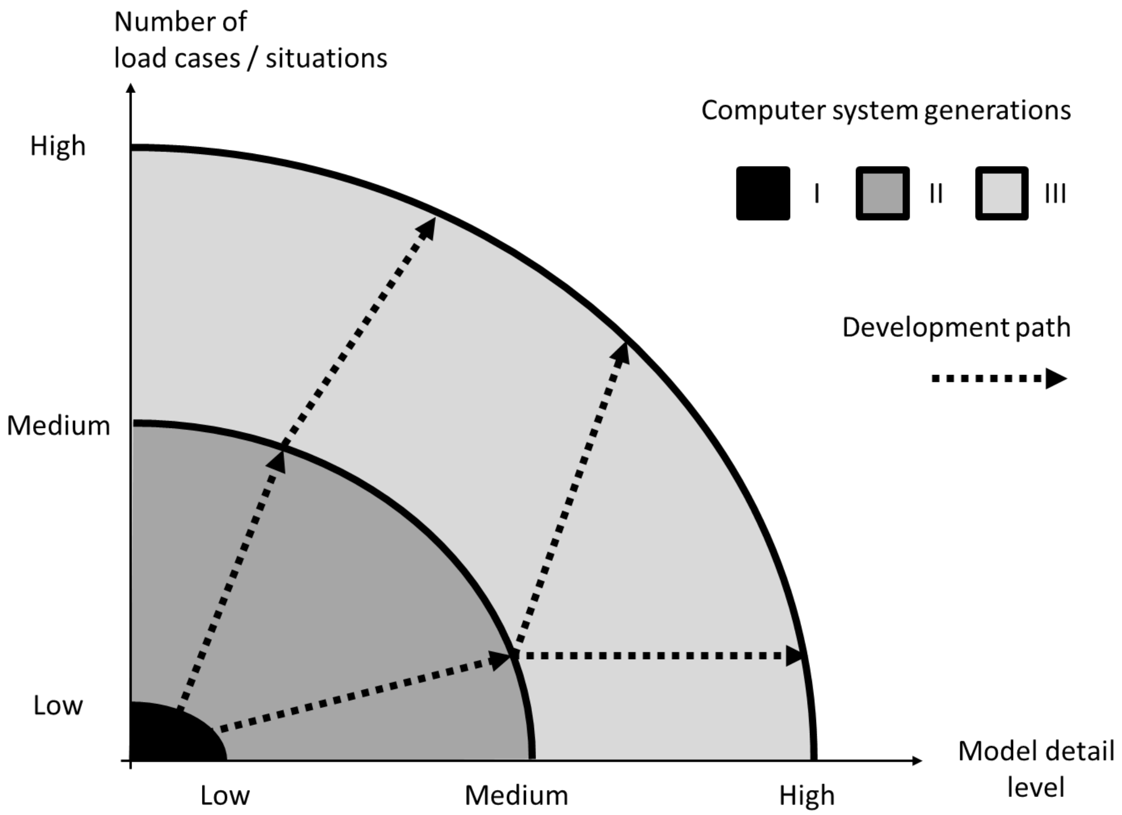


Figure 13. Schematic view on trade-off between model detail level and number of situations to evaluate during design process of passenger cars. Alternative development paths marked by dotted arrows.

6.2 Suggestions for future studies and development work

Based on the research performed for this thesis, there appears to be three obvious paths for continued work. Table 1 was therefore updated with an outline of these paths in Table 3.

The first path would be useful for going into further details of passive safety issues and vehicle structures in frontal crashes as illustrated in Table 3. Issues such as vertical misalignment and robustness in car-to-car crashes with dissimilar vehicles that were not covered by the present studies could be addressed. Furthermore, connecting crash simulation setups more closely to accident data including the probability of crash scenarios occurring may be one way of advancing towards robust structural design. A further application could be single vehicle frontal crashes with fixed objects or large animals.

A second path deals with the generalisation of the methodology to encompass other crash scenarios such as rear and side crashes. Using a set of bullet vehicle models, a structural robustness map could be established in a similar fashion as was made for frontal crashes.

A third, and perhaps the most innovative, way forward is looking into integrated safety for frontal crashes, i.e., the interaction between active and passive safety systems aiming to reduce accidents and injuries. The first step in this work is to combine the methodology for structural robustness described in this thesis with detailed occupant models. This could possibly quantify injury risks related to intrusions and decelerations on a considerably more detailed level than can be achieved using intrusion measurements and crash severity indicators such as VPI (ISO 2012) or OLC (Stein et al. 2011).

Table 3. Overview of how methods and solutions could be expanded to include additional crash scenarios and safety systems. Numbers refer to alternative future work paths.

		Frontal crashes	Rear crashes	Side crashes	Rollover, run-off-road	Pedestrian protection	...
Passive safety systems	Structures	1	Methodology generalisation →				2 →
	Restraints	↓					
Active safety systems	Mitigation	Integration ↓					
	Avoidance	3 ↓					

As continued focus is being placed on energy efficiency, reducing vehicle mass is one of the options for producing cars that use less fuel. The safety consequences of a future lighter vehicle fleet in the United States has been thoroughly analysed by NHTSA (2013). If lighter materials such as ultra-high strength steel, aluminium or composites are implemented, this must be done with robust structural response in mind. This kind of assessments during the development phase requires both detailed models showing the structural response and broad assessments of crash situations.

Another potential opportunity to increase energy efficiency fuel is electric vehicles, an area where several research projects have been initiated, e.g., ELVA (2013) and EVERSAFE (2013). The transition to alternative powertrains may introduce challenges, as well as opportunities in terms of the structural response when future vehicles are involved in crashes. Furthermore, safety design experience built around conventional vehicles may not be directly applicable to vehicles incorporating alternative powertrains. Therefore, it is proposed that it would be beneficial to apply the methodology presented in Paper III when designing electric vehicles offering robust structural response.

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