A New Approach to Assess and Optimize the Frontal Crash Compatibility of Vehicle Structures

with Focus on the European Fleet of Passenger Cars

Emad Sadeghipour, M.Sc.

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Vorsitzender: Prof. Dr.-Ing. Michael W. Gee

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1. Prof. Dr.-Ing. Markus Lienkamp
2. Prof. Dr.-Ing. habil. Fabian Duddeck

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My greatest thanks go to my family and friends for their support and understanding over the last busy years. Above all, I want to thank my parents, who have been supporting me from childhood until this level and taught me to fight to achieve my goal and practice loyalty to achieve peace.

Garching, 09.02.2017

Emad Sadeghipour

We should research as a river flows.

There might be many obstacles on the way,

but the flow never stops!

Abstract

Car-to-car compatibility is a key factor in reducing the number of injuries and road fatalities. However, despite considerable research and projects, there remains no comprehensive assessment approach for the crash compatibility of passenger cars. The aim of this work is to develop an approach to assess and optimize the frontal crash compatibility of vehicle structures.

This study first presents a definition model, which can describe the crash compatibility of vehicles in terms of kinetic energy. This definition model provides a basis for discussions and for the assessment of the test results.

Two test procedures, one with full overlap and one with offset, are necessary to assess most important compatibility parameters. Current test procedures are thus investigated to evaluate their suitability for use in a compatibility assessment approach. The evaluation results showed that a combination of the Full-Width Rigid Barrier (FWRB) and an offset test procedure with a Mobile Deformable Barrier (MDB) can address most important parameters of crash compatibility.

While the assessment of self-protection is possible through dummy and intrusion measurements, the assessment of partner-protection is still an unresolved problem. Using a moving barrier enables an innovative approach to assess partner-protection, which is based on the risk of injuries for a virtual dummy on the moving barrier. An assessment protocol is presented, which uses Occupant Load Criterion (OLC) and Acceleration-Based Criterion for Intrusions (ABC-I) to assess partner-protection.

The developed assessment approach is validated with respect to two issues: (1) correlation of assessment results with crash performance of the vehicle in car-to-car collisions and (2) efficiency of the assessment approach in improving the crash compatibility of the vehicle’s structure. The validation results confirmed a correlation between the assessment results with crash performance of the vehicle in car-to-car, and the efficiency of the assessment approach in improving the crash compatibility of the vehicle’s structure.

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1 Introduction[1]

The European Commission set a target in 2003 to halve the number of road fatalities by 2010, relative to the numbers from 2001. Although the target was not completely reached, the number of road fatalities in Europe had reduced by almost 45 % in 2010 [2, p. 1]. The European Commission continued with its policy and updated the target for road safety in 2010, which involved “halving the overall number of road deaths in the European Union by 2020, starting from 2010” [3, p. 4].

The decreased number of road fatalities aligned with this target until 2013. However, the declining trend in terms of the number of reported road fatalities slowed in 2014 and increased slightly in 2015 for the first time in the last twenty years. Fig. 1.1 shows the number of road fatalities in Europe and the desired trend necessary to reach the 2020 European Commission target.

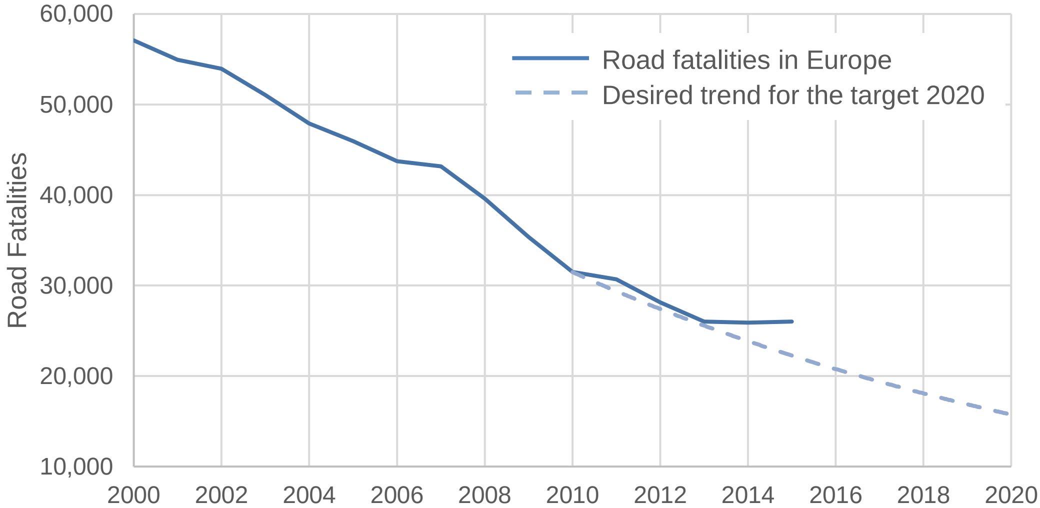

Figure 1.1: Road fatalities in Europe and targets from 2000 to 2020 [2, p. 1]

A similar trend exists in the different European countries. For example, the German Federal Ministry of Transport, Building and Urban Development [4, p. 3] set its road safety program’s aims, based on the European Union initiative, to reduce the number of fatalities by 40 % by 2020. Although a mid-term review [5, p. 3] stated that Germany is “heading in the right direction towards achieving the target,” the decreasing trend of road fatalities slowed in 2014 and increased in 2015.

The European Commission listed several reasons for the slower pace of decrease, despite technological progress in vehicle safety [2, p. 1]:

- Urbanization and a growing number of vulnerable road users
- A growing number of elderly people
- Increased traffic due to improved weather conditions and milder winters
- Decreased road and vehicle maintenance due to economic crises
- Recent driving behaviors, e.g. distracted driving due to smartphone usage

[1] The citation style of this work is according to the IEEE Editorial Style Manual [1].

Another reason for the deceleration in the number of road fatalities could be the evolution of vehicle safety, going from an era of passive to active safety. Passive safety includes all systems that limit damages, while active safety includes all systems that prevent the collision or mitigate its severity [6, p. 3]. Passive safety systems have been developed and employed for many years, and their safety potential has been exploited extensively. As such, efforts to further improve passive safety are increasing. Unlike passive safety, active safety is quite a new field and has much more potential for reducing serious injuries and the number of road fatalities.

However, it will take many years before all vehicles are equipped with adequate active safety systems. Experts from the Association of German Engineers (VDI) [7, p. 6] listed some prerequisites for the implementation of active safety systems. These prerequisites actually slow down the implementation process:

- Increased market acceptance of active safety systems
- Demonstration of the effectiveness of active safety systems
- Resolution of certain juridical cases (e.g. product liability)
- Preparations of infrastructures that will utilize the assistance systems

Assuming that all technical challenges are solved and that the aforementioned preconditions are met, the substitution of the current vehicles will be a long process. Currently, more than 250 million passenger cars are registered in Europe [8, p. 12], with an average age of 9.65 years [9]. Fig. 1.2 presents the age distribution of the passenger car fleet in Europe, an indication that the substitution of the present fleet of passenger cars into modern vehicles with active safety systems is a long time coming.

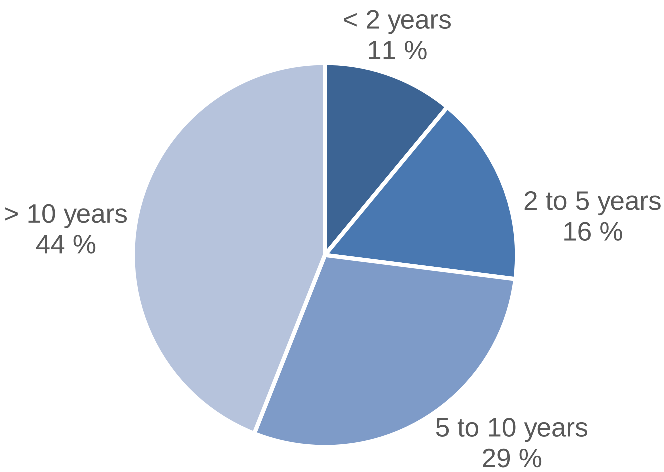

Figure 1.2: Average age distribution of the European passenger car fleet [10]

Since the preventive active safety systems cannot affect the number of injuries and road fatalities immediately, the enhancement of passive safety remains crucial in further reducing the number of injuries and road fatalities in the next few decades.

Increasingly demanding crash tests and safety requirements have enhanced the vehicle safety for occupants and other road users in the last decades. The relationship between good test results and a reduced number of fatalities in accidents verifies the efficiency of the safety requirements [7, p. 5]. Fig. 1.3 illustrates the cumulative road fatalities in Germany from 2000 to 2014 in terms of road user type.

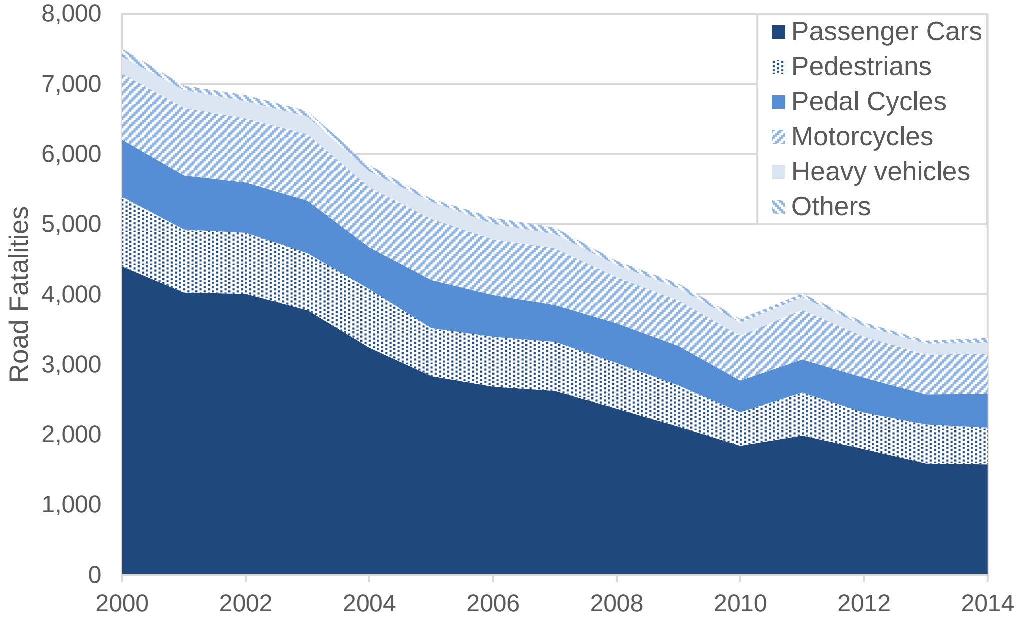

Figure 1.3: Number of road fatalities in Germany from 2000 to 2014 by road user type [11]

Although, the number of fatalities among vehicle occupants has been reduced faster than other road users, occupants are still the primary road users, accounting for almost 47 % of the total road fatalities and 43 % of total serious injuries [12, p. 81].

Owing to the different masses and geometries of vehicles, car-to-car collisions present a technical challenge for occupant protection in real accidents. Lightweight designs and new vehicle concepts and measures to increase energy efficiency will lead to greater traffic diversity; as a result, the VDI confirmed that crash compatibility is important for further enhancing passive safety [7, p. 4].

Unlike classic vehicle safety, which focused on occupant protection, crash compatibility considers self-protection and partner-protection, and therefore shows more potential for reducing serious injuries and the number of road fatalities.

Previous works [13, p. 65]; [14, p. 19] estimated the benefits of implementing crash compatibility tests in safety regulations for European vehicles as 7 % to 14 % fewer serious injuries and 7 % to 10 % fewer road fatalities. Nonetheless, despite many international investigations and several research projects in Europe, there is still no comprehensive assessment approach. Consequently, no safety regulation exists for crash compatibility in Europe.

1.1 Aim

This work proposes an assessment approach for the frontal crash compatibility of passenger cars, which can be applied as a safety regulation for market approval or for the optimization of vehicular structures. Since a frontal impact is the most common crash type with fatalities in Europe [15, p. 6] and United States [16], the crash performance of vehicles in frontal impacts is assumed as the main indicator of a vehicle's safety level and, as such, this work focuses on frontal crash compatibility.

To achieve the aim, four objectives are set:

- Propose a crash compatibility definition
- Propose a test procedure for assessing the crash compatibility
- Propose a rating system for assessing the test results
- Optimize a vehicle structure with the proposed assessment approach

1.2 Outline

The literature review in Chapter 2 consists of four sections. Section 2.1 describes the different car classifications of passenger cars and explains their safety requirements for market approval in Europe and consumer organization tests. Further, using statistics, the safety level of different car classes (in real accidents) is discussed. Section 2.2 reviews previous works regarding crash compatibility in Europe and describes the important parameters. This section reviews previous proposals for changing the safety regulations and outlines the current state of crash compatibility in crash tests. Section 2.3 describes two main methodologies for studying crash compatibility and discusses important requirements for relying on Finite Element (FE) analysis as the predominant tool in this study. Finally, Section 2.4 draws research questions for this study based on what has been discussed.

Chapter 3 proposes a definition model for crash compatibility that is broken down into four sections. Section 3.1 reviews the literature on existing definitions of crash compatibility and highlights their points of agreement and conflict. Section 3.2 outlines some requirements, based on the literature review, for a comprehensive definition model and introduces a fundamental definition model for crash compatibility. Section 3.3 applies the introduced definition model in several crash tests to assess the vehicle compatibility. The results of this assessment will be compared with full-scale crash data to validate the efficiency of the proposed definition model. Section 3.4 draws the chapter conclusion, discusses the results, and gives some recommendations for further research.

Chapter 4 proposes a test procedure for assessing frontal crash compatibility that is broken down into five sections. Section 4.1 reviews the literature on existing test procedures and summarizes the most important characteristics of different test procedures. Section 4.2 discusses the approach and requirements for evaluating the test procedures for the assessment of frontal crash compatibility. Section 4.3 studies the efficiency of the current test procedures. Section 4.4 introduces an alternative test procedure for the assessment of frontal crash compatibility, which will be analyzed with simulation analyses. Section 4.5 draws the chapter’s conclusion, discusses the results, and gives some recommendations for further research.

Chapter 5 proposes some criteria for rating the results of the proposed test procedure discussed in Chapter 4. These criteria will be used to complete the assessment of frontal crash compatibility. This chapter comprises four sections. Section 5.1 reviews the literature for approaches to rating the results. Section 5.2 introduces an alternative rating approach and describes the criteria for rating the test results. Section 5.3 describes the test protocol and the assessment approach that is based on the proposed definition model presented in Chapter 3, the proposed test procedure from Chapter 4, and the criteria discussed in Section 5.2. Section 5.4 draws the chapter's conclusion, discusses the results, and gives some recommendations for further research.

Chapter 6, which validates the entire assessment approach, comprises four sections. Section 6.1 reviews the literature on the methodologies to validate the proposed assessment approach for frontal crash compatibility. Section 6.2 introduces the validation approach in this work, which contains optimization of a vehicle structure. Section 6.3 presents the results of the validation analysis, and Section 6.4 draws the chapter's conclusion, discusses the results, and gives recommendations for further research.

Finally, Chapter 7 summarizes the entire body of work, discusses the results, and gives some recommendations for further research. Fig. 1.4 presents the structure of the work.

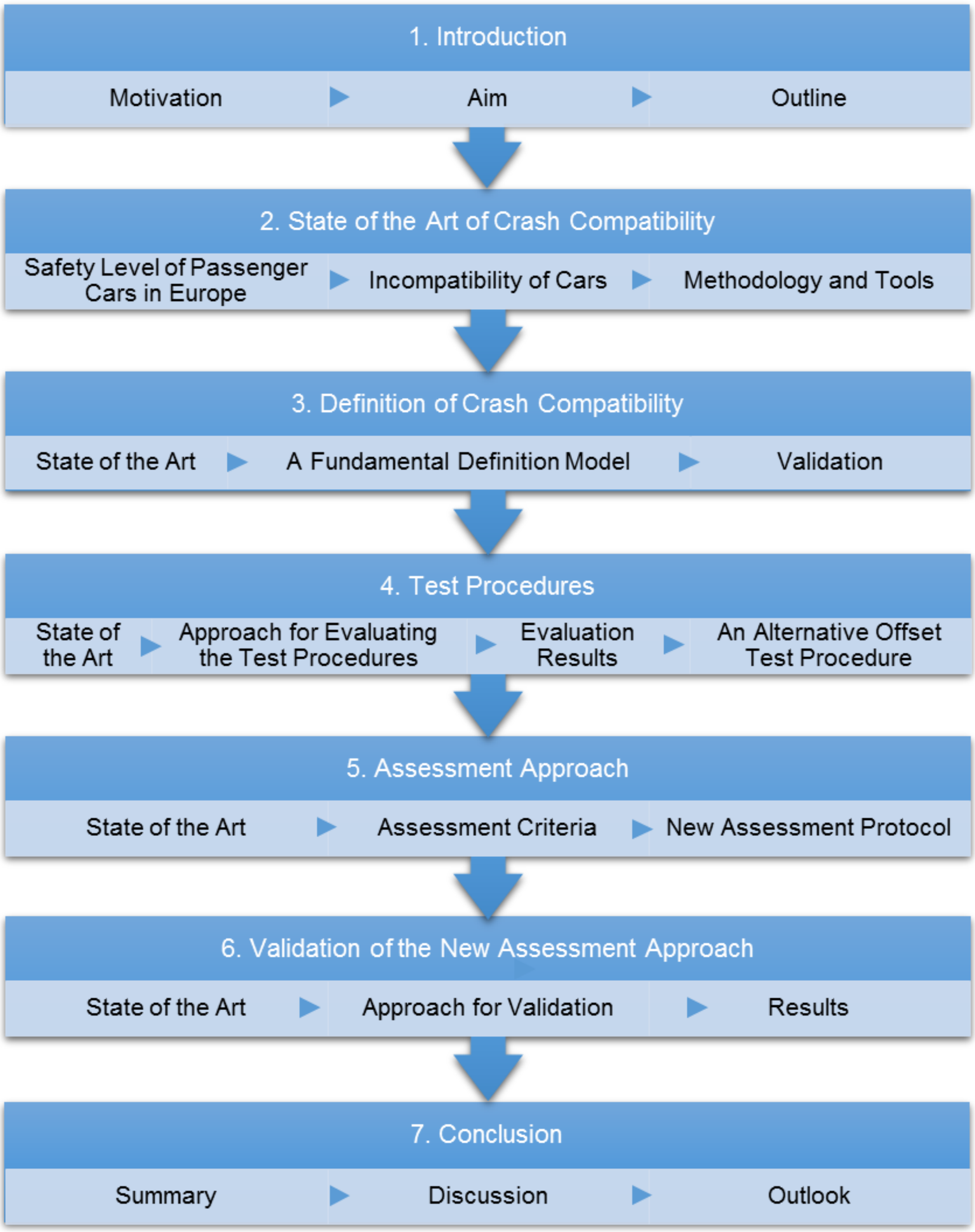

Figure 1.4: Structure of the dissertation

2 State of the Art of Crash Compatibility

This chapter outlines the state of the art of crash compatibility and places the scope of this study to focus on the European fleet of passenger cars. Hence, this part aims to find research gaps and place the research questions of this work.

The objective of Section 2.1 is to describe the diversity of safety levels in the European fleet of passenger cars. It illustrates legislative safety tests and safety requirements of the European New Car Assessment Program (Euro NCAP) for two main classifications of the European passenger car fleet and discusses the current safety level of passenger cars in terms of their performance in real-life accidents.

The objective of Section 2.2 is to provide an overview of incompatibility issues in real-life accidents and review the most important research projects on crash compatibility in Europe. It presents the project results and their proposals for changing the safety regulations to consider crash compatibility, and briefly describes the arguments for rejecting the proposals.

The objective of Section 2.3 is to describe the common methodology and applied tools in previous works on crash compatibility. Furthermore, it presents and compares the tools of this work, i.e., full-scale crash test data and simulation, with respect to their advantages and disadvantages for studying frontal crash compatibility.

The objective of Section 2.4 is to derive the research questions of this work from the state of the art. Answering these research questions should fill the research gap to achieve the aim of the work.

2.1 Safety Level of Passenger Cars in Europe

The fleet of passenger cars includes a wide variation of vehicles with different safety levels.

The term “normal passenger car” in this work applies to the vehicle category M1 according to ECE/TRANS/WP.29/78/Rev.4 of the United Nations [17], which is for “vehicles used for the carriage of passengers and comprising not more than eight seats in addition to the driver's seat”. M1 category contains a wide variation of vehicles with different market targets.

The fleet of passenger cars is not limited to the vehicle category M1. In recent years, a new category of ultra-light passenger cars entered the market, which is classified as heavy quadricycles according to Regulation No. 168/2013 of the European Parliament [18]. Quadricycles are originally derived from motorcycles as an alternative to motor-bikes or city cars [19]. European car manufacturers reused this classification to produce efficient and affordable passenger cars, which can be used for short trips in rural or urban areas. The word “microcars” in this work refers to these vehicles.

The segmentation of the passenger car market is still open and uniform vehicle segmentation does not exist in Europe. However, the Commission of the European Communities [20] declared the narrowest market segmentation for passenger cars, as shown in Tab. 2.1. The market shares and average mass in running orders are in line with the statistics of registered cars in Europe 2014. The market statistics are not yet available for microcars due to their novelty. Thus, the maximum values for the mass in running and pan-area are listed according to the regulations for their market approval.

Table 2.1: Vehicle segmentations in Europe [8, pp. 61−62]; [18]; [20]

Segment	Name	Equivalent segment by Euro NCAP	Market share[1]	Average mass in running in kg	Average pan-area[2] in m²
N/A	Microcars	Heavy Quadricycle	N/A	max. 450	max. 5.55
A	Minicars	Supermini	8.8 %	960	5.8
B	Small cars		24.3 %	1125	6.9
C	Medium cars	Small family car	30.4 %	1320	7.9
D	Large cars	Large family car	8.1 %	1515	8.7
E	Executive cars		2.9 %	1715	9.1
F	Luxury cars	N/A	0.6 %	1920	9.9
S	Sport coupés	Roadster sport	1.2 %	1550	8.3
M	Multi-purpose cars	Small MPV Large MPV	3.9 %	1495	8.5
J	Sport utility and off-road vehicles	Small off-road Large off-road	19.7 %	1485	8.1

[1] The market share of microcars is not included

[2] Pan-area is defined as length multiplied by the width of a vehicle

The focus of this work is on the European passenger car fleet ranging from heavy quadricycles to Sport Utility Vehicles (SUV) that have to meet two important groups of safety requirements: type approval regulations and requirements from consumer organizations. The United Nations Economic Commission for Europe (UNECE or ECE) set some safety regulations that are obligatory for the market approval of passenger cars. All heavy quadricycles with a higher production number of 150 units in a year [18, Annex III], and all normal passenger cars with a higher production number of 1,000 units in a year in Europe or 75 units in one member state [21, Annex XII] must pass these safety regulations to be approved for market entrance in Europe.

Euro NCAP is the main consumer organization for vehicle safety and sets several safety requirements, which are not obligatory but are decisive for the market image of cars.

Since the European safety requirements for microcars and normal passenger cars are different, they should be studied separately. The next sections describe the safety requirements for each car classification and discuss their current safety level on the roads.

2.1.1 Normal Passenger Cars: M1 Category

M1 is a widespread vehicle category for passenger cars including a wide range of size and mass. As can be seen in Tab. 2.1, the average mass ratio of normal passenger cars could be up to 1:2, between the segments A and F. The fact that Tab. 2.1 presents the average mass in running for each segment is an indication of higher mass ratios in car-to-car accidents. However, the safety requirements and crash tests do not consider the variety of passenger cars, which results in an inconsistency of the test results with real-life injury risks.

2.1.1.1 Safety Regulations for Market Approval

Safety regulations for market approval are categorized under two groups: tests at the component or system level, which set some requirements for the operation of specific safety systems (e.g., restraint systems), and full-scale tests at the vehicle level, which set some requirements for the occupant or pedestrian protection in specific crash test scenarios.

ECE has developed various regulations for the market approval of passenger cars from M1. Tab. 2.2 summarizes the relevant safety regulations for the type approval of M1 passenger cars and their scopes.

Table 2.2: Safety regulations for market approval of M_1 passenger cars [22, p. 23]

Test level	Regulation name	Scope	Reference
Components and Systems	ECE R11	Door latches and door retention components	[23]
	ECE R12	Behavior of the steering mechanism in the event of impact	[24]
	ECE R14	Restraint systems, safety-belts and their anchorages, seats and their anchorages, head restraints, child restraint systems, ISOFIX and their anchorages systems, ISOFIX top tether anchorages	[25]
	ECE R16		[26]
	ECE R17		[27]
	ECE R25		[28]
	ECE R44		[29]
	ECE R129		[30]
	ECE R21	Roof and interior fittings	[31]
	ECE R32	The behavior of the passenger compartment in rear-end and head-on collisions	[32]
	ECE R33		[33]
	ECE R42	Front and rear protective devices	[34]
Full-Scale Tests	ECE R94	Occupant protection in frontal impact	[35]
	ECE R95	Occupant protection in side impact	[36]
	ECE R127	Pedestrian safety	[37]
	ECE R135	Occupant protection in pole side impact	[38]
	ECE R137	Restraint systems in frontal impact	[39]

While safety regulations at the system level test isolated components and systems, safety regulations at the vehicle level test all safety systems and their interaction with other systems and the collision partner. These tests are therefore more comprehensive and relevant for this work. Since pedestrian safety is not within the scope of our study, ECE R127 will not be investigated in more detail.

The ECE R94 frontal impact test was developed between 1989 and 1994 by researchers of the European Enhanced Vehicle-Safety Committee (EEVC) working group 11 [40, p. 1]. The test vehicle has a frontal collision against an Offset Deformable Barrier (ODB) with 40 % overlap and at a collision speed of 56 km/h. The frontal impact test was derived from a frontal car-to-car collision with both vehicles travelling at 50 km/h with an overlap of 50 % [40, p. 3]. Various analyses on overlap effect and impact speed showed that 40 % overlap and 56 km/h correlates best with the baseline car-to-car collision [40, pp. 5-13]. Two frontal impact dummies are installed in each of the front seats. The crash test dummies are equipped with sensors to measure the exerted forces, accelerations, or displacements in the head, neck, thorax, femur, and tibia of the dummies.

The side impact test was developed between 1987 and 1989 by researchers of the EEVC working group 9 [41]. In 1998, the developed test procedure was used as the basis for ECE R95. In 2004, the test was updated based on a proposal from EEVC working group 13. In the updated version of ECE R95 [36], a Mobile Deformable Barrier (MDB) with a total mass of 950 kg collides the test vehicle on the driver's side. The MDB speed at the moment of impact should be 50 km/h, and a side impact dummy should be installed in the front seat on the impact side.

The pole side impact was developed during 1998 by the National Highway Traffic Safety Administration (NHTSA) of the United States [42, p. 2] and was adopted in 2014 by the United Nations with some updates. In the updated version of ECE R135 [38], the test vehicle strikes a stationary pole at 32 km/h on the driver's side; the pole is a rigid vertically oriented structure with an outer diameter of 254 mm. The vehicle's longitudinal centerline should have an impact angle of 75° to the vertical plane of the pole, and an adult male dummy should be installed in the front seat on the impact side.

In November 2015, the United Nations defined a new safety Regulation (ECE R137) to test the effectiveness of occupant restraint systems in a frontal full-scale test against a Full-Width Rigid Barrier (FWRB) at 50 km/h, which entered into force on June 9, 2016 [39, p. 1]. This test procedure is adapted from the Federal Motor Vehicle Safety Standard 208 (FMVSS 208) of the United States, which was published in 1997 [43, p. 1]. However, the collision speed is reduced from 56 km/h to 50 km/h.

In all of the aforementioned tests, the dummy measurements are filtered and assessed with a set of pre-defined limits. If the test vehicle passes the tests without exceeding the test limits, the manufacturer acquires an approval mark.

2.1.1.2 Safety Requirements of Euro NCAP

Euro NCAP was developed in the United Kingdom and introduced in 1997 [44, p. 1]. It has grown through sponsorships from other European countries, the European Commission, European consumer groups, and international motoring organizations, and currently consists of 12 members and seven test facilities in Europe. As claimed by Euro NCAP [44, p. 1], the aim of this program is to provide information about safety of new cars, which can help consumers to find cars with better safety. This encourages manufacturers to enhance the safety of their cars and receive recognition for their efforts to boost their market share.

Euro NCAP applies an overall safety rating, which is based on assessment results in four areas: adult protection (for the driver and passenger), child protection, pedestrian protection, and safety assist technologies [45]. Euro NCAP tests simulate some real-life accidents, which are determined as important causes for injuries or fatalities of occupants or other road users. The number of stars reflects the performance of the vehicle in the tests. However, the offered safety equipment in the vehicle also influences the rating. As described by Euro NCAP [46], "a high number of stars shows not only that the test result was good, but also that safety equipment on the tested model is readily available to all consumers in Europe". The maximum number of stars is five, and vehicles that pass only the minimum safety regulations for the market approval do not achieve any stars. Euro NCAP develops the five-star safety rating system continuously to encourage manufacturers to use advanced technologies and innovations. Fig. 2.1 provides a general guidance to the meaning of the stars in this rating system.

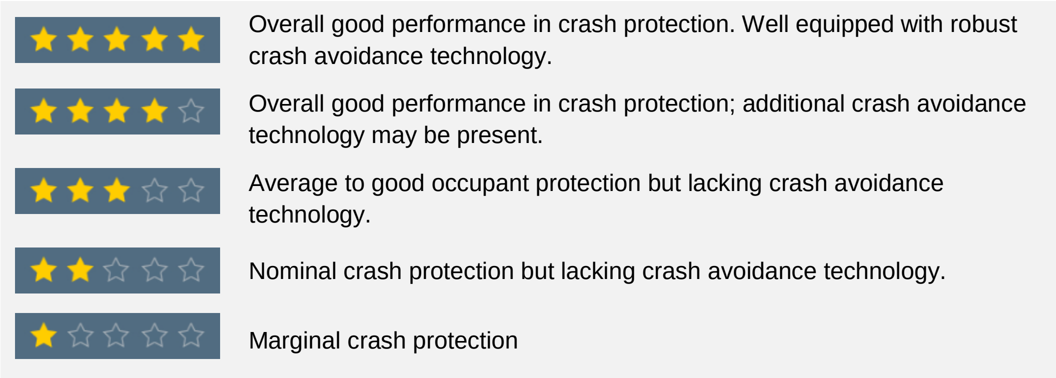

Figure 2.1: Five-star safety rating system of Euro NCAP [46]

Among four areas in the Euro NCAP rating system, the adult protection area is within the scope of this work. The score for adult protection is determined from three test series: frontal impact, side impact, and whiplash tests.

Euro NCAP adapted the test set-up of ECE R94 in 1997 and increased the collision speed to 64 km/h based on accident analyses carried out by EEVC Working Group 11 for the development of the European test procedures. Analysis of the accidents stated that the frontal impact test with increased collision speed would address about two thirds of car-to-car accidents with serious injuries and fatalities, while ECE R94 would address only a few of them [44, p. 3]. In the offset frontal impact test of Euro NCAP [47], two frontal impact dummies representing the average male should be installed in the front seats and two child dummies should be placed in child restraints in the rear seats [48].

Euro NCAP added a new test set-up to the frontal impact test series in 2015, which involves colliding against a rigid barrier with full overlap at a collision speed of 50 km/h [49]. The reason for this new set-up is to address higher decelerations and consequently higher restraint injuries, which might happen due to the higher structural stiffness of modern vehicles [50]. In the full-width frontal impact test of Euro NCAP, two small female dummies should be installed in the driver's seat and in the rear passenger side seat [45]. Fig. 2.2 shows the updated test set-ups of Euro NCAP for adult occupant protection in frontal impacts.

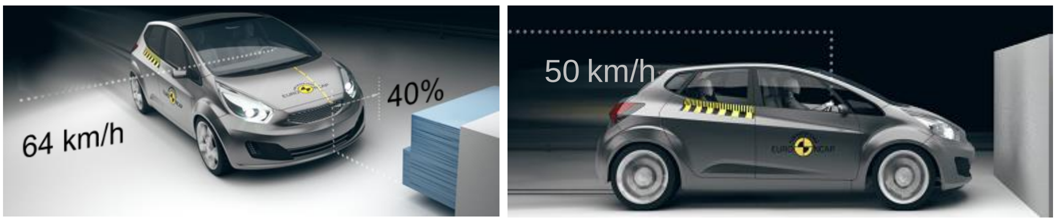

Figure 2.2: Frontal impact test series of Euro NCAP [48], [50]

In 1997, Euro NCAP adapted the side impact test from ECE R95 and applied more demanding limits for dummy measurements and some additional safety requirements to enhance vehicle safety in side impacts. In 2010, the MDB was revised and more biofidelic adult and child dummies were used in Euro NCAP side impact tests [51, p. 1]. In 2011, Euro NCAP decided to use the Advanced European Moving Deformable Barrier (AE-MDB) for side impact testing from 2015. In the new version of the side impact testing protocol [52], the AE-MDB is mounted on a trolley with a total mass of 1300 kg and collides at 50 km/h into the driver side of the stationary test vehicle with a male test dummy installed in the driver's seat.

The pole side impact test of Euro NCAP [53] has the same test set-up as ECE R135. The whiplash test of Euro NCAP [54] assesses the car seats with regard to the neck injury protection. As a test at the system level, it is not within the scope of this work.

The assessment of adult occupant protection in Euro NCAP [55, pp. 1-3] is based on the dummy measurements in five different tests: frontal impact in offset and full overlap, side impact, pole impact, and rear impact (whiplash protection). The dummy measurements for different body regions are presented in five color segments: green for good, yellow for adequate, orange for marginal, brown for weak, and red for poor. Furthermore, the structural performance of the test vehicle such as displacement of the steering wheel, pedal movement, toe-pan distortion, and displacement on A-pillar are considered in the assessment. The individual test scores in the five test scenarios are computed and contribute to the whole score, which is expressed as a percentage of the maximum achievable number of points. The number of stars is assigned regarding the individual scores for adult occupant, child occupant, pedestrian, and safety assists (Fig. 2.3).

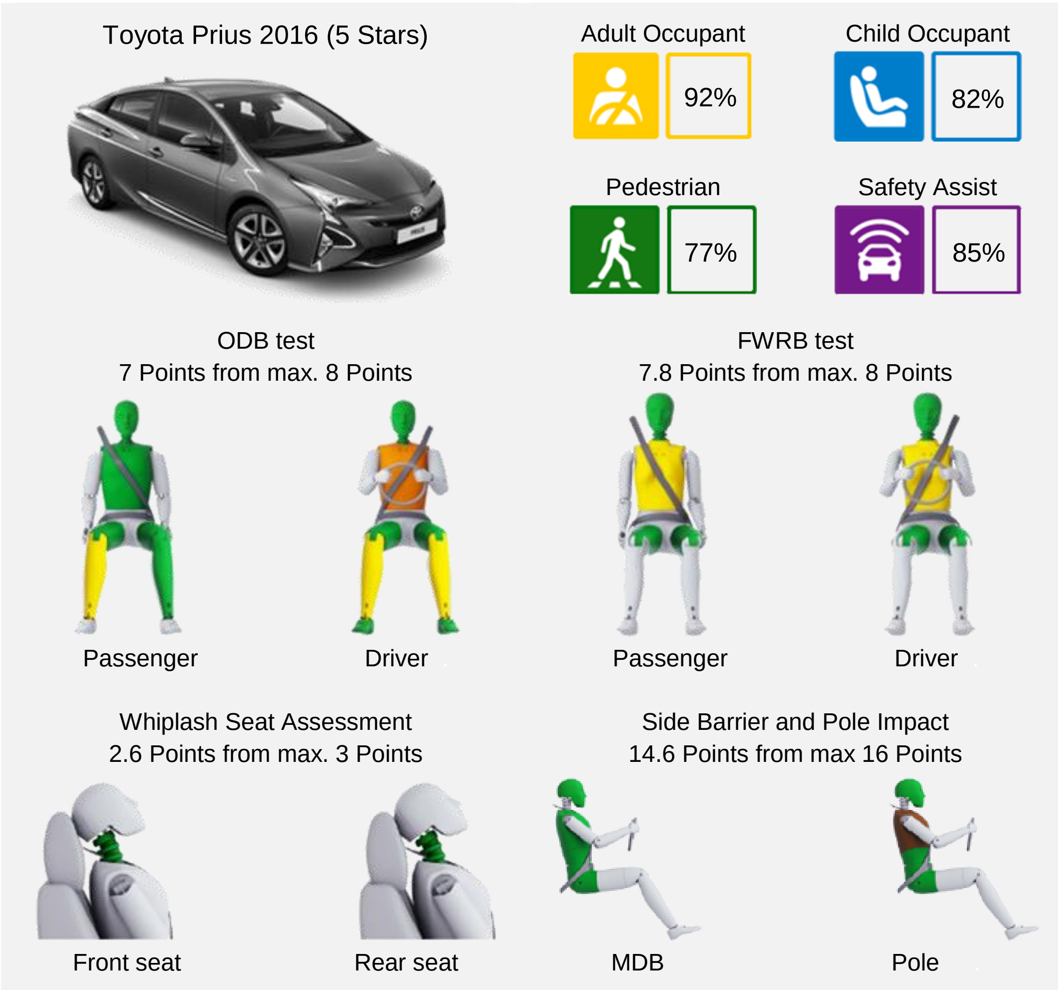

Figure 2.3: Euro NCAP test results for Toyota Prius 2016 [56]

2.1.1.3 Correlation of Crash Test Results with Real-Life Injury Risks

The aim of crash tests is to enhance vehicle safety. While the general expectation from the safety regulations is to ensure the minimum safety for the approved vehicles, it is expected that the Euro NCAP test results correlate more with real-life injury risks [57]–[61].

Lie et al. [57] employed a paired comparison statistical analysis method on police reports from accidents in Sweden between January 1994 and March 2000. The results showed an overall correlation between the Euro NCAP test results and the risk of serious injuries and fatalities. It was found that the general risk of serious and fatal injuries reduces by 12 % per Euro NCAP rating star. Cars with three or four stars were generally 30 % safer than cars with two stars. The weight of the vehicles was found to be a determining factor in car-to-car collisions, which decreases the risk of injuries by 7 % per 100 kg increase in the vehicle mass.

The German Federal Highway Research Institute (BASt) [58] applied the paired comparison statistical analysis to a sample of the German police recorded car-to-car accidents between 1998 and 2002. The dataset included 235,047 vehicles that were also tested in Euro NCAP; their crash performance in real-life accidents could therefore be compared with Euro NCAP scores. Fig. 2.4 presents the results of this study comparing the influence of the star rating and mass ratio on injury risks in frontal car-to-car accidents. Winning probability describes the chance of the vehicle occupants to be injured less than the occupants of the partner vehicle. Mass ratios less than one means that the partner vehicle is heavier.

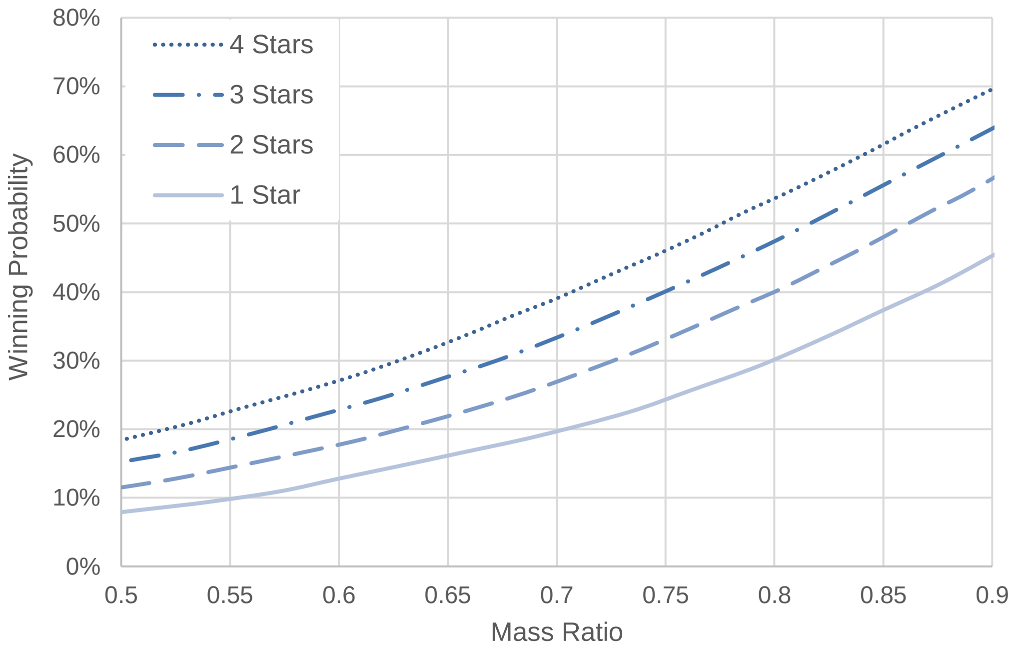

Figure 2.4: Winning probability vs. mass ratio in frontal car-to-car accidents;
As the first vehicle awarded five stars for adult occupants was as late as in June 2001 [62], the results do not include any vehicles with five stars.

[58, p. 160]

The overall Euro NCAP star rating was found to correlate with real-life injury risks. However, the mass ratio of the involved vehicles in car-to-car collisions was more decisive. The results [58, p. 160] showed that a 10 % change in the mass ratio would increase the chance of lower injuries by 20 %.

In 2006, the European project SARAC II [59] studied the relationship between Euro NCAP test results and injury outcomes in Europe, for which various data sources from Euro NCAP test results, Australian NCAP test results, British real crash data over the period 1993 to 1998, French real crash data between 1993 and 2001, German real crash data occurred from 1998 to 2002, Australian real crash data between 1987 and 2002, and New Zealand real crash data occurring from 1991 to 2002 were analyzed. A similar approach to Lie et al. [57] was used to compare the average crashworthiness ratings in real-life accidents and the Euro NCAP test results [59, pp. 6-7].

The primary results [59, p. 10] showed a general correlation between the Euro NCAP scores and injury risks in real-life accidents. In the German data, the average crash performance of vehicles with four stars was significantly better than that of three- or two-star rated cars. However, the difference between three- and two-star rated cars was not significant. A similar trend had been seen in the French results; the vehicles with three or four stars had a better performance than two-star rated cars, but the difference between three and four stars was statistically not significant. The British results stated that the crash performance of vehicles with two, three, or four stars was better than that of one-star rated cars, and the four-star rated cars had the best average crash-worthiness. Despite similar test approaches as that of Euro NCAP, no correlation could be identified between the NCAP test results and injury risks in the Australian and New Zealand crash data. This might be due to fewer analyzed vehicles, a different range of vehicle models analyzed, variations in the injury outcome coding, or a combination of these causes.

The data were analyzed further [59, pp. 12-13] to study the correlation between the test results and injury risks for the specific crash types. The British and French data provided sufficient information to compare the results of frontal and side impacts separately, while other crash data had to be excluded due to a lack of information. Similar results were achieved from British and French data; no trends were found between the Euro NCAP offset frontal impact results and frontal real-life accidents (Fig. 2.5).

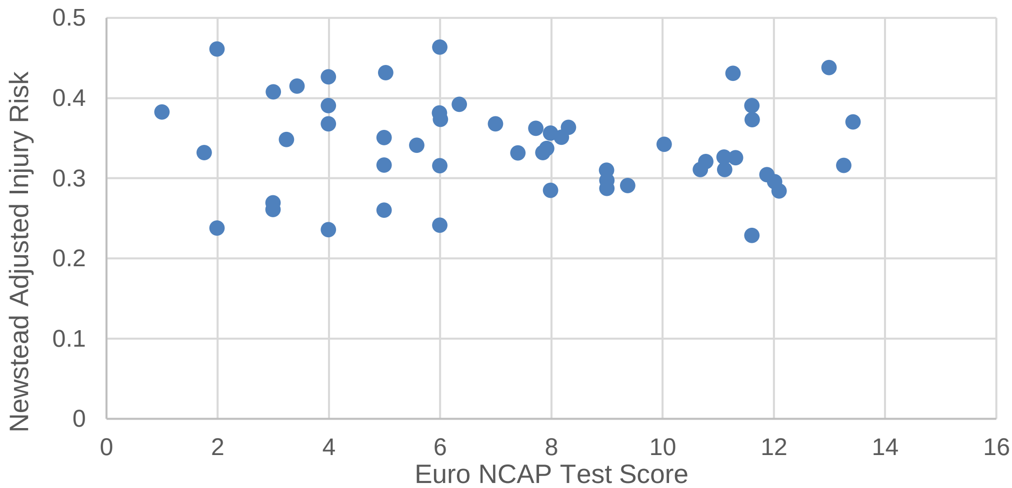

Figure 2.5: Frontal impact Euro NCAP scores vs. injury risks from British data; The Newstead adjusted injury risk estimates the probability of injuries for the drivers of vehicles involved in a crash [62, p. 14]

[59, p. 190]

The Euro NCAP side impact test results showed a better correlation with injury risks in real-life accidents (Fig. 2.6). However, in few cases, the injury risks do not correlate with Euro NCAP test scores.

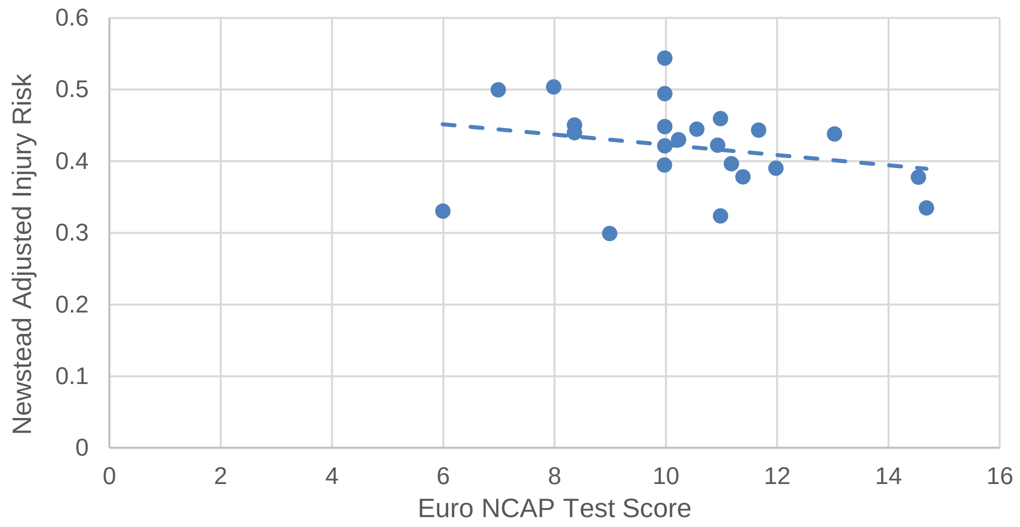

Figure 2.6: Side impact Euro NCAP scores vs. injury risks from British data

[59, p. 194]

Similar to the previous studies, the vehicle mass had been found as a more decisive factor for injury risks in real-life car-to-car accidents. The results criticized the Euro NCAP rating system, which is based on the assessment of factors that are not necessarily required to ensure good safety performance in real-life accidents [59, p. 15].

Segui-Gomez et al. [61, pp. 101-106] studied a dataset of real accidents that occurred in Britain from 1996 to 2008, which is more representative of modern vehicles compared to the previous studies. Multivariate Poisson regression models were applied to 1,259 cases that showed similar crash conditions to the frontal impact tests. The results showed no significant correlation between the Euro NCAP color segments for dummy measurements and serious injury risks in real-life frontal impacts (Fig. 2.7).

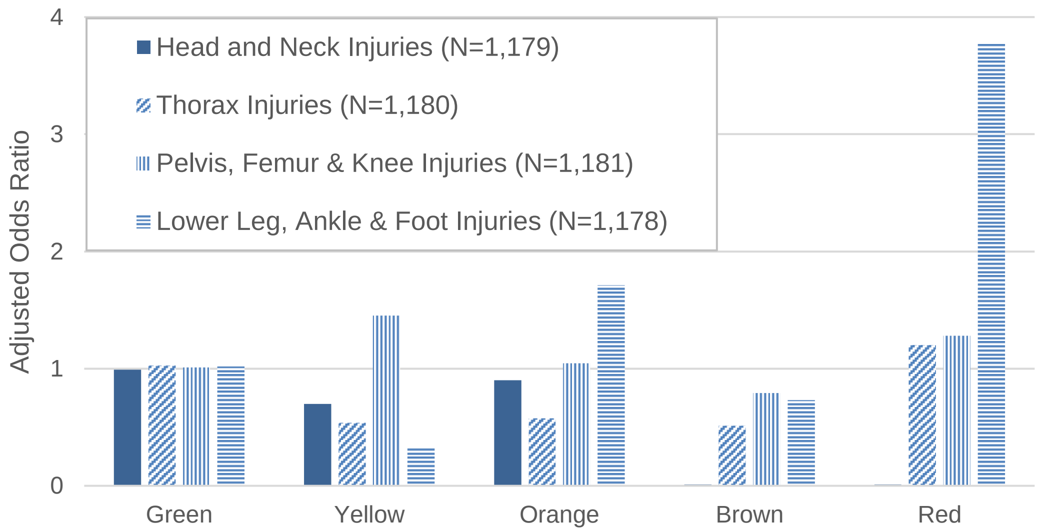

Figure 2.7: Adjusted Odds Ratio of serious injuries as front seat occupants in frontal impacts by Euro NCAP body region-specific rating; Odds Ratio > 1 is associated with higher odds of outcome

[61, p. 104]

As can be seen, reviewing the results of the previous works suggests that the overall Euro NCAP scores generally correlate with injury risks in real-life accidents. In-depth studies for different crash types showed that this correlation is not significant for frontal impacts. In frontal car-to-car accidents, the mass ratio is more decisive than the Euro NCAP ratings. The side impact test results showed a better correlation with real-life accidents.

Comparing the results of newer works (e.g., Fig. 2.5) with earlier ones (e.g., Fig. 2.4) showed that the correlation of test results with the crash performance in real-life accidents has decreased over recent years. This might be because optimization of the vehicles' structures achieves better results in the Euro NCAP tests that do not necessarily bring better vehicle safety in real-life accidents. Thus, the impact tests should be more representative for car-to-car accidents to increase the correlation and consequently reduce the injury risks in real-life accidents.

The General German Automobile Club (ADAC) conducted a series of frontal impact tests between 2005 and 2008 [63, pp. 18-24] to compare occupant protection of vehicles in frontal impacts in Euro NCAP tests and full-scale car-to-car collisions. The test set-up for car-to-car collisions is with 50 % overlap and a test speed of approximately 56 km/h for each vehicle, which is the baseline test of the Euro NCAP frontal impact test. Two male adult dummies were installed in the front seats with the same specifications, installation procedure, and instrumentation as used in the Euro NCAP frontal impact offset test. Fig. 2.8 shows the test results, by which self-protection of the test vehicles is normalized to the vehicle's performance in the Euro NCAP frontal impact offset test.

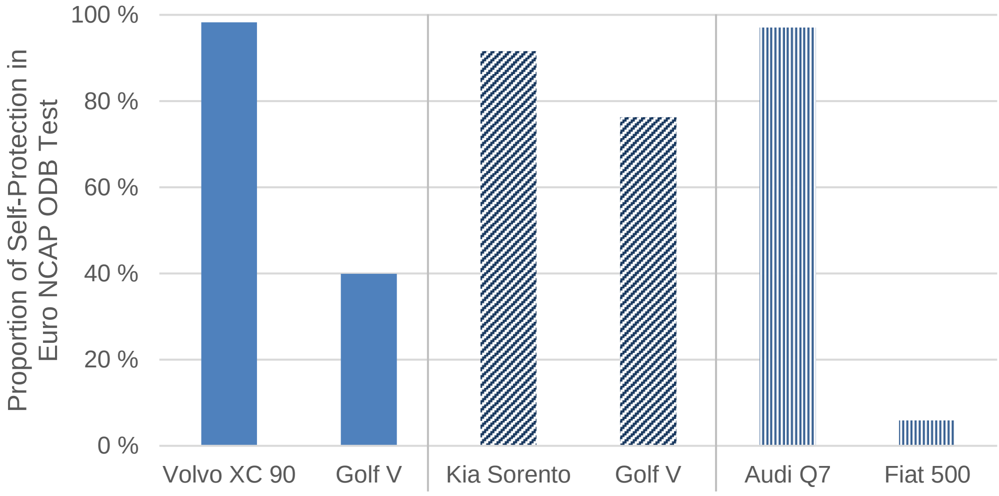

Figure 2.8: Occupant protection in three car-to-car collisions normalized to the crash performance of the involved vehicles in the ODB test; Volvo XC 90 vs. Golf V, Kia Sorento vs. Golf V and Audi Q7 vs. Fiat 500

[63, p. 24]

As can be seen, occupant protection of vehicles is different as they collide against a car and not a barrier. Even the heavy vehicles with a lower mass ratio have not reached 100 % self-protection relative to their crash performance in the Euro NCAP tests. This confirms the results of previous statistical analyses that the Euro NCAP frontal impact tests are not representative enough of car-to-car real-life collisions.

Yonezawa et al. [64] conducted several side impact tests to compare the results of ECE R95 and car-to-car tests. Fig. 2.9 presents the results of pair tests, which confirms the similarity of the side impact test to car-to-car collisions in terms of the dummy injury measurements.

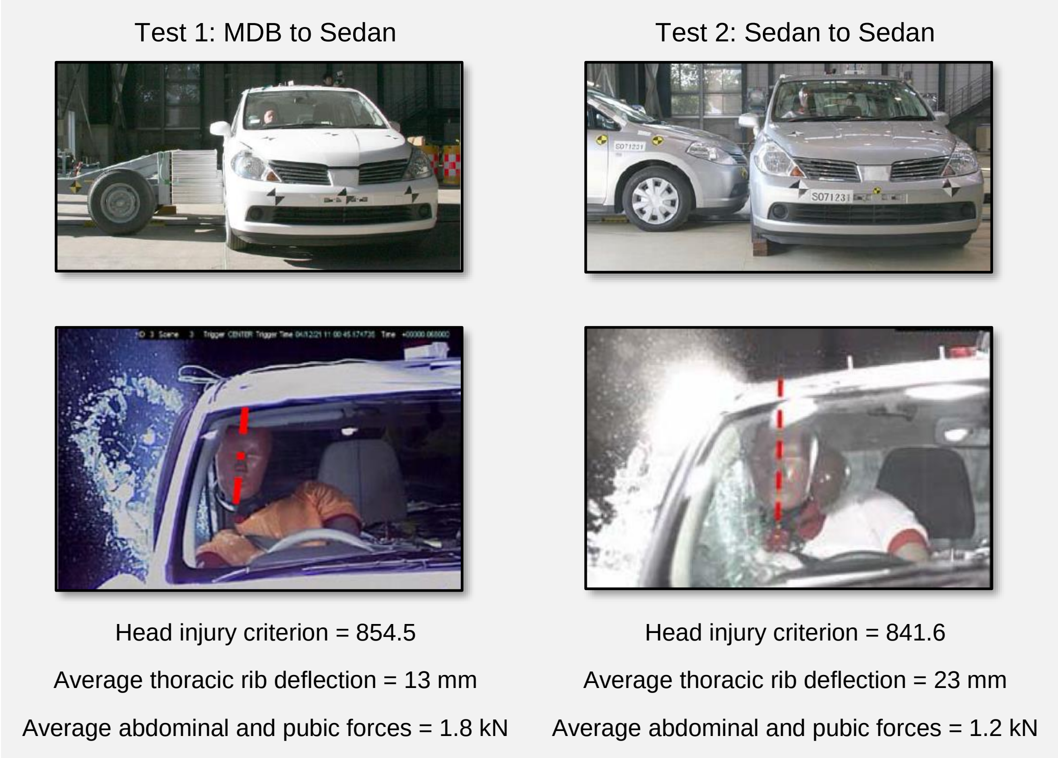

Figure 2.9: Car-to-car and moving barrier-to-car side impact tests [64, pp. 5-6]

Due to lack of correlation between frontal impact test results with car-to-car collisions, the focus of this work is on frontal impacts to ensure their assessment approaches have a greater influence on real-life serious injuries and road fatalities.

2.1.2 Heavy Quadricycles: L6e/L7e Category

In 2006, Europe had more than 300,000 quadricycles with a production volume of about 30,000 units per year [65, pp. 9-10]. Studies on market analysis [66] identified a growing market for quadricycles and estimated a market expansion up to 100,000 units per year in Europe 2017.

Owing to the technology advancements and the suitability for urban mobility, a large part of quadricycles are electric vehicles. These electric vehicles are suited to short trips, cause less impact on the environment, are affordable, and are ideal for congested cities. Technical University of Graz [67, p. 60] predicted that 20 % of the vehicle types from the urban traffic in 2025 will be electric microcars.

Besides the ultra-light weight and small size, heavy quadricycles, as a future solution for urban mobility, could have special vehicle concepts and designs. Quadricycles often have a compact deformation zone in the front and rear and have less than five occupants [67, p. 7]. Fig. 2.10 presents some prototypes and models of heavy quadricycles.

Occupants of these vehicles suffer from more severe injuries in car-to-car collisions with larger vehicles as a result of the vehicles' light weights and small sizes. Marschner and Liers [68, p. 6] predicted a 34 % increase in the Energy Equivalent Speed (EES), which is an index for collision severity, for quadricycles in frontal car-to-car collisions relative to normal passenger cars.

To address the issue of adequate safety, the VDI proposed a new car classification [69, p. 3] in 2013 for light vehicles with a curb weight of maximum 800 kg, which shall be positioned between M1 and L7e car classification. Thus, the term microcar in this work is not limited to the heavy quadricycles, but also includes possible future vehicle categories below the M1 car classification.

Figure 2.10: Some prototypes and models of heavy quadricycles [70–75]

2.1.2.1 Safety Regulations for Market Approval

Heavy quadricycles have to fulfill fewer requirements relative to normal passenger cars to acquire the approval mark. Tab. 2.3 summarizes all relevant safety regulations for the type approval of heavy quadricycles that was reviewed and updated in 2013.

Table 2.3: Safety regulations for the type approval of heavy quadricycles [18, Annex II]

Article	Scope	Vehicle categories
Annex II/B3	Electrical safety according to ECE R100	Electrified L vehicles
Annex II/B5	Avoidance of pointed or sharp parts or projections in front and rear structure	L vehicles
Annex II/B11	Mandatory requirements for safety belt anchorages and the installation of safety belts	L2e, L5e, L6e, and L7e
Annex II/B16	Avoidance of any pointed or sharp parts in interior	L2e, L5e, L6e, and L7e

As can be seen, heavy quadricycles should not pass any crash test to be approved for the market. The safety regulations are limited to requirements concerning the electrical safety, avoidance of sharp parts in the interior and structures of the vehicle, and safety belts. However, the performance and efficiency of the safety belts do not need to be tested in any full-scale crash test.

2.1.2.2 Safety Requirements of Euro NCAP

Euro NCAP tests heavy quadricycles as part of a safety companion. The frontal impact test is against a Full-Width Deformable Barrier (FWDB) at 50 km/h [76, p. 28], and the side impact test is similar to the previous version of ECE R95 from 2003, in which the MDB, weighing 950 kg, collides into the stationary test vehicle at 50 km/h [77, p. 28].

The safety companion of Euro NCAP for heavy quadricycles began in 2014 with the first test series of four vehicle models with the type approval mark in Europe. All vehicles showed poor results and a high risk of serious injuries and fatalities in the crash tests. Fig. 2.11 presents some critical performances of the restraint systems.

Figure 2.11: Ligier IXO (left), Tazzari Zero (middle), and Microcar M.Go (right) in frontal impact test of Euro NCAP

[78]

The safety belts are the only obligatory safety feature of heavy quadricycles that need to be approved by the safety regulations. However, as can be seen, some of the approved safety belts failed in the frontal crash tests of Euro NCAP, which shows the inadequacy of the safety regulations for the crash performance of the restraint systems.

In general, the tested vehicles showed a better performance in side impacts. While the tested vehicles acquired on average 3.5 from a maximum of 16 points in frontal impact tests, the average score for the side impact tests was about eight out of a maximum of 16 points. Nevertheless, the test results showed that the heavy quadricycles provide a much lower safety level than normal passenger cars [19].

The second test series of the Euro NCAP safety companion for heavy quadricycles was conducted in 2016, and the results were released in April 2016. As described by Euro NCAP [79], the objective of the second test series was to study the changes in this segment during the last two years. Four vehicle models with the market approval in Europe were tested. The test results showed very little improvement since the previous test series performed in 2014, and the provided safety level by heavy quadricycles is still low, which results in a high risk of serious and fatal injuries. Some tested vehicles were equipped with airbags; however, these failed to enhance the vehicle safety due to a lack of structural integrity in the vehicles and they appear to be a marketing attraction rather than a safety feature.

The test results showed that the safety level of heavy quadricycles is much lower than similarly sized normal passenger cars. However, some heavy quadricycles give customers the impression of a normal passenger car despite the mass differences because they look similar to small city cars. Thus, Euro NCAP called for legislative authorities to ensure a minimum crash safety level for heavy quadricycles [19]. Euro NCAP Secretary General [79] argued that significant enhancements could be acquired with simple changes. Therefore, Euro NCAP refuses the light-weight design and lower emissions as an argument for the low safety level of heavy quadricycles.

Tab. 2.4 summarizes the Euro NCAP test results of quadricycles in 2014 and 2016. The test results of a similarly-sized M1 passenger car, i.e., Toyota iQ, are presented as a reference for the common safety level of passenger cars in Europe.

Table 2.4: Euro NCAP test results for heavy quadricycles [79]

Model	Test year	Front score out of 16	Side score out of 16	Stars
Toyota iQ	2016	12	12	5
Aixam Crossover GTR	2016	2	10	1
Bajaj Qute	2016	4	6	1
Chatenet CH30	2016	6	6	2
Microcar M.GO Family	2016	4	6	1
Club Car Villager 2+2 LSV	2014	2	9	0
Ligier IXO JS Line 4	2014	2	8	0
Renault Twizzy	2014	6	7	2
Tazzari ZERO	2014	4	8	1

2.1.2.3 Current Safety Levels

Despite the growing market of heavy quadricycles in Europe, big car manufacturers show little interest in this segment, and the European market is fragmented into many tiny and regional markets for small and medium-sized manufacturers. Currently, there are more than 20 manufacturers of L6e/L7e cars in Europe [65, p. 10].

Owing to the small size of European manufacturers, their limited research and development capacity, and the small market, the production costs of heavy quadricycles are high, and they are of lower quality compared to the standards of normal passenger cars. Some manufacturers save on common safety features in their products to provide vehicles with an affordable price that is vital for their marketing to compete with similarly sized small city cars. Furthermore, affordable vehicles from this segment are not equipped with expensive driver assistance systems, and passive safety systems are regularly the first priority for occupant protection of heavy quadricycles.

Because of the limited number of heavy quadricycles on European roads, the statistical data about their crash performance in real-life accidents is limited. However, some local statistics present a high risk for the occupants of these vehicles in real-life accidents. During 2003 and 2004, collisions with injuries and fatalities were recorded in Austria [65, p. 14], and the results show that the occupants of heavy quadricycles are exposed to a higher risk of fatality in real-life accidents. While the number of fatalities for each 1,000 accidents with injuries was about 11 for normal passenger cars, it was more than 100 for the occupants of heavy quadricycles.

The lack of rigorous crash tests, demanding safety requirements, and competition from big manufacturers in the segment of heavy quadricycles have resulted in an inadequate safety level of these cars, which can be observed by analyzing the vehicle structures and safety systems of quadricycles on the market.

The only big car manufacturer that brought a microcar model to the market is Renault, which introduced the Renault Twizy in 2011. The Renault Twizy acquired two stars in the Euro NCAP test results and had the best crash performance among eight tested vehicle models. Fig. 2.12 shows the structure and safety concept of the Renault Twizy.

Figure 2.12: Vehicle structure and occupant compartment of the Renault Twizy [80], [81]

The Renault Twizy is equipped with a driver airbag and a four-point seatbelt system as standard for all models. The Euro NCAP test results [82] showed that the restraint systems worked well and the head of the driver was protected adequately. However, the stiff front structures resulted in high loads in the frontal impact test, and critical forces were recorded on the neck of the dummy. As can be seen in the picture, the occupant compartment is very compact, and there might be problems protecting the passengers in the rear seat. This was not tested by Euro NCAP, since only one dummy was installed in the front seat. However, in the frontal impact test of Euro NCAP, the dummy hit hard structures in the front, and high loadings were recorded on the driver’s knee and femur, which confirms the danger of restricted space in the occupant compartment. This issue was also observed by the Euro NCAP side impact test, where the head of the dummy traveled outside of the vehicle structure. Furthermore, the tested model of the Renault Twizy does not have any side structures for occupant protection. Thus, high forces are measured on the dummy, particularly on the chest, in the side impact test.

Nevertheless, Euro NCAP test results showed that the Renault Twizy is currently one of the safest quadricycles on the roads. Some other models in this segment lack primary safety systems. Fig. 2.13 presents the vehicle structure of a heavy quadricycle.

Figure 2.13: Frame and safety structure of the Aixam Roadline 2008 [83], [84]

The vehicle structure is designed as an aluminum spaceframe, and the occupant compartment is constructed from extruded aluminum profiles. No front structure is designed to absorb the crash energy, which means that the collision’s energy is absorbed by deformation of the occupant compartment. An analysis by the German Insurance Association (GDV) observed a similar structure type in several market approved heavy quadricycles with screwed or attached plastic parts as the body, which have insufficient stiffness for occupant protection [65, p. 16].

The Euro NCAP test results confirmed the instability of structures in some quadricycle models. In the Ligier test [85], the vehicle structure was deformed and the door pillar was separated from the windscreen in the frontal impact test. Qute's test results [86] showed instabilities of the vehicle structure, as many spot welds were released during the test. In the Tazzari test [87], the vehicle structure could survive the crash test; however, inspections after the crash test suggested that the vehicle structure had reached its limit and would not withstand a collision with higher severities. Similar results were acquired with Microcar and Aixam models [88], [89].

Despite their ultra-light weights and compact sizes, heavy quadricycles could provide adequate safety levels comparable to those of small city cars from the M1 car classification, which is demonstrated in the project Visio.M [90]. Visio.M was a research project containing 16 industrial, governmental, and academic partners with the objective of developing an ultra-light electric microcar [72]. The Visio.M vehicle was tested according to the Euro NCAP frontal impact and side impact testing protocols for normal passenger cars at the time of the project. The vehicle reached 15.7 points out of a maximum 16 points in the frontal impact test and acquired 13.7 points out of a maximum 16 points in the side impact test [90, p. 11].

2.2 Incompatibility of Cars

As described in Section 2.1, the size and mass of the vehicles within the category of passenger cars differ drastically. Different sizes, masses, and vehicle concepts affect the safety ratings and crash performance of cars, resulting in incompatibilities in real-life accidents. Incompatibility arises from three factors: mass, geometry, and stiffness [6, p. 149].

As one of the most influential parameters for incompatibilities, mass ratio is frequently discussed in publications. Considering the average mass in running of different vehicle segments (Tab. 2.1), the mass ratio of car-to-car accidents is up to 1:4 (e.g., between microcars and luxury cars from segment F) and could be even more between the extremes of each segment. A previous analysis [91, p. 100] of accident databases from Germany and the United Kingdom found a relationship between the mass ratio and the driver injury severity: higher mass ratios result in higher injury severities. Accident research data of Chauvel et al. [92, pp. 40-41] confirmed that the injury severity is strongly affected by vehicle mass in car-to-car collisions (Fig. 2.14). The occupants of light vehicles with a mass less than 950 kg take a double risk relative to the occupants of heavy vehicles with a mass more than 1750 kg.

Thomson et al. [93, p. 11] defined the geometry incompatibility or structural interaction as a factor that "describes how the structures of a vehicle deform at the local level when interacting with a collision partner".

Edwards et al. [94, p. 11] conducted a structural analysis on 55 cars from different segments and manufacturers to create a database (Fig. 2.15) of the position and dimensions of important vehicle structures, which might interact in car-to-car collisions. The selected vehicles covered 61 % of the European car market in 2003. The results showed a wide range in the position of important vehicle structures that would result in incompatibilities in car-to-car collisions.

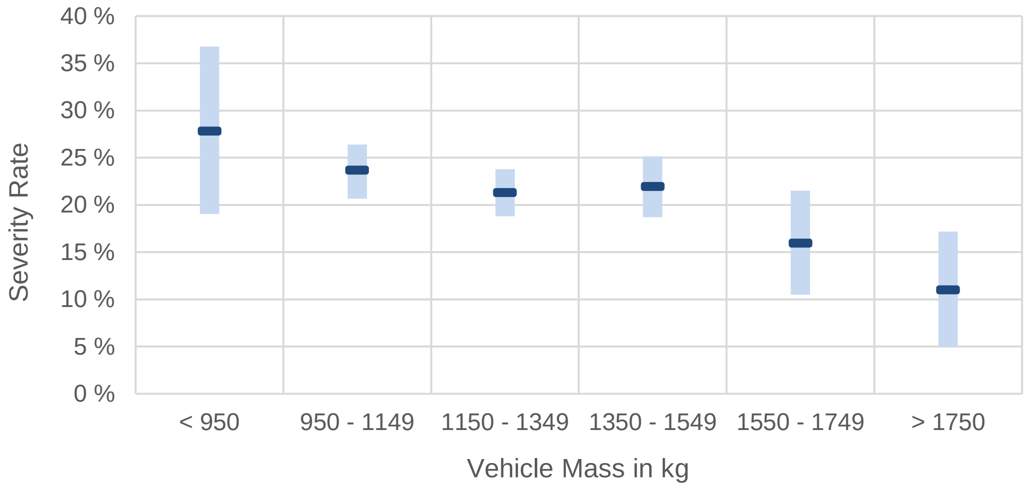

Figure 2.14: Percentage of severe and fatal injuries in 1,793 car-to-car frontal collisions with 2,871 involved occupants by vehicle mass; maximums, minimums, and averages for vehicles designed since 2000 or registered since 2004

[92, p. 41]

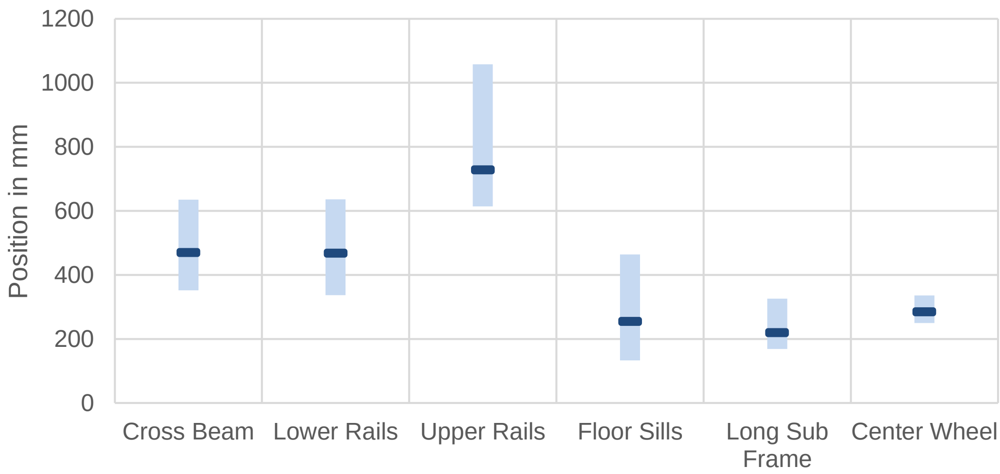

Figure 2.15: Vertical position of significant structural components of 55 passenger cars; maximums, minimums, and the weighted averages

[94, p. 11]

Three types of geometry incompatibilities are identified in real-life accidents as over/underride, small overlap, and the fork effect [91, p. 48].

Over/underride (Fig. 2.16 left) happens when the collision partner is struck above or below the main crash structures of the vehicle and the vertical structures are too weak to spread the loads to the main energy absorbers [91, p. 48]. Different vertical positions of the significant structural components are one of the main reasons for over/underride. The Japanese compatibility working group [95, p. 3] found that height differences greater than 100 mm result in over/underride.

Small overlap (Fig. 2.16 middle) happens when the collision partner is struck left or right of the range of the main crash structures of the vehicle and the bumper beam cannot spread the loads to the main energy absorbers. Consequently, the occupant compartment undergoes high intrusion values [91, p. 48].

The fork effect (Fig. 2.16 right) happens when the vehicle collides against a narrow object in the middle, and the bumper beam and other cross structures are too weak to spread the loads to the main energy absorbers [91, p. 48]. This effect results in high crushing and wasting the potential of structures for absorbing the collision's energy.

Figure 2.16: Samples of geometry incompatibilities;
Over/underride (left), small overlap (middle), and the fork effect (right)

[91, p. 53]; [14, p. 2]; [96]

Geometry incompatibilities are identified in 40 % of fatal and 36 % of serious injuries occurring to occupants of passenger cars [91, p. 60]. Over/underride and low overlap were identified as the dominant incompatibility problems in car-to-car collisions, while the fork effect was seen more in car-to-object impacts [93, p. 12].

Stiffness incompatibility consists of two issues: deformation force level of front structures and compartment strength.

Since the current frontal impact tests for market approval and from Euro NCAP use a fixed barrier in their crash set-up, the test severity and, consequently, the deformation force level of vehicles depends on the vehicle mass. Light vehicles require lower force levels to pass the test, while heavier vehicles have to provide higher force levels to absorb the collision's energy. Different force levels result in incompatibilities in car-to-car collisions, as the lighter vehicle absorbs more of the collision's energy because it cannot deform the heavier vehicle with a higher force level.

The lack of adequate compartment strength is observed in 25 % of serious injuries [13, p. 100] because of the current crash set-up of frontal impact tests with fixed barriers, which requires a compartment strength that depends on the vehicle mass. Fig. 2.17 presents the deficiency of current tests in obtaining the adequate compartment strength.

Figure 2.17: Deformations of a supermini in the ODB test with a 40 % offset at 64 km/h (left); in an equivalent car-to-car collision with a mass ratio of 1:1.3 (right)

[97, c11-c12]

2.2.1 Previous Works and Projects in Europe

Research and legislative organizations as well as manufacturers have studied the crashworthiness of vehicles for many years in Europe to enhance vehicle safety in real-life accidents. Fig. 2.18 presents the three most important works and projects about crash compatibility in Europe since 1996.

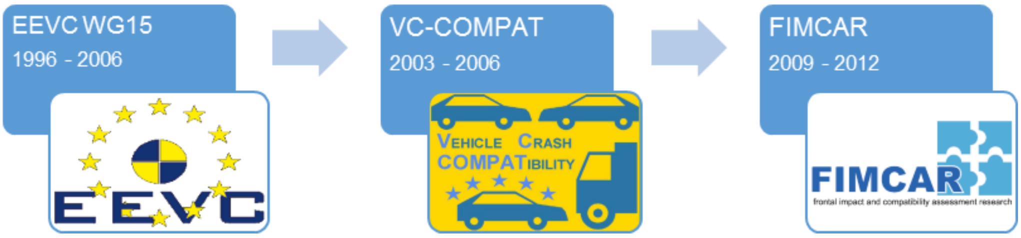

Figure 2.18: The most important European projects and works on crash compatibility [97], [94], [98]

The Enhanced European Vehicle-safety Committee Working Group 15 (EEVC WG15) was established in 1996 to work on improving car crash compatibility and frontal impact. The aim was “to develop a technical proposal for regulatory application to improve a vehicle’s frontal impact and compatibility performance” [99].

EEVC WG15 defined three objectives [97, pp. i-ii] for its works:

- Develop test procedures for assessing frontal crash compatibility
- Provide criteria for rating the test results
- Perform a benefit analysis for enhancing frontal crash compatibility

The activities of EEVC WG15 were supported by the project Vehicle Crash Compatibility (VC-COMPAT) between 2003 and 2006. The main aim of VC-COMPAT was to develop some crash test procedures [94, p. 4]. EEVC WG15 and VC-COMPAT presented their results in a suite of two assessment approaches [97, pp. i-iv] for frontal crash compatibility. Both approaches use a set of full width and offset tests to assess different properties, which are identified as relevant for compatibility.

In approach one, the vehicle should be tested against a FWDB and the ODB of ECE R94. Loads behind the full-width deformable element should be measured to assess crash compatibility. In approach two, the test set consists of the FWRB and a Progressive Deformable Barrier (PDB). The deformation pattern in the PDB should decide the crash compatibility of the test vehicle.

EEVC WG15 stated that these two assessment approaches were not developed sufficiently to allow a comparison or to finalize the assessment approach for frontal crash compatibility. Nevertheless, based on the works of EEVC WG15, VC-COMPAT, France submitted a proposal to substitute the ODB with a PDB in ECE R94 to enhance the passive safety of modern vehicles and harmonize the deformation force levels in the European vehicle fleet [100, pp. 2-3]. This proposal was criticized by the automotive industry, particularly by the German Association of the Automotive Industry (VDA), that the proposed test cannot punish aggressive structures or test the restraint systems with an unrealistic acceleration pulse [101, p. 23]. Furthermore, the VDA discussed that optimizing the vehicle structures for the proposed assessment approach would result in lower safety levels in car-to-car collisions [101, p. 27]. Thus, France’s proposal to update ECE R94 was rejected in 2010.

Frontal Impact and Compatibility Assessment Research (FIMCAR) was a research project conducted between 2009 and 2012 with the aim of answering the open questions from previous works, particularly from EEVC WG15 and VC-COMPAT, to finalize an assessment approach for the crash compatibility of cars in frontal impacts [98, p. 105].

The two assessment approaches from previous works were investigated and further developed in the FIMCAR project. FIMCAR finally selected the first approach, using FWDB and ODB with a criterion based on the load cell measurements, for the final assessment approach for the crash compatibility of cars in frontal impacts. The project results were submitted as a proposal to rule-making officials in ECE committees for final evaluation and potential adoption [98].

Besides the aforementioned studies, many other research organizations studied crash compatibility and the proposed assessment approaches. Among others, the project Safe Small Electric Vehicles through Advanced Simulation Methodologies (SafeEV) was conducted between 2012 and 2015 to develop “a clear and practicable guideline for the virtual testing of small electric vehicles” with the focus on small electric vehicles by 2025 and afterwards [102]. SafeEV reviewed previous works and proposed an approach using the Moving PDB (MPDB) for the safety assessment of microcars [103]. This assessment approach had been developed in previous works by the TNO [104] and had been studied in EEVC WG15, VC-COMPAT, FIMCAR, and works of other research organizations [14], [105]. However, several open questions remain with regard to the rating of the test results and the low crash severity of MPDB tests for heavy vehicles.

However, Euro NCAP has decided to update the frontal impact tests to consider crash compatibility in its rating system. Euro NCAP published a safety roadmap for 2020 [106, pp. 13-14], which includes substituting the current Euro NCAP frontal offset test with a moving barrier. According to the roadmap, the test protocol should be delivered in 2018 and the new test[2] will be adapted in 2020.

2.3 Methodology and Tools

The aim of this section is to discuss the general approach of the previous works and find potentials for improving vehicle safety in this study.

The general approach in previous works for studying crash compatibility of vehicles in frontal impacts can be broken down into five steps using four main tools (Fig. 2.19).

The general approach begins with a statistical analysis of collisions to identify the crash compatibility problems and potentials to enhance vehicle safety. The identified problems are investigated using in-depth statistical analyses and some theories are developed for improving crash compatibility. The theories are validated and further developed in full-scale crash tests and simulation analyses, and the results are used to develop a solution for assessing crash compatibility. Finally, the developed assessment approaches are validated using full-scale crash tests and simulation analyses.

FIMCAR criticized [91, p. 10] the accident analysis in earlier works from EEVC WG15 and VC-COMPAT that were based on old datasets. The accident data in these works were collected between 2004 and 2005 and contained few vehicle models built after 2000. Since ECE R94 became mandatory for newly registered vehicles from 2003, many cases from the accident data did not meet the mandatory safety requirements and were not, therefore, representative of the modern vehicle fleet in Europe.

[2] The author has been informed through several conversations and discussions with experts in conferences and meetings that the MPDB test procedure would be announced as the new Euro NCAP frontal impact offset test in 2018. However, there is no published material on this decision to be cited in this work.

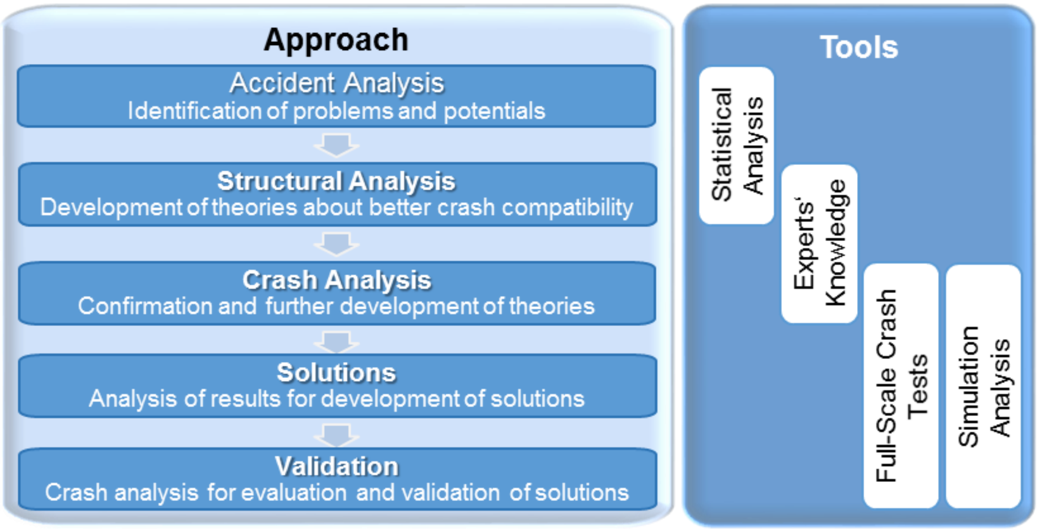

Figure 2.19: Approach and tools for studying frontal crash compatibility

FIMCAR analyzed two datasets from the United Kingdom and Germany [91], which covered a wide range of vehicles with masses from less than 750 kg to more than 2000 kg. The focus of FIMCAR was not on microcars, and about 80 % of the vehicles from the German dataset and 75 % of the vehicles from the United Kingdom dataset were within the range of vehicle mass from 1000 kg to 1749 kg [91, pp. 27-81]. Thus, special issues of microcars might be underrepresented in the FIMCAR results from the accident and structural analyses.

In this work, besides the results of the FIMCAR project, the results from the accident analysis in the Visio.M project are used to cover the entire vehicle fleet of passenger cars in Europe. Visio.M conducted a statistical analysis [68] on more than 22,000 accidents from the German In-Depth Accident Study's (GIDAS) Database with the focus on safety requirements of electric microcars, which will fill the gap in the statistical analyses of the previous works.

Expert knowledge has been used in different studies for interpreting the structural analyses and defining compatibility requirements that should be assessed in crash tests. Although there is a common understanding of crash compatibility, the previous projects failed to provide any rigorous definition for crash compatibility and its objective. FIMCAR declared the disagreement on terminology and the presence of individual definitions by citing compatibility as a reason for lack of progress in this field [98, p. 107]. Therefore, a successful research project that aims to advance crash compatibility must discuss the definition and objectives of crash compatibility to avoid inconsistency in expert opinions.

For crash analysis, development of solutions, and validation of their efficiencies, two main tools have been used: full-scale crash tests and simulation analysis. Each of these tools has some advantages and disadvantages (Tab. 2.5), and it is common to combine both to study the crash compatibility of vehicles in frontal impacts.

EEVC WG15, VC-COMPAT, and FIMCAR conducted many real crash tests, the results of which are published in different papers and reports and are available for this study. Furthermore, the NHTSA provides free access to two datasets of crash tests and real-life accidents. The NHTSA crash test database [107] contains reports of results, videos, pictures, and data measurements of more than 7,800 crash tests from various types. The National Automotive Sampling System (NASS) [108] contains more than 129,000 cases of real-life accidents on the American roads. Owing to the access to rich data sources and the high costs of real crash testing, this work does not conduct any new crash tests and only reviews results from previous works and databases of the NHTSA.

Table 2.5: Advantages and disadvantages of full-scale crash testing and simulation analysis for studying frontal crash compatibility

Tool	Advantages	Disadvantages
Full-scale crash testing	+ Similar to real-life accidents + Considers all influential parameters + Trustworthy results	− Expensive − Difficult to fade out the influence of undesirable parameters − Issues with reproducibility and repeatability − Difficult to analyze the results − Limited possibility for variation of the vehicle models
Simulation analysis	+ Lower costs relative to crash testing + Possibilities for studying the influence of individual parameters + No problem with reproducibility and repeatability + Simplicity of extensive analysis of the results + Full control for varying the vehicle models	− Issue of trustworthiness of the results − Need to perform full-scale crash tests to validate the models

One of the main tools for studying crash compatibility in this work is virtual testing with the Finite Element (FE) simulations. Virtual testing and FE simulations have made a great progress in recent years, and it is expected that virtual testing can replace real testing for most safety regulations in the near future [109, p. 33]. However, an analysis should be conducted on the FE simulations that are used in this study to assure the trustworthiness of the results.

The objective of this analysis is to assure that the considered simplifications and numerical errors in a simulation analysis do not affect interpretations of the simulation results. The analysis consists of two parts: verification and validation.

The American Society of Mechanical Engineers (ASME) defined verification as “the process of determining that a computational model accurately represents the underlying mathematical model and its solution” [110, p. 11], which consists of code and model verification.

The code used for this work is LS-DYNA, which is a general-purpose FE software developed by Livermore Software Technology Corporation (LSTC). This is a common code for automotive crash analysis and is introduced as an acceptable analysis code [111, p. 240]. For pre- and post-processing, LS-PrePost from LSTC and HyperGraph from the software suite of Altair HyperWorks are used. To have comparable results, all simulations are done on the same computer cluster with 32 CPUs (E5-2670 Intel Xenon 8 Core CPU 2.60 GHz). Depending on models’ complexity and simulation time, each simulation took between 5 hours (e.g. microcar in the FWRB test) and 39 hours (e.g. Toyota Camry vs. Toyota Camry in the car-to-car test).

Verification of a simulation model is not standardized, and many methods in existence are based on the experience of experts. Ray et al. [111, pp. 105-108] categorized relevant issues for model verification into five groups: geometry generation, mesh sensitivity and quality, contact stability, energy balance, and time step issues. Cordero et al. [112, pp. 19-21] provided a list of requirements (Tab. A.1 in Appendix A) to evaluate the model regarding the verification issues. In this study, simulation models are considered verified if they fulfill these requirements.

ASME defined validation as "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model" [110, p. 11]. Therefore, predictability of a simulation model might vary in different applications. E.g., a vehicle model that is developed and validated for side impacts is not necessarily validated for frontal impacts. Cordero et al. [112, pp. 21-22] provided a list of requirements (Tab. A.2 in Appendix A), which evaluate the predictability of a model. In this study, the simulation models are considered validated if they show a good correlation with the kinematic, time history signals for acceleration and deformations of a set of real test results in the application range. This will ensure the trustworthiness of the simulation analyses for investigating the crash compatibility of vehicles in frontal impacts. Appendix B presents the simulation models used in this work and describes the results of their trustworthiness analyses.

2.4 Research Questions

Crash compatibility has been identified in Chapter 1 as an issue with high potential for saving lives on European roads. An analysis of the fleet of European passenger cars in Section 2.1 showed the diversity of vehicle concepts and hence the importance of crash compatibility. Furthermore, accident analyses in Sections 2.1.1.3 and 2.1.2.3 showed that test results from the current safety regulations, particularly for frontal impacts, do not correlate with real-life injury risks. The aim of this work and hence the main research question of this study is:

> How should the frontal crash compatibility of European passenger cars be assessed?

Answering this question will result in a new assessment approach for the market approval of passenger cars in Europe, which will reduce the injury and fatality risk of real-life accidents and hence support the European Commission's target to further reduce the number of road fatalities.

As described in Section 2.2.1, previous works have dealt with this question and presented various proposals to assess frontal crash compatibility, which have not yet been accepted. Regarding the previous works, four more research questions should be answered to reach the main aim of this thesis. Each question describes the objective of one chapter:

- Chapter 3: What is the definition of crash compatibility?
- Chapter 4: Which test procedure should be used to assess and/or optimize frontal crash compatibility?
- Chapter 5: How should the test results be rated to complete the assessment approach for frontal crash compatibility?
- Chapter 6: Is the developed assessment approach valid? How should a vehicle structure be optimized for frontal crash compatibility?

3 Definition of Crash Compatibility[3]

The aim of this chapter is to provide a fundamental definition of crash compatibility that serves as a common basis for discussing the assessment approaches. Fundamental, in this case, means that the definition model is general and independent from test procedures or assessment approaches.

The objective of Section 3.1 is to review the state of the art and present the most important definitions for crash compatibility from previous works and projects. It highlights and compares points of agreement and disagreement to underline the differences and conflicting issues.

Section 3.2 presents the proposed fundamental definition model for crash compatibility. First, three requirements for a definition model are derived from the state of the art. The elements of the definition model are described and discussed in regard to the derived requirements. Finally, the application of the definition model is explained using examples.

The objective of Section 3.3 is to validate the efficiency of the developed definition model. First, an assessment approach is developed by implementing the definition model in Euro NCAP frontal impact tests. Several vehicles are assessed in this approach, and their crash performance in real-life accidents is compared. The efficiency of the definition model is considered validated if the better rated vehicles show better performances in real-life accidents.

Section 3.4 summarizes the results of this chapter and discusses the limitations of the results that can be investigated in future works.

3.1 State of the Art of Compatibility Definitions

Unlike conventional vehicle safety that focused on self-protection, crash compatibility considers both self- and partner-protection. Incompatibility parameters, also known as aggressiveness, are categorized into three groups: mass, geometry, and stiffness [6, p. 149]. However, besides this common understanding from crash compatibility, no rigorous definition is widely accepted from the community of vehicle safety experts. As described by Johannsen et al. in the final paper of the FIMCAR project [98, p. 107], "one explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility."

This part aims to review the literature for different descriptions and definitions of crash compatibility. The issue of individual interpretations and objectives in discussing crash compatibility is explained, and the differences, particularly between the industry and research organizations, are highlighted.

3.1.1 Current Definitions

The definitions of crash compatibility are reviewed in three literature groups:

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[3] This chapter is taken in part from an article [113] published in VDI Conference Vehicle Safety 2015. This article was prepared by Sadeghipour (main author) during his work. For more information, refer to the author's contributions [113, p. 33].

1. Works before 2000, which tried to form a common understanding of crash compatibility as this topic was introduced and raised.
2. European research projects, which tried to develop an assessment approach for crash compatibility and implement it in safety regulations.
3. Individual researchers who supported the European research projects or criticized their works.

3.1.1.1 Before 2000

The term compatibility had been used in several publications before 2000. However, no strict definition could be found for crash compatibility in the literature review of Van der Sluis [114] between 1985 and 2000. He determined some common understandings among the variety of definitions and presented a list of definitions [114, p. 8] from the publications to give an overview of the objectives and aims of compatibility in the research community of that time:

1. EEVC WG 15 summarized its research activities until 1998 in a paper [115] and defined the term compatibility as follows: “In protecting car occupants most activity has been associated with improving the occupant’s own car to aid his protection. In future, improvements should be possible from improving the front of the other car involved. The term ‘compatibility’ has been coined to describe this subject”.
2. Niederer et al. [116] investigated compatibility measurements for ultra-light vehicles, with a curb mass less than 600 kg, using real crash testing and lumped parameter models. They defined compatibility as follows: “In qualitative terms, vehicles are denoted as collision compatible if their deformation characteristics are such that they do not impose excessive loads on the occupants of the collision partner under a well-defined set of crash conditions. In particular, a collapse of the passenger compartment of the impacted car has to be avoided”.
3. Shearlaw and Thomas [117] reviewed real world accidents to investigate the relation between structural interaction and injury outcomes. They defined incompatibility as inequality in the distribution of deformations and structural characteristics between the vehicles.
4. Audi, Volkswagen, and Seat [118] investigated the potential of computer simulations as an aid to develop crash compatible vehicles and validated their results with full-scale car-to-car crash tests. They did not define crash compatibility, but explained its objective as follows: “The goal of compatibility is [...] to enhance partner-protection without decreasing occupant protection or to optimize occupant protection in such a manner that the overall safety of the vehicle is maximized”.
5. Klanner et al. [119] proposed a rating procedure to assess the aggressiveness and compatibility of cars. They defined compatibility as follows: “Compatibility of a vehicle is defined by both self-protection and partner-protection performance. A compatible car must feature good self-protection and low aggressiveness”.

Van der Sluis [114, p. 3] summarized the definitions and descriptions as one purpose for crash compatibility: “The capability of cars to protect their occupants in crashes, while at the same time produce as less harm as possible to occupants of opponent cars.”

3.1.1.2 European Research Projects

EEVC WG15 did not provide a definition for crash compatibility, which resulted in some disagreements when the working group investigated the PDB approach. EEVC WG15 illustrated several important physical processes and properties that influence the crash compatibility of a vehicle. However, the working group could not identify any validated quantitative method that translates these properties into criteria for assessing crash compatibility. Thus, EEVC WG15 [97, p. 33] declared the necessity for a rigorous definition of crash compatibility, which can evaluate the performance limits of vehicles and outline their requirements for assessing crash compatibility.

Similarly, the VC-COMPAT project did not provide any definition for crash compatibility and remained with the common understanding that crash compatibility considers both, self- and partner-protection.

The FIMCAR consortium also did not provide any definition for crash compatibility. However, the consortium reviewed the previous works and provided a list of issues [98, p. 107] that are relevant to the objectives of crash compatibility:

- “Compatibility consists of self- and partner-protection”.
- “Improved compatibility will decrease injury risks for occupants in single- and multiple-vehicle accidents”.
- “Compatible vehicles will deform in a stable manner, allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved”.

3.1.1.3 Individual Researchers and Other Experts

Kramer [6, p. 149] categorized the aggressiveness parameters of collisions into three groups of mass, stiffness, and geometry. He defined the compatibility as a term that includes strategies, design policies, and measures to make vehicles compatible against the aggressive properties of different vehicles. Kramer assumed the velocity change as a measure for the collision severity and associated it with the vehicle mass to describe the potential of crash compatibility for different vehicles (Fig. 3.1).

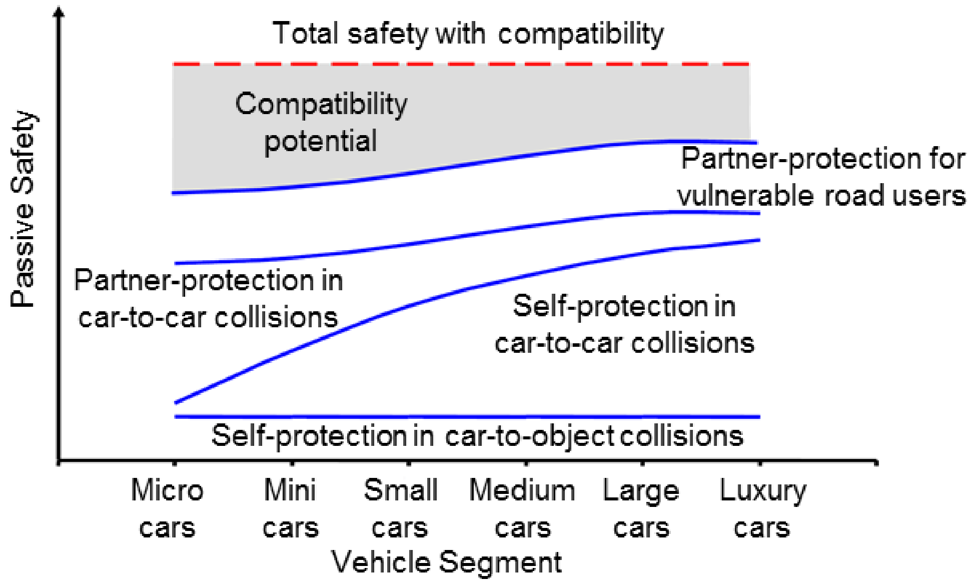


Figure 3.1: Potential of passive safety and compatibility for different vehicles according to the Kramer’s model

[6, p. 156]

Kramer used this model to explain the compatibility measures and their priorities [6, p. 156]. However, the model distinguishes the potential of self- and partner-protection from the potential of crash compatibility, which is not clarified by Kramer. Furthermore, the definition of Kramer does not demand any changes in aggressive designs.

Schwarz and Zobel from Volkswagen AG [120, p. 1] described crash compatibility as "a combination of self- and partner-protection in such a way that optimum overall safety is achieved," which means that the "compatibility tries to minimize the number of fatalities and/or injuries, regardless of the vehicle in which the injuries or fatalities occur." They added that customers expect further enhancements to occupant protection, and compromising of self-protection for more partner-protection is inadmissible.

In the same manner, O'Brien [95, pp. 122-128] considered the risk of injury to all road users and defined crash compatibility as "the optimization of vehicle design to minimize the number of injuries and fatalities that occur in all collisions in the accident environment." He explained that the mean risk of injury in a compatible collision is equal to the mean risk of injury measured in crash tests.

3.1.2 Points of Agreement and Conflict

The literature review shows an agreement between researchers and the automobile industry that crash compatibility should consider partner-protection in addition to self-protection. However, the border between the required levels of self- and partner-protection is unclear. While some researchers demand less aggressiveness in heavier vehicles, it is not acceptable for the automobile industry to reduce self-protection of these vehicles. These different perspectives are mainly due to the lack of a strict definition for crash compatibility as a reference for the discussions. The following sections describe the most important conflicts between different interpretations and perspectives of crash compatibility, which should be clarified in a definition model.

3.1.2.1 Conflict of Overall Safety

Schwarz and Zobel [120] and O'Brien [95] used the terms overall safety or accident environment in their definitions. They did not consider the risk of injuries for occupants of a single vehicle and considered the risk of injuries for all involved parties. However, considering the mean risk of injury in the accident environment will result in underrepresented injury risks for lighter vehicles in car-to-car collisions, which is explained by the following example.

Considering four different cases of a car-to-car frontal impact with full overlap at two different collision speeds and with two different mass ratios (Fig. 3.2). The collision severity for occupants of each collision scenario can be represented by the difference in the collision speed of the vehicle before and after the collision. The impulse-momentum theory, Eq. (3.1), can be used to estimate the after-collision speed of a vehicle:

$$v_a' = \frac{m_a v_a + m_b v_b + m_b k (v_b - v_a)}{m_a + m_b}, \tag{3.1}$$

where v_a' is the vehicle speed after the collision in km/h, m_a and v_a are the vehicle mass in kg and vehicle speed in km/h before the collision, respectively, and k is the coefficient of restitution that is estimated to be 0.10 for car-to-car in-line collisions [121, p. 39].

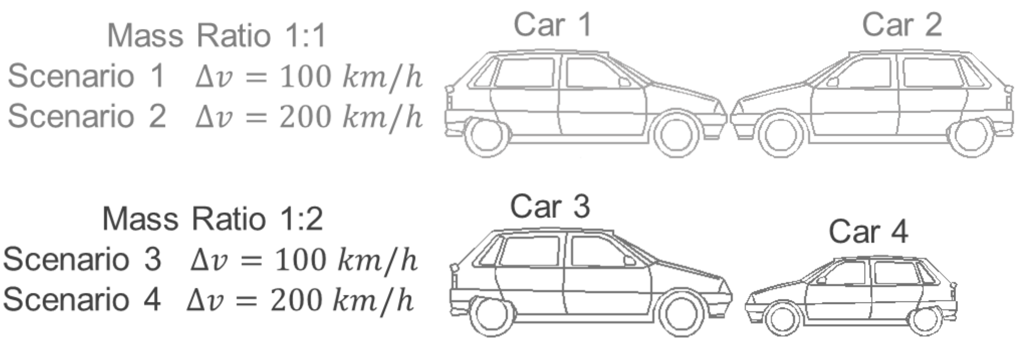


Figure 3.2: Four cases of car-to-car frontal impact at two different collision speeds

Graphics from [122]

O'Brien [95, pp. 82-86] conducted a statistical analysis on frontal car-to-car and car-to-object collisions and determined a function to relate the mechanical severity of the collision, represented by Δv, to the injury severity of the vehicle occupants (Fig. 3.3).

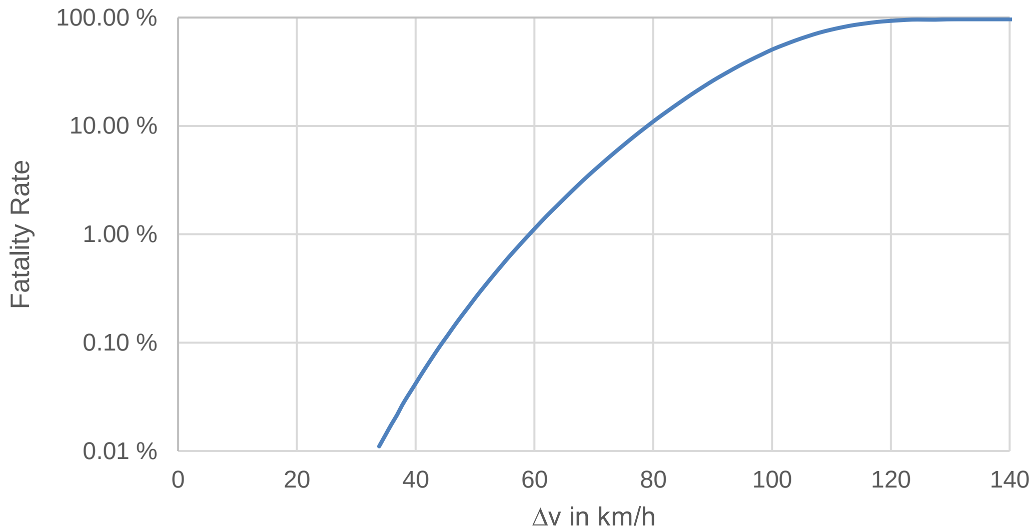


Figure 3.3: Comparison between collision Δv and the degree of injury to belted passenger vehicle occupants involved in frontal collisions.

[95, p. 86]

Inserting the estimated Δv from Eq. (3.1) in the function of O'Brien (Fig. 3.3) results in the risk of fatality for occupants of each vehicle in different collision scenarios and the total risk of injury in the collision's environment (Tab. 3.1).

Table 3.1: Risk of fatality at the vehicle level and in the collision's environment (bold)

Δv in km/h	Mass ratio 1:1			Mass Ratio 1:2		
	Risk for car 1	Risk for car 2	Total risk	Risk for car 3	Risk for car 4	Total risk
100	0.006	0.006	**0.006**	0.000	0.056	**0.028**
200	0.773	0.773	**0.773**	0.056	0.964	**0.510**

The example of car-to-car collisions clarifies that the risk of fatality in the collision's environment depends on the collision's severity. For car-to-car collisions at 200 km/h, the total risk of fatality in the collision's environment (i.e. mean risk according to the definition of O'Brien) is lower with the mass ratio 1:2 than with the mass ratio 1:1. While the "aggressiveness" of the heavier vehicle threatens the life of the lighter vehicle's occupants, this collision could be interpreted as more compatible than a collision between two identical vehicles, because the total risk of fatality in the collision's environment is less.

O'Brien [95, p. 122] added an extra requirement for a compatible collision: "The mean risk of injury in a compatible collision should always be equal to the mean risk of injury measured in the equivalent design load cases (i.e., crash tests)". With this requirement, the collisions with the mass of ratio 1:2 is categorized as incompatible, since the risk of injuries for occupants of the lighter vehicle is higher than in crash tests.

3.1.2.2 Lack of Reference

Many descriptions and definitions of crash compatibility include comparative terms without providing a reference for comparison, thus causing different interpretations. This issue is explained using two examples:

1. The FIMCAR consortium explained that improved compatibility will reduce the risk of injuries. However, it is unclear by which reference the risk of injuries should be measured. Considering a car-to-car collision with a mass ratio of 1:1.5, the lighter vehicle shows improved compatibility if a car-to-car collision with a mass ratio of 1:2 is the reference for the risk of injury. At the same time, the lighter vehicle shows poor compatibility if a car-to-car collision with a mass ratio of 1:1 is set as the reference for the risk of injury.
2. The FIMCAR consortium described the exploitation of the deformation zone as a requirement for compatible vehicles. However, it is not clear when and relative to which test scenario the exploitation of the deformation zone should be measured.

Although these descriptions and definitions help to understand crash compatibility, they will reach their limit by discussions about the proposed assessment approaches.

3.1.2.3 Difference between Safety and Crash Compatibility

Most descriptions and definitions do not distinguish between crash compatibility and safety. These definitions help to understand crash compatibility, but as proposed assessment approaches are discussed and incompatible vehicles have to be identified in car-to-car collisions, some problems arise due to individual interpretations.

If incompatibility arises in a collision, it is challenging to find the incompatible vehicle based on the current definitions. E.g., the occupants of a microcar that is not equipped with the minimum safety systems are subject to a high risk of injuries, even if the collision partner is a compatible vehicle with excellent partner-protection.

Compatibility and safety are different characteristics that are mixed in current definitions. E.g., the occupants of a luxury car, which is over-equipped with modern safety systems, would not be injured in a minor crash against a light vehicle, even if both vehicles are incompatible. Furthermore, the risk of injury depends, among other things, on the collision severity, and even compatible vehicles with a high level of safety cannot exclude the risk of injury in highly severe collisions.

Therefore, distinguishing between crash compatibility and safety is necessary for judging the crash performance of different vehicles. This helps to improve the crashworthiness of light vehicles without penalizing the safety level of heavier vehicles.

3.2 A Fundamental Definition Model

This section describes the approach of a fundamental definition model for crash compatibility that can be used as a reference for discussing the assessment approaches and crashworthiness of vehicles. Fundamental means that the definition model is general and independent from special crash test procedures or assessment approaches. Considering the issues discussed in Section 3.1.2, a fundamental definition should fulfill three requirements:

1. Includes no conflict with the objectives and general understanding of crash compatibility.
2. Describes a clear reference by which the improvement of crash compatibility should be assessed.
3. Describes a clear difference between safety and crash compatibility to distinguish between compatible and incompatible vehicles.

The definition model consists of a reference for the vehicle safety (safety level) and an index (compatibility rate) for measuring the crash compatibility of vehicles. Combining these values results in an overall rating for vehicle safety and compatibility.

3.2.1 Safety Level

Kramer [6, p. 2] defined safety as the lack of dangers, which is explained as a situation in which the risk is smaller than the largest still tolerable risk of a particular technical process or state. According to this definition, a safe vehicle should protect its occupants and exclude the risk of severe injuries or death. However, safety is a relative term and no car can exclude the risk of injuries for all types of crash scenarios. The safety level describes the severity of a collision in which the vehicle is still safe for its occupants. Considering the EES as an index for collision severity, and the vehicle mass as an important parameter for the crashworthiness of the vehicles, the safety level can be defined in terms of the kinetic energy of a collision:

> *Safety level* of a vehicle is the maximum dissipated kinetic energy of a collision at which occupants of the vehicle are not injured or are tolerably injured.

Safety level can be defined for both passive and active safety. The passive safety level contains the dissipated kinetic energy by an ideal crushing of the whole deformation zone and an ideal use of all restraint systems (seat belts, airbags, etc.). The active safety level contains the dissipated kinetic energy by an ideal use of available active safety systems in the vehicle (e.g., advanced emergency braking systems, adaptive cruise control systems). This work focuses on the passive safety level[4], which is presented in schematic form in Fig. 3.4.

[4] From here onwards, “safety level” refers to the passive term of the proposed definition.

The safety level describes the theoretical safety potential of the vehicle that might be unfeasible for many crash constellations. However, it serves as a reference for comparative terms about the crash performance of vehicles in different scenarios.

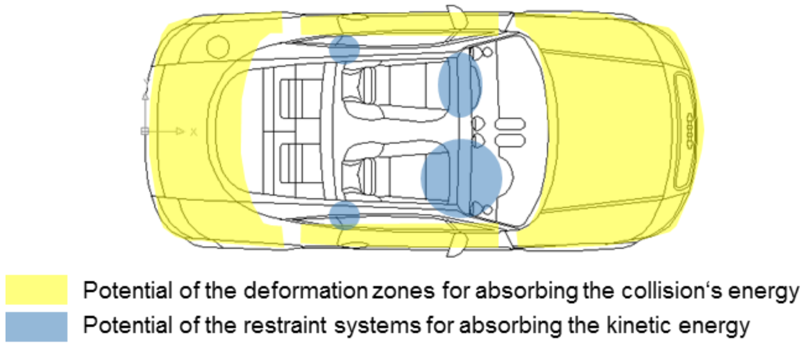


Figure 3.4: Schematic of the safety level

Graphic from [123]

3.2.2 Compatibility Rate

A compatible system is defined in Merriam Webster [124] as "a system that is designed to work with another device or system without modification." Therefore, a compatible vehicle should be able to use its safety systems as intended by design, in different situations and as they come to interact with other parties. Regarding the defined safety level as a reference for evaluating crash compatibility in a specific crash scenario and considering both self- and partner-protection:

> *Compatibility rate* is the ratio of the maximum dissipated kinetic energy by a car in a specific crash scenario without intolerable injuries for all participants to the *safety level* of that car.

Similar to the safety level, compatibility rate can be defined for both passive and active safety. The passive compatibility rate describes the ability of the vehicle to use its passive potential safety systems, such as using a large part of the deformation zone and an appropriate deployment of the airbags in the desired time to collision. The active compatibility rate describes the ability of the available active safety systems in the vehicle to avoid or mitigate the collision as intended by design, such as the activation of the advanced emergency breaking systems in the desired time to collision. This work focuses on the passive compatibility rate[5] (Fig. 3.5).

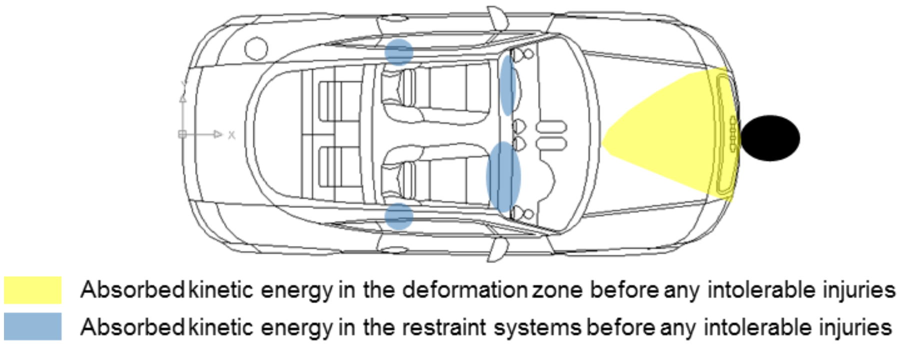


Figure 3.5: Schematic of the compatibility rate

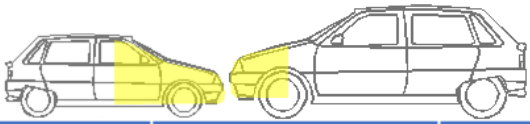
Graphic from [123]

[5] From here onwards, "compatibility rate" refers to the passive term of the proposed definition.

The definition of the compatibility rate uses the term “all participants,” which includes self- and partner-protection depending on the crash scenario. E.g., in a car-to-object collision, partner-protection does not influence the compatibility rate, while in a car-to-car collision with a high mass ratio, partner-protection is decisive for the compatibility rate of the heavier vehicle. Thus, a vehicle could have different compatibility rates in different crash constellations.

3.2.3 Application for Frontal Crash Compatibility

The safety level and the compatibility rate can be combined to provide a fundamental definition model to describe the crash compatibility of vehicles quantitatively. Fig. 3.6 explains this approach using an example of a car-to-car collision with a mass ratio of 1:2.



Vehicle mass	Safety level for frontal impact	Dissipated energy in car-to-car collision	Compatibility rate for car-to-car collision
2m	300 kJ	150 kJ	50 %
m	150 kJ	180 kJ	120 %

Absorbed collision’s energy in the structure of the vehicle

Figure 3.6: Application of the safety level and compatibility rate to a car-to-car collision with a mass ratio of 1:2

Graphics from [122]

Both vehicles are equipped with similar safety systems and achieve the same scores in a crash test, e.g., in the FWRB test. Thus, the deformation force level of the heavier vehicle is higher, and it has a higher safety potential (i.e., a safety level of 300 kJ vs. 150 kJ) due to its larger deformation zone and higher mass.

The lighter vehicle will be over-crushed in the car-to-car collision against the heavier vehicle and will absorb more energy (i.e. 180 kJ instead of 150 kJ) than its crash system is designed to absorb. Thus, the compatibility rate of the lighter vehicle is more than 100 %, and the heavier vehicle has a lower compatibility rate (i.e., 50 %) due to its aggressiveness. Consequently, the risk of intolerable injuries is higher for occupants of the lighter vehicle.

The developed definition model fulfills the requirements presented at the beginning of this section. The definition model supports the objectives of crash compatibility; an improved compatibility reduces the risk of injuries. If partner-protection of the heavier vehicle is improved, i.e., it can absorb more collision energy in car-to-car collisions, its compatibility rate will rise and the injury risks will decrease. If self-protection of the lighter vehicle is improved, its safety level will increase and the injury risks will decrease.

Furthermore, the safety level of the vehicle, in terms of the dissipated kinetic energy, can be used as a reference for comparing the crash performance of a vehicle in different scenarios. Thus, it is clear which vehicle caused the incompatibilities in a car-to-car collision.

The definition model can also distinguish between safety and crash compatibility. In this example, if the lighter vehicle is not equipped with safety systems, it will be reflected in its safety level. At the same time, the heavier vehicle can still reach an acceptable compatibility rate if it can absorb a part of the collision's energy in car-to-car collisions.

3.3 Validation

This section aims to validate the efficiency of the proposed definition model in evaluating the vehicles' crash performance in real-life accidents. As described in Section 3.2, the proposed definition model is fundamental and can be implemented in different test procedures to assess frontal crash compatibility.

For the validation analysis, the definition of the safety level and the compatibility rate are applied exemplarily into the Euro NCAP frontal impact tests, and the assessment results are compared with the injury risks in real-life accidents. The efficiency of the fundamental definition model is considered validated if the assessment results are consistent with the injury risks in real-life accidents.

3.3.1 Implementation in the Euro NCAP Frontal Impact Tests

At least two test scenarios are required for the implementation of the proposed definition model. The safety level should be assessed in an ideal crash test scenario for the safety systems of the vehicle, whereby the theoretical safety potential can be determined approximately. The compatibility rate should be assessed in a test scenario or a set of test scenarios that represent real accidents in which incompatibility issues would arise.

The FWRB test from the Euro NCAP frontal impact test protocols [50] is used to assess the safety level of the vehicles. The full-width constellation allows the vehicle to use its entire deformation zone. Furthermore, the rigid flat barrier provides an ideal interaction surface for the vehicle's crash structures. The non-deformable barrier makes the crash behavior more predictable and helps to optimize the restraint systems for the crash pulse of this test scenario. Thus, the FWRB test can symbolize an ideal crash scenario to assess the safety level of the vehicles.

According to the definition (Section 3.2.1), the safety level of a vehicle is the maximum possible kinetic energy of a collision by which the occupants of the vehicle are not injured or are tolerably injured. To estimate the maximum possible kinetic energy, the collision speed should be raised gradually until intolerable injuries occur for the first time. However, this approach is infeasible and necessitates many expensive crash tests. Thus, a simplification is made. The collision speed remains constant, as determined in the test protocols, and the change in the kinetic energy is measured at the occurrence moment of intolerable injuries, which can be determined from dummy measurements. The velocity change of the vehicle on the recorded moment of intolerable injuries results in a change to the kinetic energy, which is the safety level of the vehicle. Fig. 3.7 illustrates the approach for measuring the safety level.

The ODB test from the Euro NCAP frontal impact test protocols [48] is used to assess the compatibility rate of the vehicles. As described in Section 2.1.1.2, this test simulates a car-to-car collision with 50 % overlap. The deformable barrier provides an interaction surface similar to the deformation zone of the collision partner and could address some incompatibility parameters of car-to-car collisions. Therefore, the ODB test can represent car-to-car collisions with incompatibility issues.

The change in the kinetic energy until the first occurrence of intolerable injuries in the ODB test can be estimated using the same approach used in the FWRB test for the safety level (Fig. 3.7). It is assumed that the deformable barrier absorbs about 45 kJ, which Delannoy et al. [125, p. 3] showed to be independent of the vehicle mass.

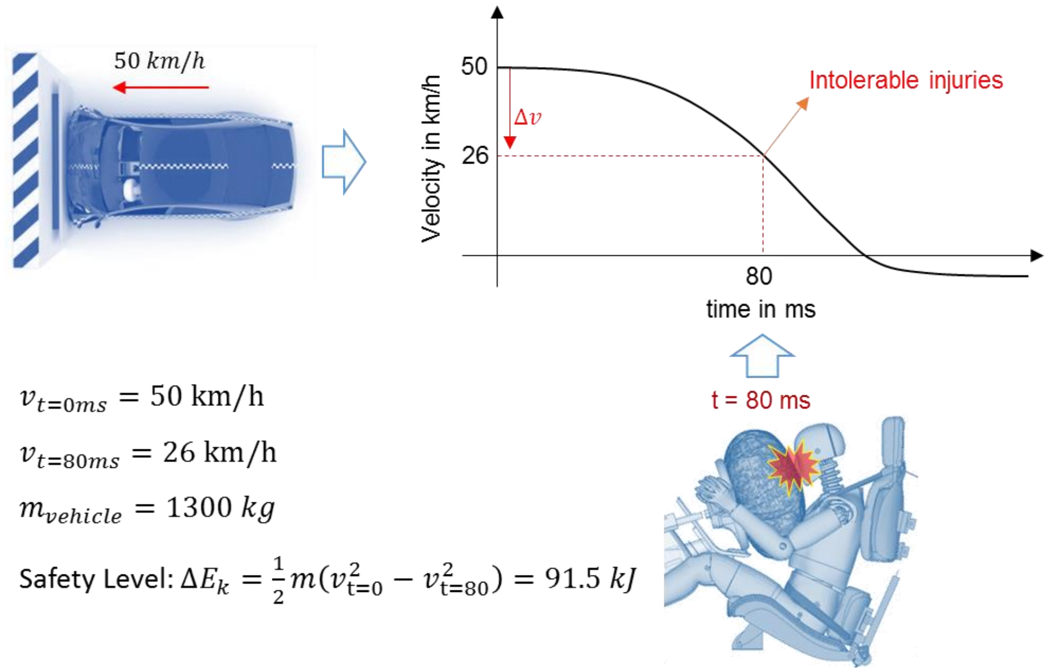


Figure 3.7: Measurement of the safety level in the FWRB test from Euro NCAP

According to [113]

The estimated change in the kinetic energy of the vehicle subtracted by 45 kJ indicates the used safety potential of the vehicle in the ODB test. The ratio of the used safety potential to the safety level gives the compatibility rate of the vehicle for frontal impact car-to-car collisions (Fig. 3.8).

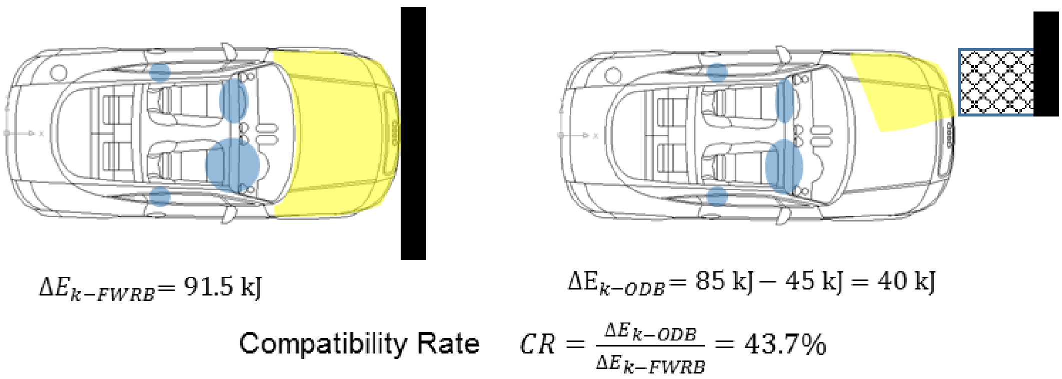


Figure 3.8: Measurement of the compatibility rate in ODB test from Euro NCAP; 85 kJ is the change of kinetic energy before intolerable injuries estimated with the same approach as in Fig. 3.7 and $v_{t=0} = 64\ \frac{\text{km}}{\text{h}}, v_{t=50} = 49\ \frac{\text{km}}{\text{h}}$ and $m_{vehicle} = 1300$ kg

Graphics from [123]

The Euro NCAP test protocols do not assess partner-protection, and hence the estimated safety level and compatibility rate only consider the vehicle's self-protection. Nevertheless, since the definition model uses the kinetic energy of the collisions, mass incompatibilities are addressed to a certain extent.

3.3.2 Validation Approach

The validation approach applies the proposed definition model to the crash performance of the vehicles in Euro NCAP frontal impact tests (as described in Section 3.3.1) and compares the safety level and compatibility rate of each vehicle with the injury risk of its occupants in real-life accidents. Fig. 3.9 illustrates the validation approach.

The NASS Crashworthiness Data System [108] is searched for real frontal car-to-car accidents where the involved vehicles are tested in both FWRB and ODB scenarios according to the NHTSA Vehicle Crash Test Database [126]. The safety level and compatibility rate of the vehicles are estimated using the test results and compared with the injury risk to the vehicles' drivers in real car-to-car accidents. The rating system is considered validated if occupants of the vehicles with a significantly higher safety level and compatibility rate have less injury risks in real life car-to-car accidents. The limits for intolerable injuries are adapted from the green classification of dummy measurements in the Euro NCAP test protocols from 2004 [113, Tab. 1].

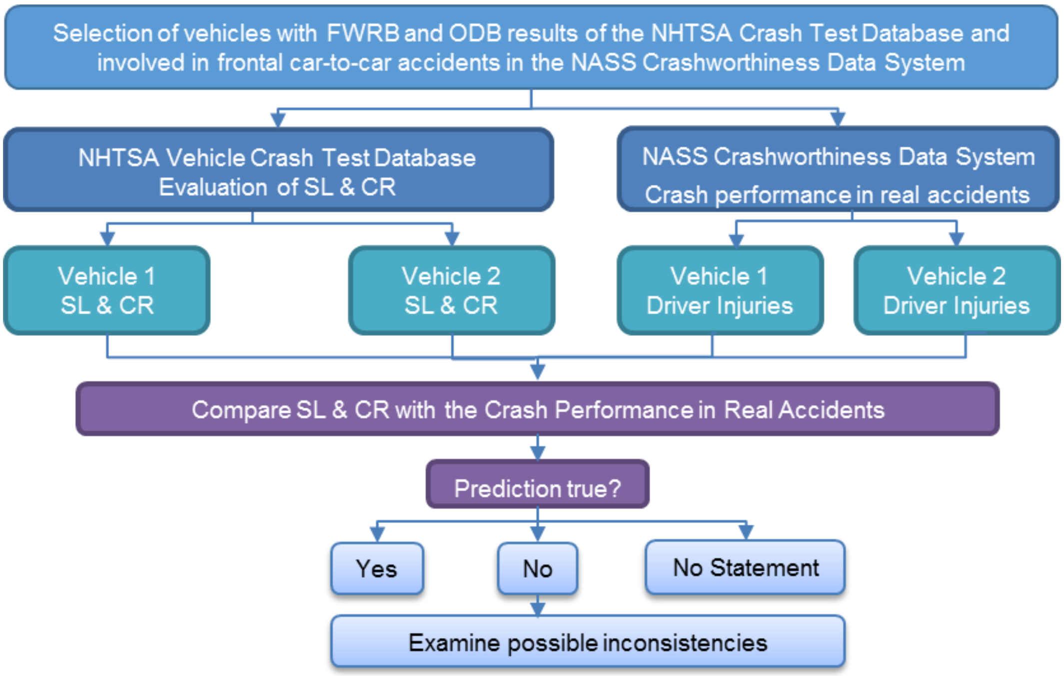


Figure 3.9: Validation Approach; SL = Safety Level, CR = Compatibility Rate

According to [113]

3.3.3 Results

In total, 34 real frontal car-to-car accidents were found in the NASS Crashworthiness Data System with 60 involved vehicles, which were tested with FWRB and ODB in the NHTSA Vehicle Crash Test Database. The analyzed vehicles covered a wide range of vehicle models, constructed between 1994 and 2004 by 29 different car manufacturers, with a mass ranging from 1231 kg to 2193 kg.

The collision severity of nine real car-to-car accidents was too low, and the drivers of both parties were subjected only to minor injuries. The collision severity of one car-to-car collision was too high, i.e., both drivers died. No comparisons between the crash performances of the involved vehicles in these ten cases were possible. Therefore, the total number of investigated accidents for validation of the definition model was reduced to 24 cases, which involved 23 vehicle models.

In 50 % (i.e., 12 out of 24) of the remaining evaluable car-to-car accidents, the definition model showed consistent results: drivers of the vehicle with a higher safety level and compatibility rate (multiplication of both) had lower injuries than the driver of the partner vehicle with a lower safety level and compatibility rate.

In 50 % of the accidents, the definition model showed inconsistencies: the driver of the vehicle with a higher safety level and compatibility rate had more severe injuries. These twelve cases were investigated in-depth to clarify; if the inconsistency of the evaluation results with injury risks is caused by the definition model.

In ten cases, the inconsistency between the rating results and the risk of injury has been explained by the following issues, and was not caused by the deficiency of the definition model:

- In seven accidents, the crash constellation was unbalanced for the involved vehicles, e.g., one party experienced a roll over.
- In two accidents, the more severely injured occupants were older.
- In one accident, the more severely injured occupant failed to use the seat belt.

The inconsistency between the rating results and the injury risks of the occupants in real-life accidents has not been explained in only two cases. Owing to a lack of information about the car-to-car accident, an in-depth investigation for these two cases was not possible. Fig. 3.10 illustrates the results of the validation, which are presented in Appendix C with more details.

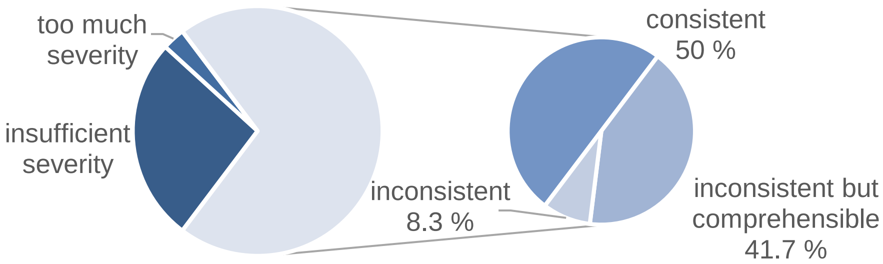


Figure 3.10: Validation results of the compatibility rating with the applied proposed definition model in the Euro NCAP frontal impact test protocols

According to [113]

The US NCAP star rating results, which were also compared with the injury risks of the studied vehicles in real-life accidents, were consistent with only 30 % of the studied cases. Applying the definition model increased the consistency of the rating results to 50 %, which confirms the efficiency of the definition model. Notably the Euro NCAP frontal impact tests do not assess all important parameters for crash compatibility (e.g., partner-protection), and applying the definition model to a more appropriate assessment approach would result in greater consistency with injury risks in real-life accidents.

3.4 Summary and Discussion

Section 3.1 reviewed different publications and literature and discussed the most important definitions and descriptions of crash compatibility. The literature review highlighted the deficiencies of the current definitions and the need for a more rigorous definition for crash compatibility to use as reference in further discussions on the assessment approaches.

Section 3.2 described an alternative definition model comprising safety level and compatibility rate. The definition model is based on dissipated kinetic energy of the collision.

Section 3.3 described an exemplary application of the definition model in the Euro NCAP frontal impact tests to validate the model's efficiency. The results of the NHTSA Crash Test Database were used to assess the safety level and the compatibility rate of 60 vehicles, the crash performance of which could be studied in 34 real-life frontal car-to-car accidents from the NASS Crashworthiness Data System. The results showed the consistency of the evaluation results with injury risks in 50 % of the studied real-life accidents.

However, a vehicle's safety and crash compatibility are not the only influential parameters in injuries. Haddon [127, pp. 416-417] defined a two-dimensional matrix to explain the influential parameters for injuries in real-life accidents. The first dimension of the Haddon matrix consists of three phases of pre-crash, crash, and post-crash. The second dimension of the matrix consists of three factors: human, vehicle, and environment. The rating results of crash tests cover the factor of vehicle only in the pre-crash and crash phases, which represents only two of nine influential parameters for the injury risks. Human factors such as the age of the occupants, seating positions, size of the occupants, and body injury limits influence the injury risks in real-life accidents, but these cannot be addressed in the current crash tests.

Furthermore, the rating results are based on a pre-defined crash scenario, which might vary from real-life accidents in many different aspects (e.g., collision speed, overlap, impact angle, and collision partner). It is therefore impossible to have a 100 % correlation between the rating results and the injury risks in real-life accidents. Applying the definition model has increased the consistency of the rating results that confirms the efficiency of the developed definition model.

This work focuses on passive safety and frontal crash compatibility. However, the proposed definition model can be developed further for active safety systems to integrate efficiency of both active and passive safety systems in one model. The concept of the definition model for active safety systems will be explained briefly as a recommendation for future works.

It is proposed here to define the active safety level (SL_{act}) as the maximum kinetic energy that can be avoided or mitigated using active safety systems before a collision against a detectable wall (Fig. 3.11).

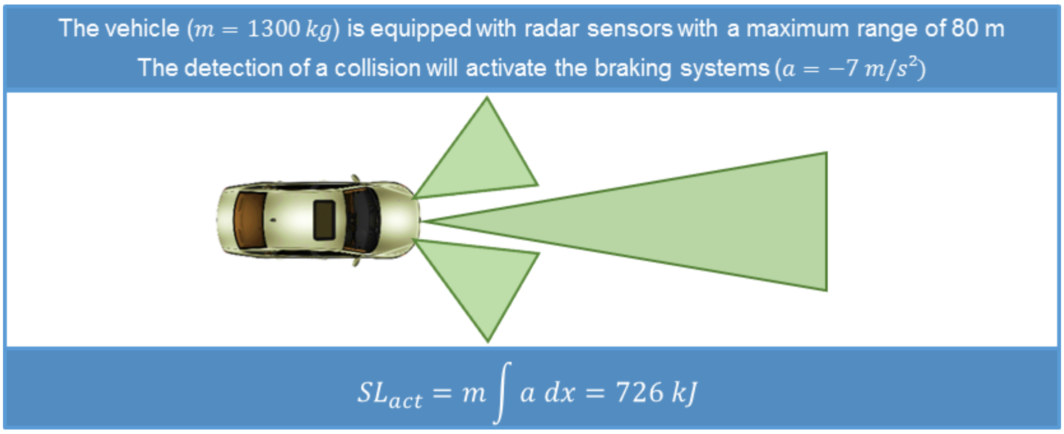


Figure 3.11: Estimation of the active safety level

According to [128, pp. 25-39]

To estimate the active compatibility rate (CR_{act}), some standard scenarios will be defined that represent common real-life accidents with different constellations. The mitigated kinetic energy by the active safety systems should be measured in each standard scenario. The active compatibility rate of each scenario is defined as the ratio of the mitigated kinetic energy in that scenario to the safety level. The whole active compatibility rate can therefore be defined as a weighted average of the compatibility rates in different standard scenarios (Fig. 3.12), which describes the capacity of the active safety systems in real-life accidents.

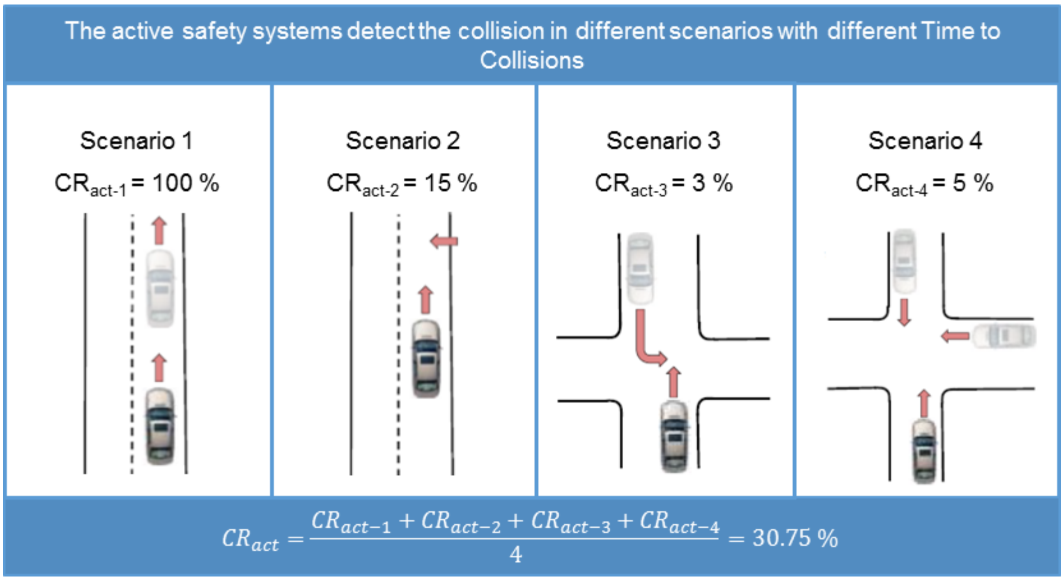


Figure 3.12: Concept of the definition model for active safety systems

According to [128, pp. 25-39]

The efficiency of the further developed model for active safety systems was investigated using Dyna4 V2.5 simulations in an internal study [128]. Further studies with real tests are necessary to complete the definition model.

The active and passive terms of the proposed definition model can be combined for each crash scenario, as in the following equation, to express the collective safety of the vehicle:

$$\begin{aligned} &Collective\ safety\ for\ a\ specific\ scenario \\ &\qquad = CR_{passive} \times SL_{passive} + CR_{active} \times SL_{active}, \end{aligned} \tag{3.2}$$

where the active terms demonstrate the ability of active safety systems to avoid or mitigate the collision and the passive terms present the capacity of the vehicle and its restraint systems to absorb crash energy before occurrence of intolerable injuries.

4 Test Procedures[6]

This chapter aims to find a set of test procedures for assessing the frontal crash compatibility of passenger cars in Europe. The focus is on the test constellation and used barriers, which should be consistent with the proposed definition model from Chapter 3 and cover the most important parameters of crash compatibility. Rating of the test results and the assessment approach will be discussed in Chapter 5.

The objective of Section 4.1 is to review the current test procedures and study their appropriateness for the assessment approach of frontal crash compatibility. It introduces five important test procedures, and describes their advantages and disadvantages with respect to application of the fundamental definition model.

Section 4.2 describes an evaluation approach for selecting the test procedures. The most important parameters of crash compatibility are presented and the requirements of the test procedures are discussed.

Section 4.3 evaluates the current test procedures from Section 4.1 with respect to fulfillment of the requirements in Section 4.2. Simulation analysis and crash test results from previous works are used for this evaluation.

The evaluation results are used in Section 4.4 to develop an alternative test procedure for assessing the frontal crash compatibility of passenger cars in Europe. The alternative test procedure is evaluated using the same approach and requirements presented in Section 4.2.

Section 4.5 summarizes the results of this chapter and discusses the limitations of the results that can be investigated in future works.

4.1 State of the Art of Test Procedures

Previous works of FIMCAR, VC-COMPAT, and EEVC WG15 discussed five barriers that are used in assessing frontal crash compatibility. Besides the ODB from ECE R94, the frontal offset test of Euro NCAP and FWRB – which is used in American regulations and the new Euro NCAP frontal impact tests – three other barriers are established in the community:

- Full-Width Deformable Barrier (FWDB)
- Progressive Deformable Barrier (PDB)
- Moving Progressive Deformable Barrier (MPDB)

The following sections describe each test procedure, present the advantages and disadvantages, and discuss the capability of the test procedures for assessing both self-protection and partner-protection.

4.1.1 Full-Width Rigid Barrier

FWRB is defined as a flat block of reinforced concrete that has a minimum width of 3 m and a height of 1.5 m, and weighs a minimum of 70 tons [49, p. 30]. In different test

[6] This chapter is derived in part from two articles [129], [130] published in TÜV-Conference crash.tech 2014 and the 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV). These articles were prepared by Sadeghipour (main author) during his work.

procedures, the test vehicle collides at collision speeds ranging from 32 km/h to 56 km/h with an impact angle of 0°, which can be up to 30° in some special test procedures [22, p. 28].

The FWRB test should represent both, car-to-car and car-to-object frontal impacts with full overlap [43, pp. 2-6]; the test was first published by the NHTSA as a crash test for the standard FMVSS No 208 [43, P1-1]. The impact velocity was set to 48 km/h for FMVSS No. 208 and was increased in 2009 to 56 km/h by the US NCAP. This test procedure is also used in the European safety regulations for passenger cars (ECE R137), the new test protocols of Euro NCAP frontal impact, and in other countries such as China and Japan.

Two issues arise in the FWRB tests: Since the barrier is a fixed object, the crash energy and thus the crash severity depends on the vehicle mass. This is in contrast to the crash severity and thus the risk of injuries in real-life car-to-car accidents, which is higher for lighter vehicles. Furthermore, the flat surface of the FWRB provides an optimal interaction between the crash structures and the collision partner, which is not a realistic representation of real-life car-to-car accidents (Fig. 4.1). Previous studies, such as the FIMCAR project [98, p. 111], showed inconsistencies between the deformation behavior of vehicles in FWRB tests and car-to-car collisions.

Figure 4.1: Unrealistic deformation pattern in the FWRB test [98, p. 111]

The FWRB test procedure provides no deformable element and activates the whole width of the vehicle deformation zone, which results in a short deformation length and consequently a high crash pulse. Therefore, the FWRB is challenging for the restraint systems and tests them with more stringent crash pulses.

In the FWRB test, self-protection can be assessed using dummy measurements and displacement values of vital components (e.g., A-pillar) of the occupant compartment. The barrier does not provide any possibility for the assessment of partner-protection. A Load Cell Wall (LCW) can be used to evaluate the load distribution of the vehicle on the wall to assess partner-protection. However, previous studies [131, p. 3] mentioned two issues for the infeasibility of this method:

1. Front parts, which first impact the rigid wall, are decelerated immediately, which generates unrealistic high forces. Similarly, the impact of the engine, called engine dumping, results in high inertial forces.
2. The effect of local stiff structures in front of the vehicle is over-represented, and the influence of structures, which are slightly back from the collision surface, is under-represented.

4.1.2 Full-Width Deformable Barrier

The FWDB test has been developed by the Transport Research Laboratory of the United Kingdom (TRL) as a modification of the FWRB test at 50 km/h and with a 0° impact angle. Modifications are the addition of a deformable element and a high resolution LCW to the FWRB [132, p. 5].

Adolph et al. [133, p. 78] described the barrier characteristics in the FIMCAR deliverables. The deformable element consists of two layers with 150 mm depth joined with a muslin interlayer. The first layer is an integrated aluminum honeycomb block with a crushing strength of 0.34 MPa, and the second layer consists of honeycomb segments of 125 x 125 mm² with a crushing strength of 1.71 MPa. The barrier should have a minimum height of 750 mm and a minimum width of 2000 mm. The rear surface of the second layer should be mounted using a 0.5 mm aluminum sheet to a rigid wall.

Due to the presence of the deformable block in front of the rigid wall, the deformation mode of the test vehicles against FWDB is more comparable to car-to-car tests relative to their performance in FWRB tests (Fig. 4.2), which was confirmed in different studies for small and minicars [134, p. 5] and for normal passenger cars [98, p. 111].

Figure 4.2: Comparison of front structure deformation pattern in different frontal impact tests: FWDB test (left), car-to-car test (right)

[98, p. 111]

The low depth and high crushing stiffness of the deformable element have little effect on the vehicle deceleration pulse. Previous studies of Mizuno et al. [134, pp. 6-7] showed that the FWDB test results in high crash pulses, similar to the FWRB, which makes it appropriate for assessing the performance of the restraint systems (Fig. 4.3).

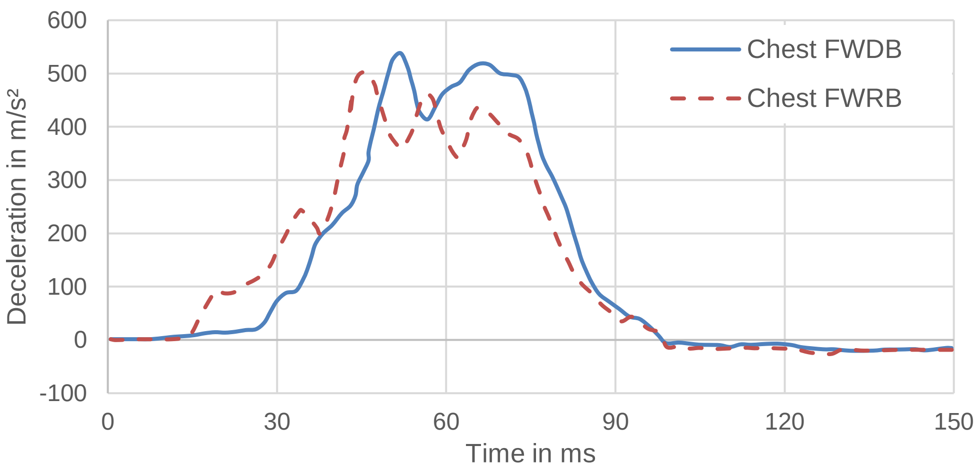


Figure 4.3: The chest deceleration of the occupant of a minicar in FWDB test (55 km/h) and FWRB test (55 km/h)

[134, p. 6]

The LCW of the FWDB consists of 128 cells with a 125 x 125 mm² nominal contact surface that are mounted in eight rows between the deformable element and the rigid wall. The LCW should be mounted 80 mm above the ground level to ensure its third and fourth rows are located at the specified height defined in the regulation part 581 from the FMVSS for testing the bumpers in low speed impacts [135, p. 30]. The third and fourth rows of the LCW are described as a common interaction zone, which should encourage all vehicles to have crashworthy structures at this height [132, p. 5]. Fig. 4.4 presents the FWDB, the load cell wall and the common interaction zone.

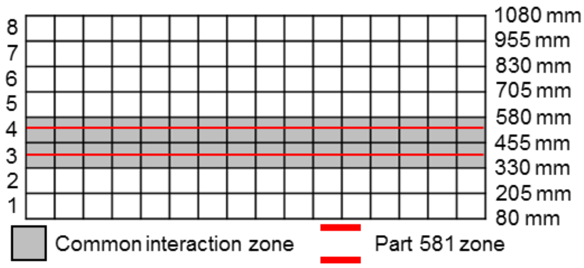


Figure 4.4: LCW of the FWDB and the common interaction zone of the US part 581 bumper test

[132, p. 5]; [97, p. 12]

Measurements of the LCW can be used to assess the car's frontal stiffness distribution and can demand homogenous fronts for vehicles, which is assumed by TRL as a requirement for good structural interaction and consequently good partner-protection [131, p. 3]. Self-protection can be assessed in a similar way to the FWRB test using dummy measurements and intrusion values into the occupant compartment.

4.1.3 Offset Deformable Barrier

The ODB of ECE R94 has a width of 1000 mm, a height of 650 mm, and a total depth of 540 mm (Fig. 4.5).

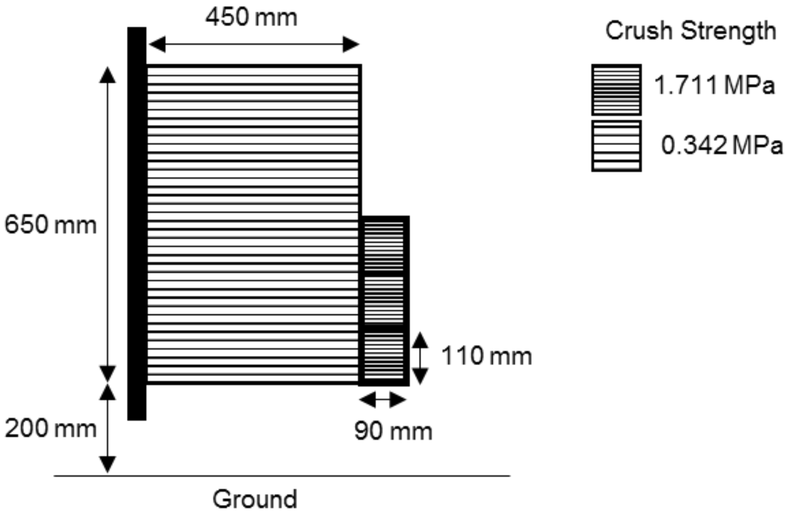


Figure 4.5: ODB of ECE R94

According to [136, p. 65]

The barrier consists of two deformable blocks with different crushing strength, which provide an available total energy of absorption capacity of about 150 kJ [101, p. 18]. However, the strength of the barrier is too low for modern vehicles and the ODB will bottom out (Fig. 4.6) in almost every test [97, D1]. Thus, the main impact occurs between the car and the rigid wall behind the ODB.

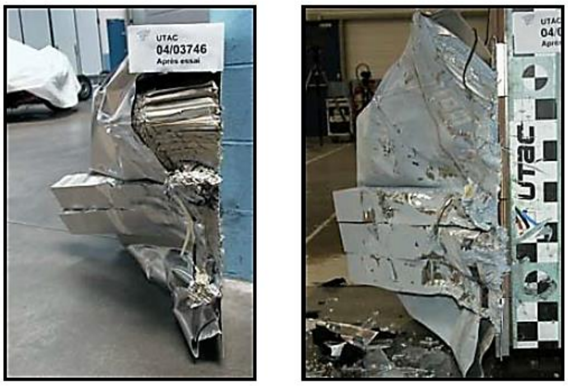


Figure 4.6: Bottoming out of the ODB in crash tests with modern vehicles [125, p. 3]

Because of the bottoming out, the absorbed energy in the barrier is almost independent of the car mass [125, p. 3] and results in a lower test severity for light vehicles (Fig. 4.7), which is in contrast to the crash severity of car-to-car accidents.

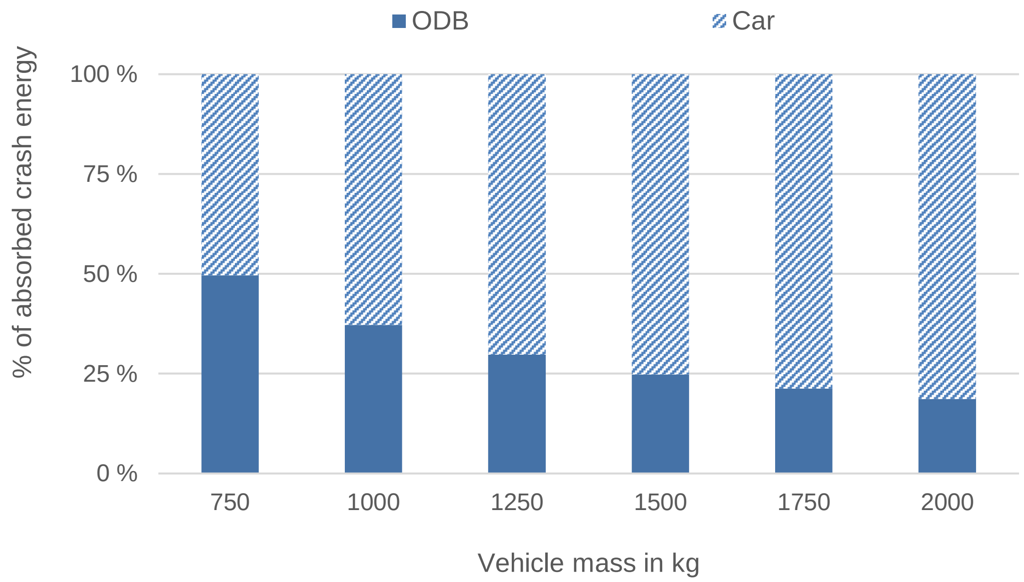


Figure 4.7: Severity of the ODB crash test at 56 km/h for different vehicles [125, p. 3]

The ODB test has a similar issue as that of the FWRB in load measurements behind the deformable block [97, D1]. Furthermore, owing to the barrier's instability for modern vehicles, which results in different deformations for the same vehicle model [97, p. 35], partner-protection cannot be assessed using the barrier deformations. Self-protection can be assessed in a similar way to the FWRB and FWDB tests using dummy measurements and intrusion values in the occupant compartment.

4.1.4 Progressive Deformable Barrier

The PDB test has been developed by UTAC CERAM, which is an independent group providing services for regulation and testing [137]. The barrier has been improved several times, and thus there are many variations of the PDB. However, the test's set-up remains the same, with an overlap of 50 % and a collision speed of 60 km/h.

Lazaro et al. [138, pp. 42-49] described the XT-version of PDB in deliverables of the FIMCAR project. The barrier core has a width of 1000 mm, a height of 700 mm, and a total depth of 790 mm (Fig. 4.8). The PDB consists of four aluminum honeycomb cores with different dimensions and strengths. The first and last core provide a constant crushing load, while the middle cores are designed to provide a progressive load in depth. The aluminum cores are covered with an outer cladding and can be mounted on a rigid wall or a trolley using a back plate.

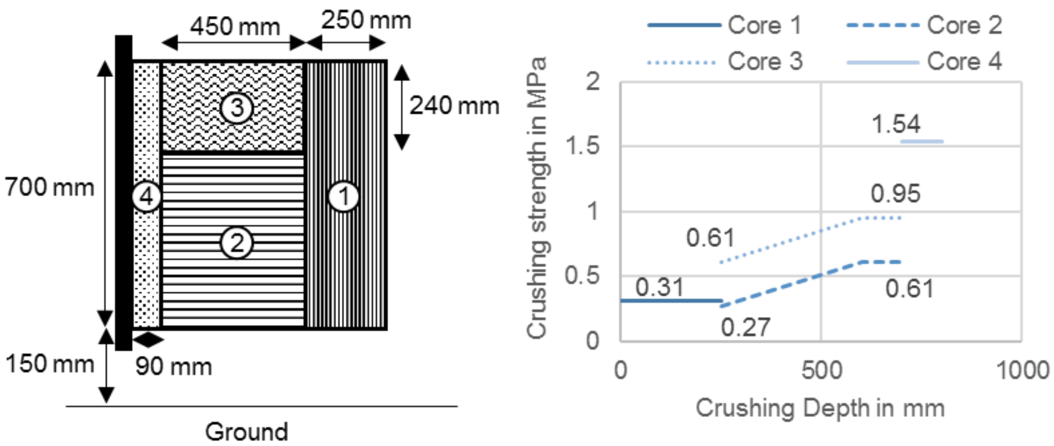


Figure 4.8: PDB-XT

According to [139, p. 19]

The PDB is a modification of the ODB with the intention of harmonizing the test severity among vehicles of different masses [97, p. 24]. The progressive strength and the high depth of the barrier prevent bottoming out of the deformable block and results in an almost constant crash severity for different vehicle masses (Fig. 4.9). The PDB should test lighter vehicles with a higher collision severity than the ODB and hence encourage them to increase their strength.

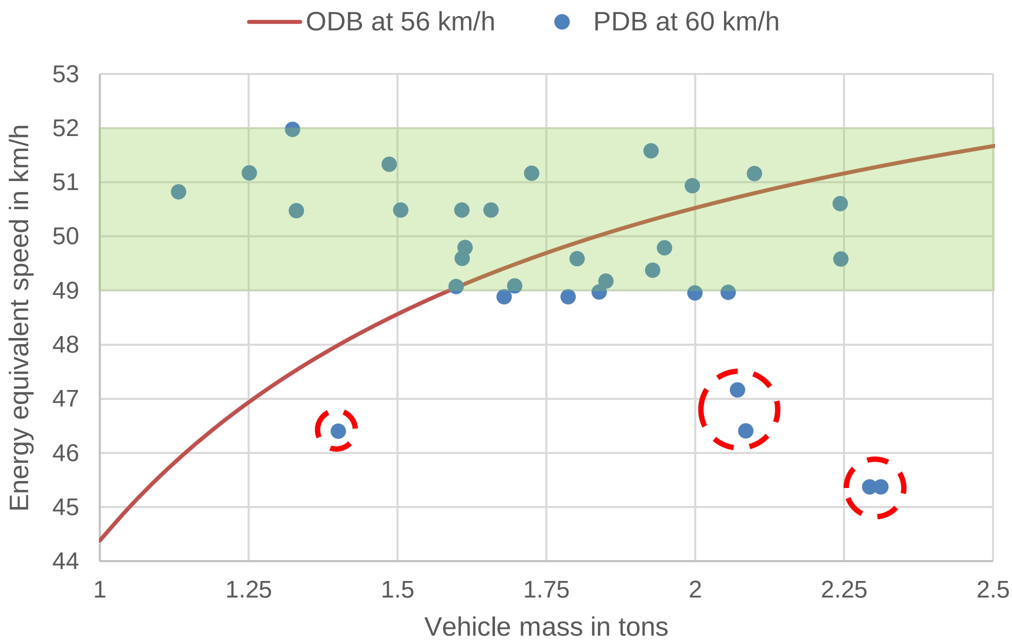


Figure 4.9: Test severity of the PDB and the ODB for different vehicles

[140, p. 17]

As can be seen, the EES of the PDB test remains constant (green corridor in Fig. 4.9) for most vehicles regardless of the vehicle mass. Only in five cases (marked with circles) is the measured EES out of the marked corridor for the constant severity [140, p. 17]. The issue of decreasing the test severity compared to the severity of ECE R94 (i.e. EES of about 50 km/h) with the vehicle mass has also been observed in the simulation analysis of the FIMCAR project [138, pp. 36-40].

The PDB is designed to reflect the homogeneity of the vehicles' load spreading on the barrier face to assess partner-protection. However, previous studies from the VDA [97] showed that the PDB provides too much deformation potential, which can be misused by aggressive vehicles. The simulation results of modified vehicles with a reduced deformation zone showed that the PDB cannot distinguish the aggressive design from the standard design (Fig. 4.10 and Fig. 4.11).

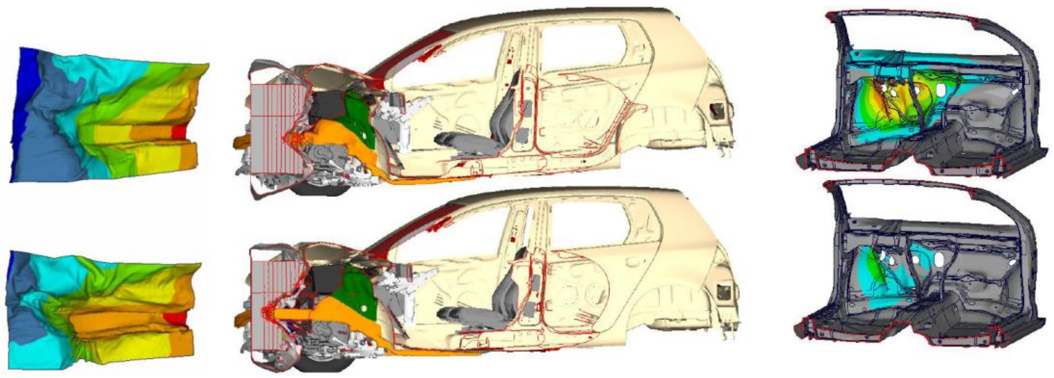


Figure 4.10: Deformations for the standard vehicle design (top) and the aggressive design with rigid front rails (bottom) in the PDB test

[101, p. 19]

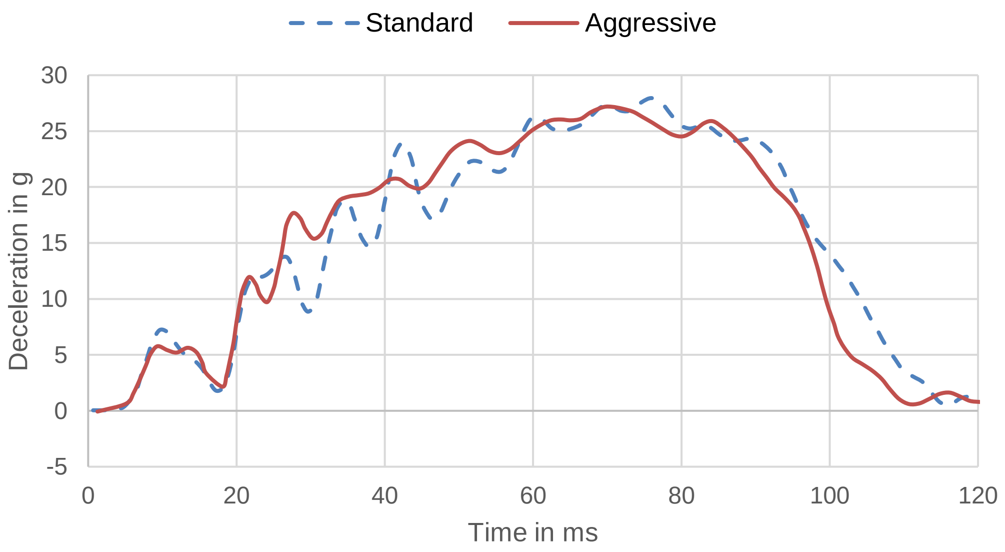


Figure 4.11: Acceleration of the B-pillar for the normal vehicle design (dashed line) and the aggressive design with rigid front rails (solid line) in the PDB test

[101, p. 20]

4.1.5 Moving Progressive Deformable Barrier

The Netherlands Organization for Applied Scientific Research (TNO) equipped a trolley with the PDB and developed the MPDB. The trolley represents an average car and its inertia, and the deformable element represents the stiffness of the vehicle. The objective was to develop a more representative test procedure for real-life accidents to assess frontal crash compatibility [104, p. 2].

Schram and Versmissen [104, p. 2] used European vehicle geometry databases to find important specifications of the trolley, such as mass, center of gravity (CG), and inertia properties, to represent average vehicles in Europe (Tab. 4.1). The developed MPDB is investigated and calibrated in MPDB-to-wall and MPDB-to-car tests.

Table 4.1: MPDB design specifications [104, p. 2]

Description	Average EU Vehicles	Trolley
Total mass in kg	1200–1700	1500
CG location from front, w.r.t. length in m	0.720–0.980	0.900
Vehicle front to CG distance in m	1.700–2.000	1.900
Vehicle front to rear axle distance in m	3.200–3.700	3.500
Overall length in m	3.800–4.700	4.250
CG height in m	0.560–0.640	0.600
Axle height in m	0.270–0.290	0.280
Wheel base in m	2.450–2.750	2.600
Mass front axle in kg	710–990	900
Mass rear axle in kg	465–735	600

The benefit of the MPDB test is that it is more representative of the kinematics of car-to-car collisions. Similar to real-life accidents, the lighter vehicles are tested with higher severity, and the crash severity is lower for heavier vehicles. This was confirmed in the TNO's MPDB-to-car tests [104, p. 7] at 100 km/h (i.e., 50 km/h for each party) and with 50 % overlap. For the test vehicles with a mass ratio near one, the test severity was close to the fixed PDB test. For lighter vehicles (mass ratio < 1), the test severity was increased, as observed on the accelerations and deformations of the vehicle. For heavier vehicles (mass ratio > 1), the test severity was decreased.

The MPDB test procedure is identified with a high potential for assessing the car-to-car crash behavior by relevant groups in Europe and the United States. FIMCAR developed a test protocol with the MPDB as a base to harmonize the works of different initiatives in this field [141, p. 27]. Similar to the PDB test, deformations on the barrier face can be used to assess partner-protection, and self-protection can be assessed using dummy measurements and intrusions into the occupant compartment.

4.1.6 Comparison of Barriers

Generally, the full-width barriers result in high acceleration loads and are therefore more challenging for the restraint systems of the vehicles. Because of activation of the whole width of the deformation zone, the full-width barriers are potential test procedures for assessing the safety level.

The offset barriers cause high intrusions and are more challenging for the compartment of the vehicles. Owing to baseline situations of the offset tests, which is a car-to-car collision, the offset tests are potential test procedures for assessing the compatibility rate. Therefore, the aforementioned test procedures are divided into two groups of full-width and offset barriers and are discussed separately. Tab. 4.2 and Tab. 4.3 summarize the advantages and disadvantages of each test procedure.

Table 4.2: Advantages and disadvantages of full-width test procedures; Graphics from [123]

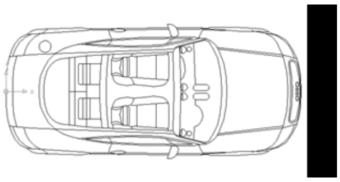
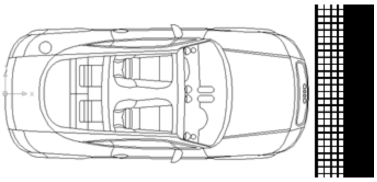
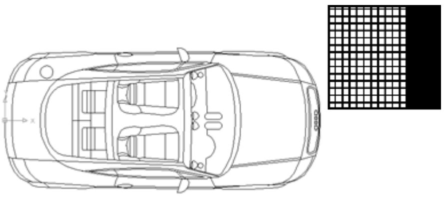
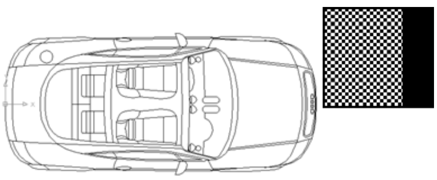
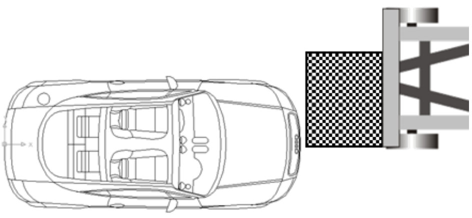
FWRB Collision speed 48–56 km/h, full overlap 	+ Worldwide standard test and easy to introduce from a harmonization viewpoint [93, p. 16] + Stable barrier without any instability issues + Stringent crash pulse for restraint systems − Test severity is in contrast with the car-to-car collisions' severity − Unrealistic structural interaction and vehicle deformation pattern − No approach for assessing partner-protection
FWDB Collision Speed 50 km/h, full overlap 	+ More representative of structural interaction and deformation pattern for real world accidents + Possibility for assessing partner-protection using load cell measurements + Stringent crash pulse for restraint systems − Test severity is in contrast with the car-to-car collisions' severity

Table 4.3: Advantages and disadvantages of offset test procedures

ODB Collision speed 56–64 km/h, 40% offset 	+ standard test and easy to introduce from a harmonization viewpoint [93, p. 20] − Test severity is in contrast with the car-to-car collisions' severity − No approach for assessing partner-protection
PDB Collision speed 60 km/h, 50% offset 	+ Possibility for assessment of partner-protection using deformations on the barrier face + More demanding test severity for light vehicles − Insufficient test severity for heavy vehicles − Possible misuse of the deformation potential of the barrier
MPDB Collision speed 50 km/h, 50% offset 	+ Possibility for assessment of partner-protection using deformations on the barrier face + More representative of car-to-car collisions + More demanding test severity for light vehicles − Insufficient test severity for heavy vehicles − Possible misuse of the deformation potential of the barrier

4.2 Approach for Evaluating the Test Procedures

Previous works of EEVC WG15, VC-COMPAT, and FIMCAR used a similar approach to evaluate the test procedures. First, incompatibility issues are investigated using crash analyses, and a list of main compatibility problems are established and prioritized for inclusion in the assessment approach (Tab. 4.4). Priority 2 issues are identified as important, but not necessarily critical for inclusion in the assessment approach [98, p. 109].

Table 4.4: Main compatibility issues from the FIMCAR project [98, p. 109]

Structural Interaction	Alignment	Priority 1
	Load spreading	Priority 1
Front end force	Deformation forces	Priority 2
	Energy absorption management	Priority 1
Compartment integrity	Sufficient for single vehicle accident	Priority 1
	Enhanced for light vehicles in car-to-car accidents	Priority 2
Restraint system	Test restraint capacity	Priority 1
	Assess range of pulses	Priority 1

The compatibility issues listed in Tab. 4.4 are used to create a list of technical requirements for vehicles that should be fulfilled to ensure crash compatibility. Finally, the test procedures are evaluated with regard to the assessment of these requirements. Since no test procedure can fulfill all requirements, a combination of two test procedures is proposed for the assessment of crash compatibility [98, p. 110].

The critical point in this evaluation process is the separation of the requirements and the use of different tests to evaluate the crash performance of vehicles that would blend the interaction of parameters with each other. E.g., a good horizontal load spreading between longitudinal members reduces the deformation way and loads on the compartment, but increases the crash pulse of the vehicle. However, the horizontal load spreading and compartment integrity should be assessed in offset tests, while the capability of the restraint system to account for high crash pulses should be assessed in full-width tests. Thus, it is necessary to consider the interaction effects in the list of assessment requirements for evaluation of the test procedures.

The general approach of this study is based on the proposed fundamental definition from Chapter 3. At least two test procedures are necessary to estimate the safety level and compatibility rate of vehicles. The test procedure for assessing the safety level should represent an ideal single-vehicle collision, which might be a full-width test procedure to allow the vehicle to use its entire deformation zone and consequently exploit its safety potential. The test procedure for assessing the compatibility rate should represent car-to-car collisions with incompatibility problems, which might be an offset test procedure to cover more incompatibility issues.

Besides the requirements for implementing the fundamental definition, the test procedures have to be able to cover all important issues of the frontal crash compatibility for passenger cars, which have been discussed in previous works [94], [95], [97], [98]. The most important issues are compartment strength, restraint systems, structural interaction, and force levels.

The following sections modify, reevaluate and develop the analysis of previous works for implementing the fundamental definition with data for microcars, which was not covered in the previous works of EEVC WG15, VC-COMPAT, and FIMCAR. Furthermore, requirements for evaluation of the offset and full-width test procedures will be discussed.

4.2.1 Compartment Strength

The compartment strength is particularly important for preventing intrusions into the occupant compartment and relevant injuries for both sides. Statistical analyses from FIMCAR [91, p. 29] showed that intrusions are more common in collisions with lower offset values (Fig. 4.12). The offset value is measured from the vehicle corner, and 0 % overlap means the corners of the vehicle front are not contacted.

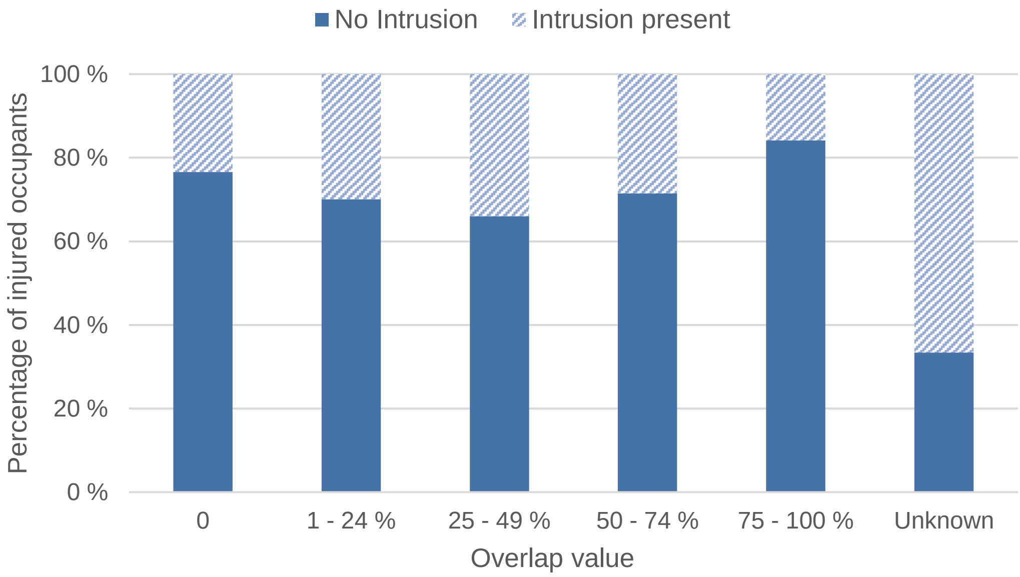


Figure 4.12: Percentage of injured occupants in frontal collisions with and without intrusion [91, p. 29]

Since, intrusions were present in only 16 % of collisions with high overlap values, i.e., more than 75 % overlap, the compartment strength should be assessed primarily in an offset test procedure and is not the focus of full-width test procedures.

The compartment strength is more important for light vehicles in car-to-car collisions, where the lighter vehicle has a higher velocity difference and thus a higher impact on its occupant compartment. Therefore, the offset test procedure should represent the unbalanced severity of car-to-car collisions, i.e., higher for lighter vehicles. However, since the stability losses of significant compartment parts happen more often in car-to-object collisions [91, p. 74], the offset test should not have a lower severity than the current safety requirements for the compartment of heavy vehicles.

4.2.2 Restraint Systems

Restraint systems should be assessed to ensure their potential for occupant protection in real-life accidents. In crash analysis, the term restraint injuries implies that the injuries are caused by the high deceleration of the vehicle and a consequently high loading of occupants from the restraint systems [91, p. 36]. By restraint injuries, the restraint systems would have worked without problems and correctly, but their safety potential was lower than the crash severity. Restraint injuries happen in all types of collisions. Serious and severe injuries are more present in car-to-car and car-to-object collisions (Fig. 4.13).

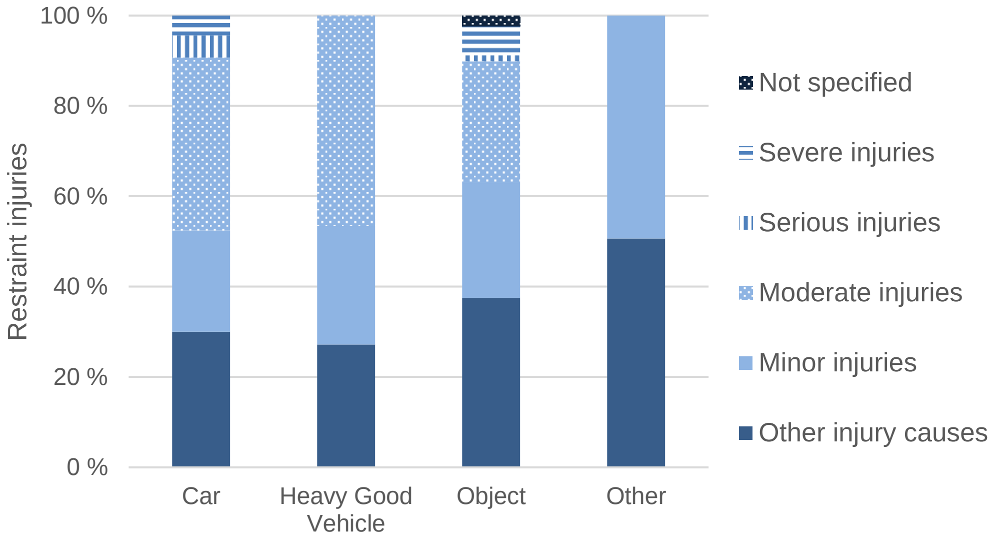


Figure 4.13: Restraint injuries by collision partner groups [91, p. 86]

More in-depth crash analyses showed that high injury risks are more present in full-overlap car-to-car collisions and car-to-object collisions, and when there are no compartment intrusions [91, p. 90]. Thus, the full-width test procedure should assess the vehicle with high acceleration pulses, where the crash severity depends on the vehicle mass to represent the car-to-object collisions.

Furthermore, as described in Section 2.1.2, microcars confront with a higher collision severity in car-to-car collisions with heavier vehicles [68, pp. 6-10]. The lighter vehicle is pushed back and the difference of collision speed increases, resulting in high crash pulses. Thus, the offset test procedure for assessing the compatibility rate should provide high acceleration pulses for light vehicles, depending on the vehicle mass.

The second compatibility issue for the restraint systems is calibration of their trigger time. Crash tests performed in previous studies showed that some restraint systems are optimized for the prescribed tests (e.g., FWRB and ECE R94), and their efficiency would decrease in other test modes. E.g., FIMCAR showed that the airbag deployment would delay in the FWDB test, thus causing higher injuries compared to a FWRB test with a lower collision speed [98, p. 111]. Thus, both offset and full-width test procedures should have a representative acceleration time for real-life accidents to demand an effective design of the restraint systems.

4.2.3 Structural Interaction

Structural interaction describes the local deformation of the structure in interaction with a collision partner [93, p. 11]. Structural interaction contains two issues of load spreading and structural integrity. High load spreading ensures a high amount of energy absorption in the front structures, and high structural integrity ensures the robustness of the structure under different loading conditions [130, p. 2].

High structural interaction is assumed in different works as a requirement for partner-protection. However, as described in our previous work [130, p. 2], structural interaction does not have a direct impact on the occupants' injuries; it affects intrusions and restraint loads, which directly influence injury risks. Improving the structural interaction results in a good management of the crash energy and uses a higher potential of the deformation zone. High structural interaction reduces intrusions and, at the same time, increases the acceleration pulse. In a similar way, low structural interaction increases the deformations and reduces the acceleration pulse. Thus, depending on the cause of injuries, compartment strength, potential of restraint systems, and the collision type, high or low structural interaction could be desired. Fig. 4.14 employs a mass-spring model to present the acceleration pulses of three different vehicles with normal, moderate, and high structural interaction in different crash scenarios with varying collision speeds and offset values.

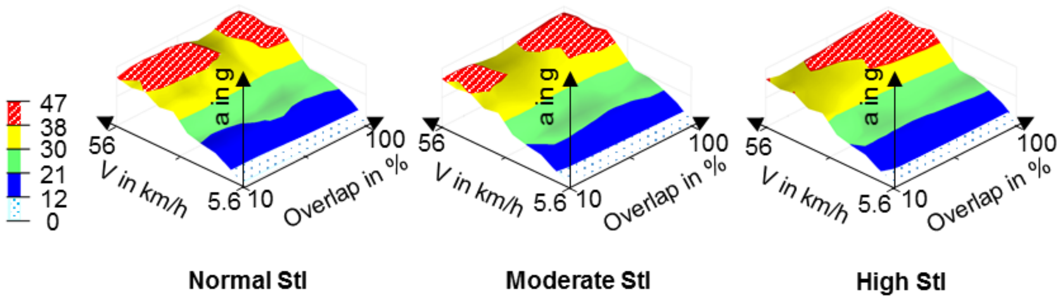


Figure 4.14: Acceleration pulses of different mass-spring models with normal, moderate, and high structural interaction in different crash scenarios; StI = Structural Interaction

According to [130, p. 3]

As can be seen, the ideal structural interaction for high collision speeds depends on the offset value. For high overlap, since a larger part of the deformation zone is involved, lower structural interaction results in longer deformation ways and lower acceleration pulses. For small overlap, since a small part of the deformation zone is involved, higher structural interaction results in a better load spreading and prevents an impact with the high strength compartment, which results in lower acceleration pulses.

It is shown in our previous work [130], using a simulation analysis with full vehicle models and a review of crash test results from other studies, that a high structural interaction does not necessarily reduce the injury risks and vice versa. Therefore, structural interaction cannot be used as a single requirement for partner-protection. The test procedures for the assessment of frontal crash compatibility should be able to reflect the effects of the structural interaction on the acceleration pulses and intrusion values of the vehicle. If these values could be also measured for the collision partner, i.e., on the barrier, partner-protection can be assessed in a test procedure.

The compatibility rate is measured in the offset test procedure, and the full-width test should only assess the vehicles' safety levels. Therefore, the structural properties should not necessarily be assessed in the full-width test procedure.

4.2.4 Force Levels

Force levels describe the deformation force of the vehicles' structures. Because fixed barriers are used in different safety regulations, the force levels currently depend on the vehicle mass; thus, in a car-to-car collision, the crash structure of the lighter vehicle is exhausted, while the crash structure of the heavier vehicle would not deform due to the higher force levels [91, p. 45]. Previous studies in VC-COMPAT [94, p. 7] suggested harmonizing the force levels of the vehicles' structures to solve the problem of over-crushing light vehicles in car-to-car collisions.

However, using the fundamental definition of crash compatibility and two test procedures to assess the safety level and the compatibility rate would automatically address the issue of force levels. The full-width test procedure should demand a force level to ensure the safety of occupants in single vehicle collisions, and the barrier of the offset test procedure should represent the average force level of normal passenger cars to simulate car-to-car collisions and the issue of unbalanced force levels in real-life collisions.

4.2.5 Conclusion

The assessment approach should consist of an offset and a full-width test procedure to allow implementation of the fundamental definition presented in Chapter 3. The full-width test assesses the safety level for single vehicle collisions, and the offset test assesses the compatibility rate for car-to-car collisions with compatibility problems. This is consistent with the presented results from real-life in the previous sections. Regarding the main compatibility issues, some requirements (Tab. 4.5) are determined for both offset and full-width test procedures for a comprehensive assessment approach.

Table 4.5: Requirements for the test procedures of a comprehensive assessment approach

Compatibility Parameter	Requirements	Relevant for: Offset	Relevant for: Full width
Compartment strength	Assessment of the compartment integrity in an offset test procedure	X	
	High loads for light cars as observed in car-to-car accidents	X	
	Comparative severity with current crash tests for heavier vehicles	X	X
Restraint systems	Assessment of the restraint systems with high acceleration pulse in a full-width test		X
	Higher acceleration pulse for light vehicles in the offset test procedure	X	
	Representative acceleration-time pulse	X	X
Structural interaction	Reflection of low and high structural interaction in intrusions and acceleration pulses	X	
Force levels	Demands an adequate force level for single vehicle collisions		X
	Barrier should represent the average force level of normal passenger cars	X	
Fundamental definition	Suitable crash constellation for evaluation of the potential safety		X
	Representative crash constellation for car-to-car collisions	X	

4.3 Evaluation Results

This section investigates the most important test procedures and barriers for assessing frontal crash compatibility with respect to their capability of fulfilling the requirements presented in Tab. 4.5. The objective is to study whether the fundamental definition given in Chapter 3 can be implemented in the proposed tests. The criteria for rating the crash test results to finalize the assessment approach will be discussed in Chapter 5.

As described in Section 4.2, two test procedures are necessary for measuring the safety level and the compatibility rate. The test procedure for measuring the safety level should be full-width, and the test for measuring the compatibility rate should be with partial overlap. Since the requirements and objectives of these test procedures are different, the suitability of the test procedures for each category will be discussed separately.

4.3.1 Full-Width Test Procedures

The FWRB and the FWDB are evaluated regarding the requirements presented in Tab. 4.5:

Compartment strength: While the FWRB is already a worldwide standard test and therefore provides comparative severity with current crash tests for heavier vehicles, the FWDB is currently only used in the frontal impact test of the Euro NCAP for heavy quadricycles. The test speed of the FWDB is set to 50 km/h, which meets the desired crash severity identified by FIMCAR's accident analysis [98, p. 112]. Since the barrier is fixed, the crash severity is also adequate for heavy vehicles, and the severity of the FWDB test is comparable with the FWRB regarding the compartment strength. Mizuno et al. [134, p. 5] observed even larger intrusions into the compartment of minicars in the FWDB test, when conducting tests with the same collision speed as in the FWRB test.

Restraint systems: As described in Section 4.1, both FWRB and FWDB provide a high acceleration pulse for the test vehicles, and the deformable element of the FWDB has little effect on the acceleration pulse of the crash test. However, the barriers differ regarding the representability of the acceleration pulse for real-life accidents. The crash analyses of FIMCAR [98, p. 111] and Japanese research on minicars [134, p. 7] showed that the FWDB test has more representative acceleration characteristics for car-to-car collisions with high overlaps (Fig. 4.15).

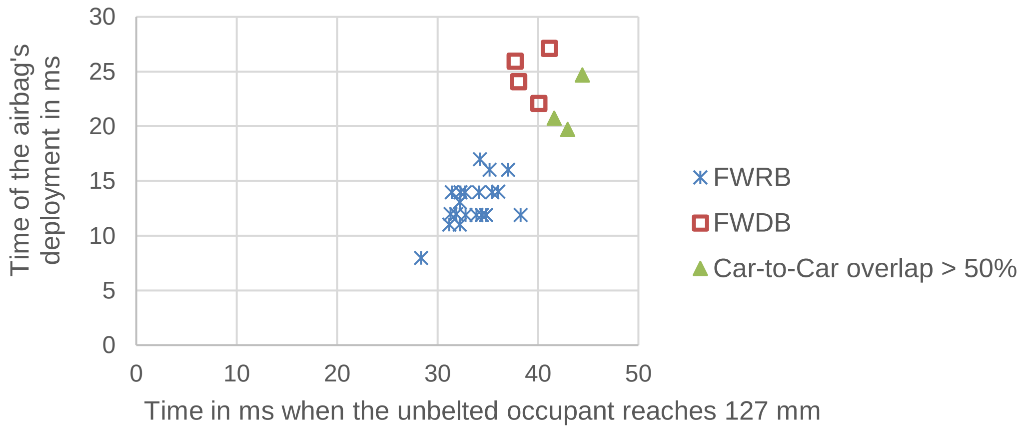


Figure 4.15: Minicar crash tests shown by the airbag deployment time and the time when the unbelted occupant reaches 127 mm

According to [134, p. 7]

However, for car-to-rigid object collisions with high overlaps, the acceleration pulse of the FWRB might be more representative, owing to the similarity of the barrier to the collision partner.

Structural interaction: Since the FWRB has no deformable element and provides a perfect interaction surface, this test procedure cannot reflect structural properties of the vehicle in intrusions or acceleration pulses. Previous work of EEVC WG15 [97, p. 35] described that properties of the structures set back from the vehicle front and connecting structures do not influence the test results.

Crash analyses in previous works [98, p. 111]; [134, p. 5] showed that the FWDB results in a more realistic deformation mode than the FWRB test. However, the low depth of the deformable element and the full-width crash constellation limit the potential of the FWDB to detect the structural properties, which was analyzed in a simulation study with validated vehicle models in our previous work [130]. Neither the FWRB nor the FWDB can reflect the structural properties correctly or distinguish between vehicles with low and high structural interactions.

Force levels: Both test procedures use a fixed barrier and therefore demand a force level with respect to the vehicle mass. The FWDB is equipped with a deformable block that can absorb energy and influence the force levels.

FIMCAR [133, p. 70] and TRL [132, p. 8] claimed that the absorbed energy from the FWDB is within ±5 % of the vehicle's kinetic energy. However, the tested vehicles in the previous works were not designed for the FWDB test. Hollowell et al. [43, pp. 4-6] expressed some concerns regarding misuse-scenarios for a similar FWDB, for which the designers took full advantage of the energy absorption potential in the barrier to stiffen the crash structure or reduce the deformation zone of the vehicles. Bottoming out of 10 cells (e.g., using a stiff bumper surface of 15.6 cm x 1 m) in the FWDB absorbs an energy of about 48 kJ, which is equal to 38 % of the kinetic energy of a vehicle with 1300 kg at 50 km/h. Bottoming out has already occurred in the FWDB tests [133, p. 290] and is quite possible; therefore, the modified vehicle designs would use the deformation potential of the FWDB to pass the test with high force levels.

Conclusion: Tab. 4.6 summarizes the evaluation results for the full-width test procedures.

Table 4.6: Evaluation of full-width test procedures

Requirements	FWRB	FWDB
Comparative severity with current crash tests for heavier vehicles	+	+
Assessment of the restraint systems with a high acceleration pulse	+	+
Representative acceleration-time pulse for car-to-car / car-to-object collisions with high overlaps	-/+	+/-
Optional for full-width test procedures: Reflection of structural properties in intrusions and acceleration pulses	(-)	(-)
Demands an adequate force level for single vehicle collisions	+	-
Suitable crash constellation for evaluating the safety level	+	-

Representing the acceleration characteristics of both car-to-car and car-to-object collisions with high overlaps in one single test procedure is impossible due to their differences.

While the FWRB provides a perfect structural interaction for the vehicle structures, the FWDB challenges the integrity of the vehicles' structures with the deformable element. The results of the FWDB do not represent the theoretical safety potential of the vehicle. Thus, the FWRB is the best candidate for assessing the safety level.

4.3.2 Offset Test Procedures

The ODB, PDB, and MPDB are evaluated regarding the requirements presented in Tab. 4.5:

Compartment strength: The strength of the deformable element in the ODB is much lower than the force levels of modern vehicles, which were developed after the implementation of ECE R94. Thus, the ODB will be fully crushed in almost every test with normal passenger cars [138, p. 26], and the test vehicle will hit the rigid wall behind the barrier and produce high severity loads for the occupant compartment of the vehicle. A Japanese crash analysis [134, p. 7] showed that the crushing strength of the ODB is comparable with the force levels of minicars. Due to the light weight of minicars and their low crash energy, a part of the deformable element remains uncrushed and the minicar does not hit the rigid wall. Therefore, assessment of the compartment strength for microcars could be inadequate in the ODB test procedure. As discussed in Section 4.1.3, the crash severity of the ODB test raises with the vehicle mass. Therefore, it is not representative of compartment loads in car-to-car collisions, which decrease with vehicle mass.

The stiffness of the PDB is higher than the ODB and comparable with the force levels of the current vehicle fleet in Europe [142, p. 2]. The 50 % overlap and the progressive stiffness of the barrier in the PDB and MPDB test procedures normally result in high intrusions [138, p. 35]; [140, p. 26]; [141, p. 12] and an adequate assessment of the compartment integrity. However, simulation analyses [140, p. 26] and crash tests [138, p. 35] of the FIMCAR project have shown that the intrusions in the PDB tests with heavy vehicles is lower than in the ECE R94. This issue was also observed in one MPDB test with a SUV [141, p. 12]. Thus, it is doubtful that the PDB and MPDB test procedures can assess the compartment integrity of heavy vehicles adequately.

As described in Section 4.1.4, the objective of the PDB was to harmonize the collision severity in term of EES for the entire fleet of passenger cars in Europe. Thus, severity of the PDB test procedure is higher for light cars compared to the ODB test. However, the PDB test procedure cannot represent the kinematics of car-to-car collisions with unbalanced crash severities. On the contrary, the MPDB test can represent the crash kinematic of car-to-car collisions and therefore simulate the unbalanced compartment loadings in car-to-car collisions better.

Restraint systems: The ODB test procedure produces acceleration pulses that are similar to car-to-car offset collisions with mass ratios close to one (Fig. 4.16). However, the ODB cannot represent the unbalanced velocity differences and consequently the crash pulses of vehicles in car-to-car collisions with mass ratios higher than one.

Simulation [140, p. 36] and crash test results [142, p. 10] from the FIMCAR project showed that the PDB test procedure produces slightly higher acceleration pulses than the ODB test procedure. The acceleration pulses have the same form, particularly at the beginning of the collision, which is decisive for triggering the restraint systems (Fig. 4.17).

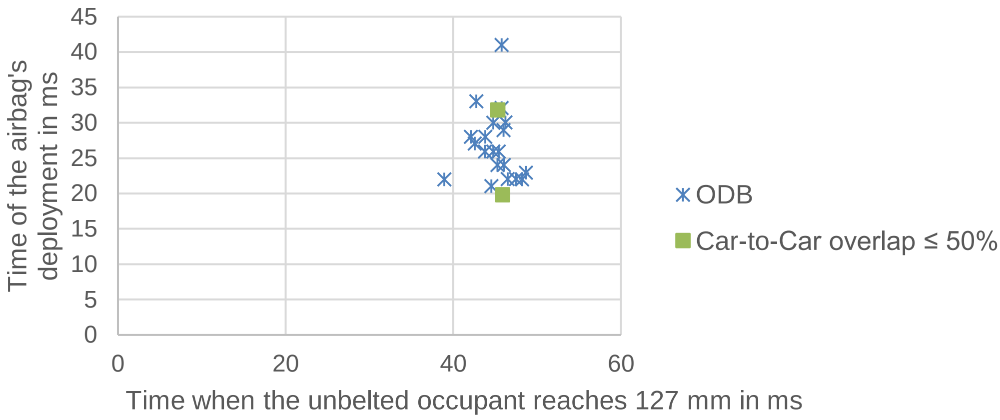


Figure 4.16: Minicar crash tests shown by airbag's deployment time and the time when the unbelted occupant reaches 127 mm

According to [134, p. 7]

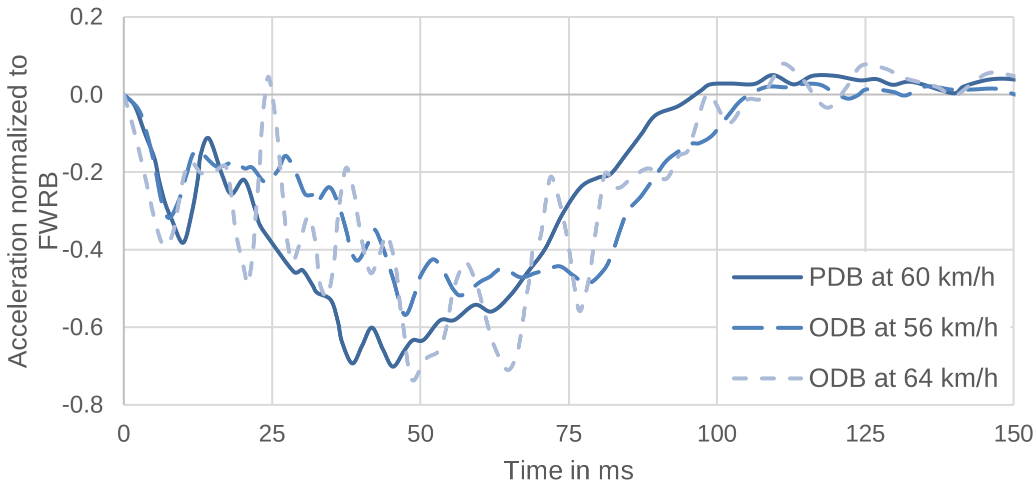


Figure 4.17: Acceleration pulse of the Fiat 500 normalized to the absolute value of maximum acceleration peak in the FWRB test at 56 km/h

According to [140, p. 39]

Therefore, the PDB is also assumed to have a representative acceleration pulse for car-to-car tests with a mass ratio close to one, as observed in the ODB test procedure. The acceleration pulses in the MPDB test depend on the mass ratio and are generally higher due to more kinematics in the test procedure. Thus, the MPDB can represent car-to-car collisions with different mass ratios.

Structural interaction: The deformable block of the ODB is unstable in tests with modern vehicles. Previous studies by EEVC WG15 [97, p. 35] showed that the ODB can be deformed differently in tests with the same vehicle model. Therefore, the ODB cannot assess the structural integrity of vehicles. The offset constellation of the ODB test provides the potential to reflect low horizontal structural interactions in higher deformation and intrusion values. However, the unstable deformable element cannot distinguish between low and high vertical structural interactions. The PDB and the MPDB are designed to assess the structural interaction of vehicles, and they showed repeatability and robustness in crash tests performed in the FIMCAR project [140, p. 39].

Our previous work [130] conducted simulation analyses to investigate the capability of different barriers to reflect structural properties in the test results. The structural properties of a validated simulation model, i.e., Toyota Yaris from National Crash Analysis Center (NCAC) [143], are varied to create four different vehicle models with varying structural properties (Tab. 4.7). Mini E-Car represents electrified microcars with low horizontal and vertical structural interaction. E-Car represents vehicles with low horizontal structural interaction, and Strong Car represents vehicles with high horizontal and vertical structural interaction.

Table 4.7: Variations of the Toyota Yaris with different structural properties [143, p. 4]

Model Name	Structural Property	Changes relative to the original model
Mini E-Car	Low horizontal and vertical structural interaction	1- No motor block or radiator in the front to represent electric vehicles without the load path of the motor block in the middle 2- Reduced height by 50 mm to represent microcars with the risk of override 3- Added a battery pack to the rear section
E-Car	Low horizontal structural interaction	1- No motor block or radiator in the front 2- Added a battery pack to the rear section
Basic Model	Normal	No changes
Strong Car	High horizontal and vertical structural interaction	1- High strength material for front structural components (e.g., bumper and radiator frame) 2- Higher thickness for front structural components (e.g., bumper and radiator frame) 3- The density of the materials is scaled to retain a similar mass as the basic model

The structural properties of the vehicle models are validated in two tests. Vertical structural interaction is tested against the bumper of the Research Council for Automobile Repairs [144] at 56 km/h, and the horizontal structural interaction is tested against the original Yaris model with 50 % overlap and a collision speed of 100 km/h (i.e., 50 km/h for each party). The test results confirmed the structural properties presented in Tab. 4.7, and the vehicles with higher structural interaction had more homogenous deformation patterns (Fig. 4.18).

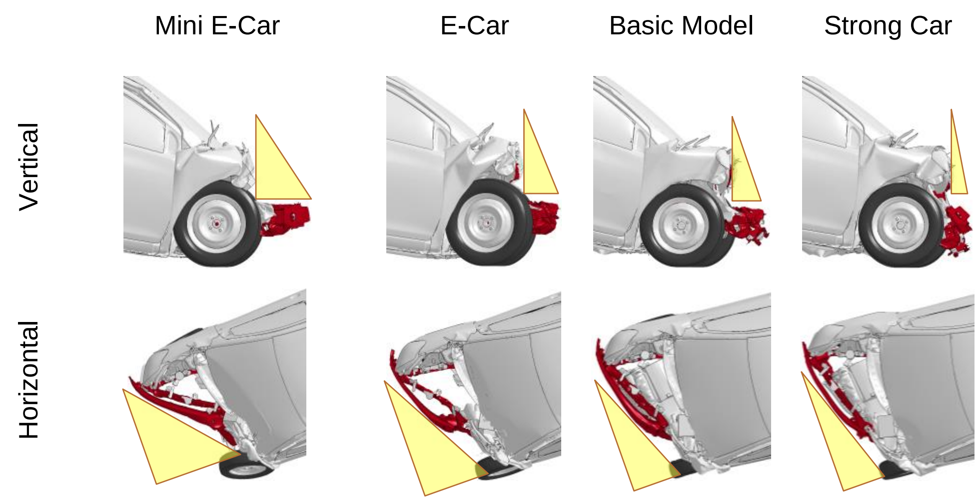


Figure 4.18: Test results corresponding to the structural properties [130, p. 4]

These vehicle models are simulated in the ODB and PDB test procedures. The ODB test results [130, pp. 6-7] showed that the structural differences influence the acceleration pulses, but do not affect the intrusion values. However, the PDB can reflect the structural properties in the acceleration pulses and intrusion values of the vehicles.

Force levels: As described in Section 4.1.3, the ODB cannot represent the force levels of the new generation of cars and is too soft to assess the force levels. The PDB and MPDB are intended to represent the opponent vehicle in a car-to-car collision [142, p. 3] and should therefore represent the force levels of the vehicle fleet of passenger cars in Europe. However, some crash tests from ADAC [14, p. 9] showed that the load spreading in the deformable element of the MPDB test procedure is different from the deformation patterns that occur in comparable car-to-car collisions (Fig. 4.19). ADAC experts stated that the upper part of the PDB is stiffer than an average car.

Figure 4.19: Deformations in car-to-car test (left) and car-to-MPDB test (right) [14, p. 9]

Furthermore, the PDB and MPDB provide a high potential of deformation, which makes the deformable element unlikely to bottom out. The automotive industry criticized the large deformation potential, which provides a possibility of abuse to increase the vehicles' force levels without influencing the test results [97, p. 26].

Conclusion: The baseline test of the ODB, PDB, and MPDB test procedures is a car-to-car collision. Therefore, constellation and test set-up of these barriers are appropriate for use in assessing the compatibility rate.

Tab. 4.8 summarizes the evaluation results for the offset test procedures.

Table 4.8: Evaluation of offset test procedures

Requirements	ODB	PDB	MPDB
Assessment of the compartment integrity in an offset test procedure	+	+	+
High loads for light cars as observed in car-to-car accidents	-	+	+
Comparative severity with current crash tests for heavier vehicles	+	-	-
Higher acceleration pulse for light vehicles in the offset test procedure	-	-	+
Representative acceleration-time pulse	+	+	+
Reflection of low and high structural interaction in intrusions and acceleration pulses	-	+	+
Barrier should represent the average force level of passenger cars	-	-	-
Representative crash constellation for car-to-car collisions	+	+	+

As can be seen, none of the proposed offset test procedures fulfill the important requirements for a comprehensive assessment approach and evaluation of the compatibility rate. The MPDB is the best candidate and might be able to fulfill all requirements with some improvements. ADAC made some changes to the MPDB test procedure [14, pp. 9−11] to improve its representability of the force levels of normal passenger cars. However, the issue of less severity for heavier vehicles and the potential for misuse remain open. Thus, an alternative offset test procedure is needed for assessing the compatibility rate.

4.4 An Alternative Offset Test Procedure

As discussed in Section 4.3.1, the FWRB test fulfills all important requirements for evaluating the safety level. To complete the assessment approach, an alternative offset test procedure is needed that can fulfill the most important requirements for evaluating the compatibility rate presented in Tab. 4.8.

Results of Section 4.3 showed that the MPDB test has the highest potential for use in the assessment approach, and the concept of the MDB might be further developed to find an alternative offset test procedure. However, development of a new barrier necessitates many resources and is not within the scope of this work. Therefore, current MDBs from different side and rear impact test procedures from safety regulations or consumer organizations in Europe and the United States are reviewed to find the most appropriate barrier concept for evaluating the compatibility rate in an offset frontal impact test. The Advanced European Mobile Deformable Barrier (AE-MDB) is found to have the highest potential regarding the barrier's geometry and deformation pattern. The following sections investigate the AE-MDB, which will be used in this study as a reference for a further development of the MPDB.

4.4.1 Deformable Barrier

The AE-MDB is the result of many studies and projects conducted since 2002. In 2011, Euro NCAP agreed to adopt this barrier for future side impact test protocols [51, p. 2]. The geometry of the barrier face and stiffness of the deformable elements represent the front-end of an average vehicle from today's passenger car fleet in Europe (Fig. 4.20).

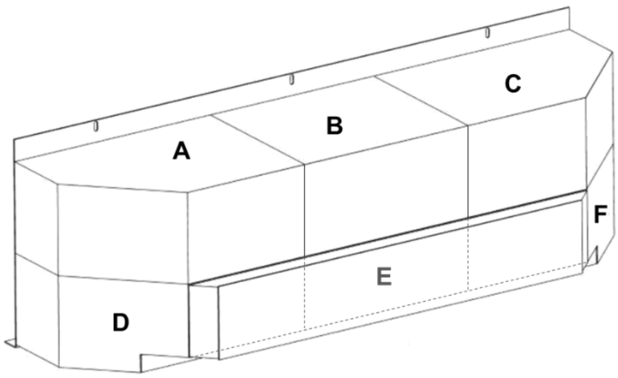


Figure 4.20: Deformable element of the AE-MDB

According to [51, p. 2]

The deformable element consists of six single blocks of aluminum honeycomb with progressively increasing force levels, which were analyzed in our previous study [129, pp. 5-6]: Blocks D and F represent the energy absorbers (i.e., main load paths), and blocks A, B, C, and E represent the remaining deformation zone of an average vehicle. While blocks A, B, and C have similarly low force levels, Block E provides a relatively high force level to represent the engine block of the average vehicle. Furthermore, an additional single beam element is attached to the front of the lower row of blocks, which represents the bumper of an average vehicle. The bumper element of the AE-MDB covers the whole common interaction zone of Part 581 from FMVSS 208 for the crash structures.

The mass of the AE-MDB was set to 1500 kg, i.e., similar to the MPDB, in its first version. However, some studies were conducted on the representability of the barrier for the European passenger car fleet by the University Institute for Automobile Research Madrid, BASt using accident research data (GIDAS/CCIS), Euro NCAP data, and the European Environment Agency [51, p. 2]. The results showed that a trolley mass of 1300 kg is more representative of the European passenger car fleet. The characteristics of the AE-MDB are slightly different from the average European vehicle ranges that are used in the development of the MPDB (Tab. 4.9), which could be due to the different databases used for the development of the MPDB and the AE-MDB.

Table 4.9: AE-MDB characteristics (according to [104, p. 2]; [145, p. 1])

Description	Average EU Vehicles	AE-MDB
Total mass in kg	1200–1700	1300
CG location from front, w.r.t. length in m	0.720–0.980	1.0
Vehicle front to CG distance in m	1.700–2.000	2.0
Vehicle front to rear axle distance in m	3.200–3.700	Not specified
Overall length in m	3.800–4.700	Not specified
CG height in m	0.560–0.640	0.5
Axle height in m	0.270–0.290	Not specified
Wheel base in m	2.450–2.750	3.0
Front and track width of the trolley	Not available	1.5
Mass front axle in kg	710–990	Not specified
Mass rear axle in kg	465–735	Not specified

4.4.2 Test Set-up

The overlap value of the AE-MDB test is set to 50 %, which is the overlap of the baseline test of the ECE R94 and Euro NCAP [146, p. 7], and is therefore well-established in tests with MDBs (e.g., in the MPDB test). Furthermore, as described in Section 4.2.1, the overlap value of 50 % is representative of most collisions with intrusions. Therefore, this overlap is suitable for assessing the compartment strength of the vehicles.

The test speed determines the crash severity, which can be described using two parameters: Delta-v and EES.

Delta-v is the change in the vehicle speed before and after the crash, which represents the crash severity with respect to the restraint loads. Since the offset test represents car-to-car collisions, the delta-v of the test should be comparable to values of car-to-car collisions. Test results from the FIMCAR project showed delta-v values of about 75 km/h for light vehicles [147, p. 13], which is comparable with Euro NCAP's test results, i.e., also between 70 km/h and 75 km/h [141, p. 11].

EES represents the crash severity with respect to the deformations in the vehicle, which is a decisive factor for assessing the compartment strength and an objective of the offset test procedure for both light and heavy vehicles. Thus, the collision speed should be set in a manner that ensures the EES of the AE-MDB test is not lower than in the ECE R94 test for heavy vehicles.

A series of simulations with validated vehicle models and different masses is conducted in this work to find the EES and velocity changes of vehicles in the frontal impact test with the AE-MDB. Fig. 4.21 presents the results of the EES for different vehicle masses and test speeds (barrier and the test vehicle have equal test speeds).

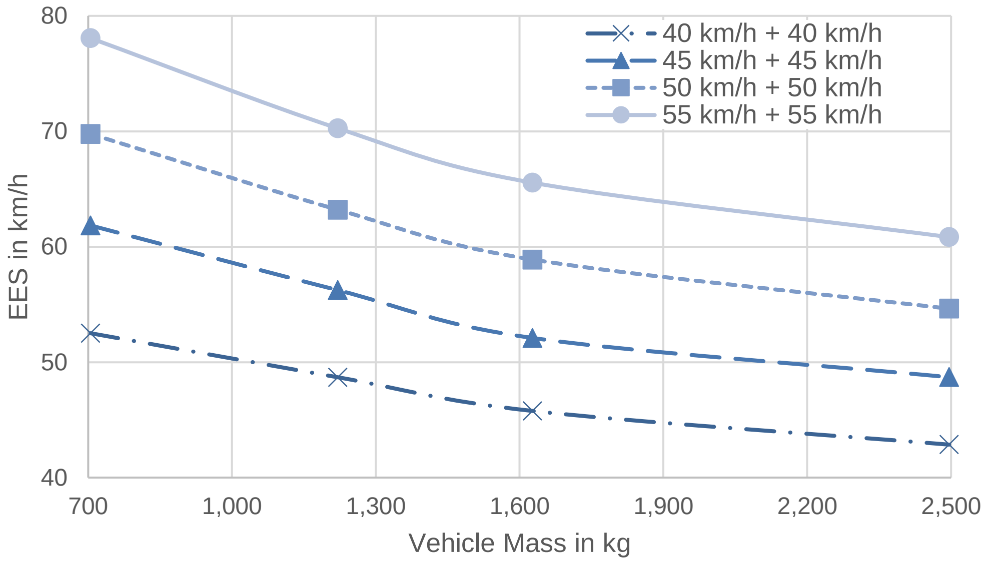


Figure 4.21: EES of different vehicle masses in the AE-MDB test

The results show that a collision speed of 90 km/h (i.e., 45 km/h for each party) results in an EES range of 49 km/h to 62 km/h for the mass range of 700 kg to 2500 kg (less for heavier vehicles). The heaviest passenger car segment in Europe is the segment F with an average mass of 1920 kg (Tab. 2.1), which undergoes an EES of more than 51 km/h. Thus, the severity of the AE-MDB test at 90 km/h is higher than the ECE R94 for passenger cars with a mass of up to 2200 kg and covers more than 87 % of car-to-car collisions with severe injuries [91, p. 72].

The delta-v values are strongly dependent on the vehicle mass and vary between 50 km/h and 60 km/h for vehicles lighter than 1300 kg. For heavier vehicles, the delta-v values are about 35 km/h, which is due to the rebound of the moving barrier. However, lower delta-v values for heavy cars are acceptable, since the potential of their restraint systems is assessed in the full-width test.

4.4.3 Evaluation Results

The AE-MDB is evaluated according to the requirements listed in Tab. 4.5:

Compartment strength: Owing to the limited energy absorption by the deformable elements, the test vehicles have to absorb the remaining crash energy. Therefore, the severity of the AE-MDB test will not drop drastically with an increased vehicle mass. The simulation results (Fig. 4.21) show that the compartment integrity of heavy vehicles can be assessed adequately with the AE-MDB test. Furthermore, the MDB produces higher loads for light cars, which is similar to car-to-car accidents.

Restraint systems: Our previous work [129, pp. 6-7] conducted a simulation analysis with different vehicle models from NCAC (i.e., Geo Metro, Toyota Yaris, and Ford Taurus) against the AE-MDB and an average passenger car (i.e., Dodge Neon), in terms of the vehicle mass, to test the representability of crash-pulses in the AE-MDB test for car-to-car accidents (Fig. 4.22).

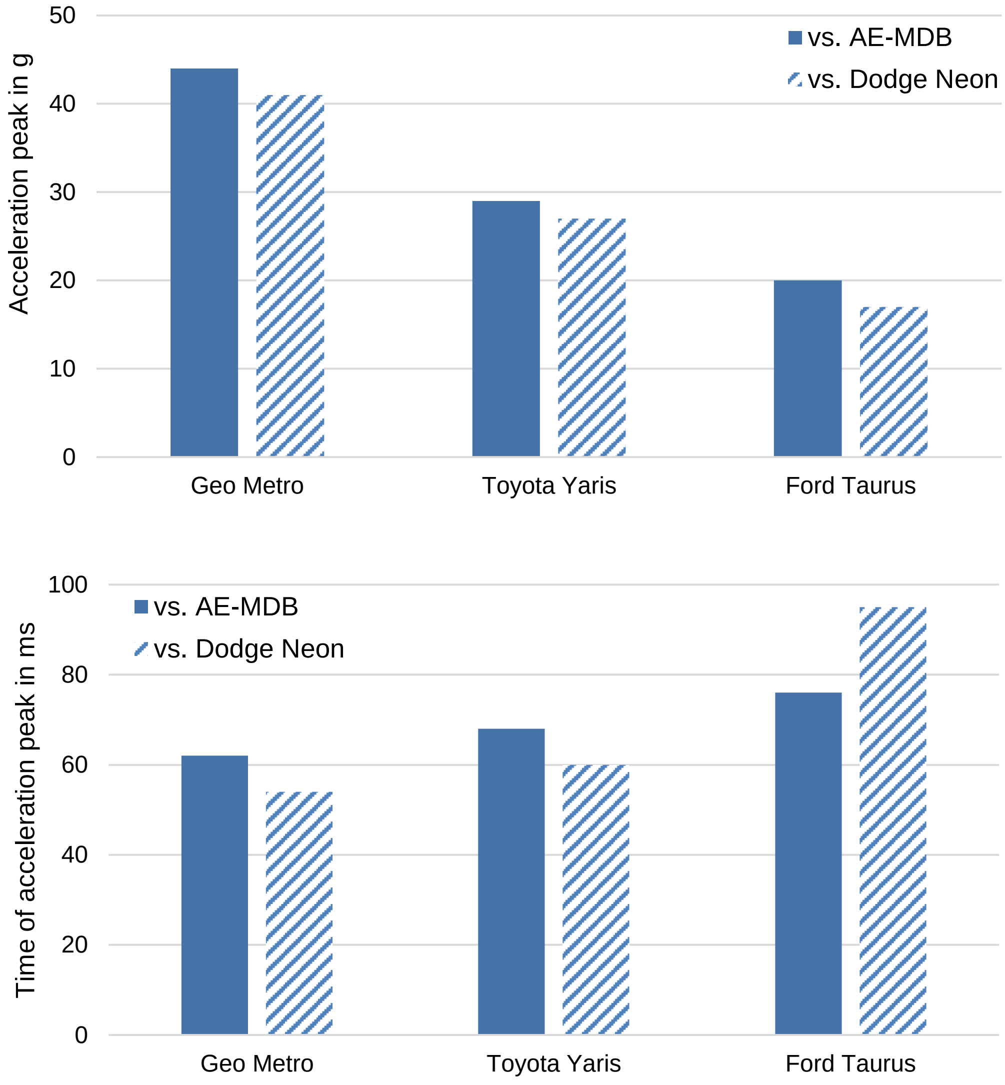


Figure 4.22: Acceleration peak (top) on the seat rail of the driver side in a longitudinal direction and the time of acceleration peak (bottom) for the AE-MDB and car-to-car tests

According to [129, pp. 6-7]

The simulation results showed that the acceleration pulses of the AE-MDB tests are similar to car-to-car collisions with respect to the maximum accelerations (average difference of about 12 %) and their peak times (average difference of about 7 %). Furthermore, the delta-v values remained at the same level and showed an average difference of about 11 %.

Structural interaction: Our previous work [130, p. 8] conducted a simulation analysis with different variations of a vehicle model (i.e., Mini E-Car, E-Car, Basic Model, and Strong Car, as described in Tab. 4.7) to investigate the ability of the AE-MDB to reflect structural properties in the test results (Fig. 4.23).

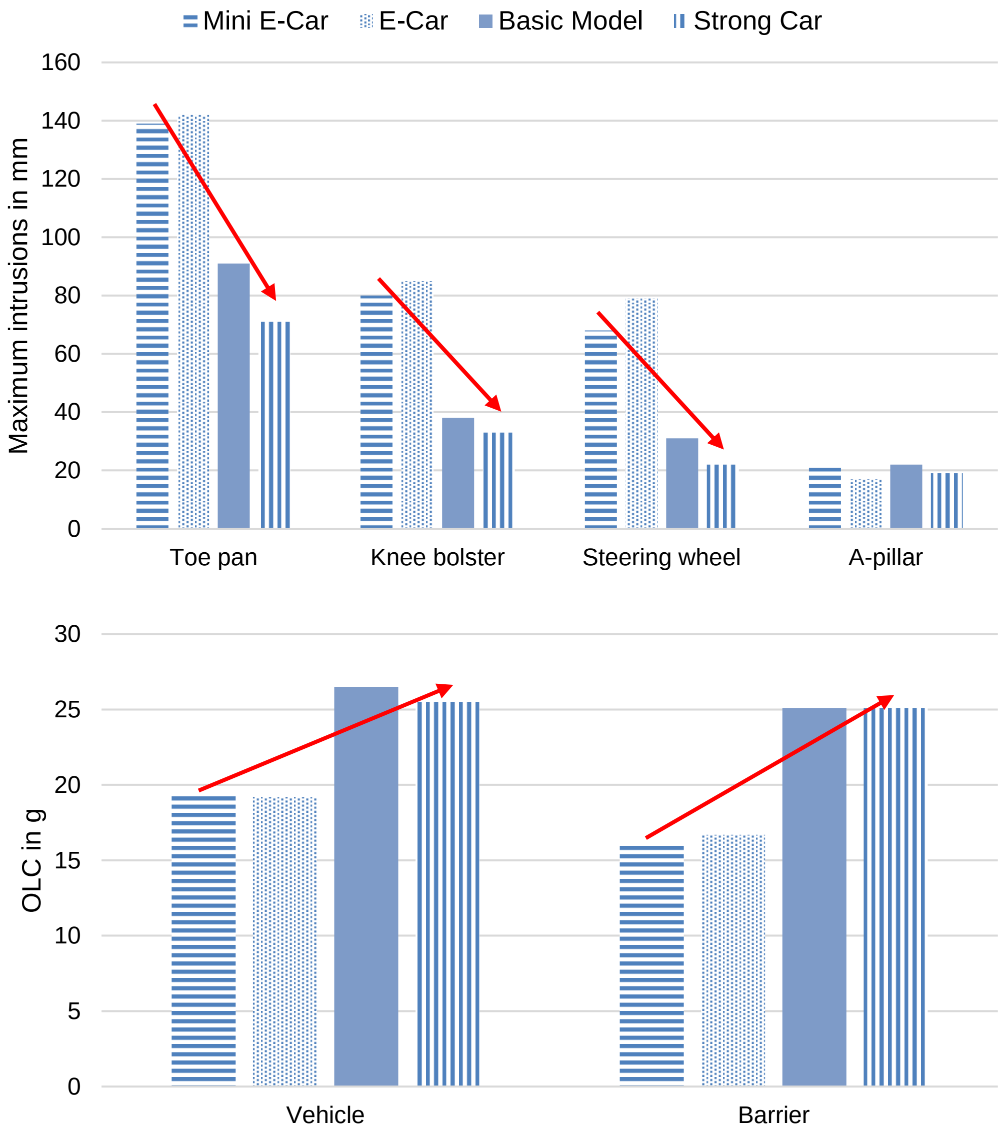


Figure 4.23: Maximum intrusions (top) and OLC values (bottom) of vehicles with different structural properties in the AE-MDB test

According to [130, p. 8]

The results showed similar trends to those seen in car-to-car collisions. The vehicles with higher structural interaction (i.e., Basic Model and Strong Car) produced higher acceleration pulses and were deformed less. The AE-MDB could also simulate the override issue of vehicles with low vertical structural interaction (i.e., Mini E-Car), which occurred in the equivalent car-to-car collision due to the lower height of the light vehicle.

Force levels: The barrier face of the AE-MDB is more representative of the front-end of passenger cars than the PDB's barrier face. The AE-MDB has a limited deformation depth that prevents misuse of the deformable elements for stiffening the vehicle structures. Then, after the bottoming out of the deformable element, the rigid plate of the trolley is contacted. The impact of vehicles with high force levels on the rigid plate of the trolley generates high crash pulses in the vehicle and the moving barrier.

Conclusion: Tab. 4.10 summarizes the evaluation results of the AE-MDB test procedure. As can be seen, this test procedure fulfills all the important requirements and can be used in the assessment approach of crash compatibility.

The baseline situation of the AE-MDB test is a car-to-car collision. Furthermore, the geometry of the barrier faces with chamfered corners, a bumper beam in the common interaction zone, and similar block stiffness of the front-end of vehicles, enables the simulation of incompatibility issues, such as over-/underride.

Table 4.10: Evaluation of the alternative offset test procedure with the AE-MDB

Requirements	AE-MDB
Assessment of the compartment integrity in an offset test procedure	+
High loads for light cars as observed in car-to-car accidents	+
Comparative severity with current crash tests for heavier vehicles	+
Higher acceleration pulse for light vehicles in the offset test procedure	+
Representative acceleration-time pulse	+
Reflection of low and high structural interaction in intrusions and acceleration pulses	+
Barrier should represent the average force level of normal passenger cars	+
Representative crash constellation for car-to-car collisions	+

4.5 Summary and Discussion

Section 4.1 studied current test procedures from previous works and investigated five important test procedures to find their advantages and disadvantages for use in an assessment approach for frontal crash compatibility. Section 4.2 described the evaluation approach of the previous works and compared it with the approach of this study, which is based on the fundamental definition model presented in Chapter 3. The test procedures were categorized into full-width and offset tests, and a requirement list was established to evaluate the test procedures. Section 4.3 evaluated the current test procedures by reviewing crash tests from other works and simulation analyses. The FWRB test showed good results, but no offset test has fulfilled all the requirements. Therefore, Section 4.4 developed an alternative offset test procedure, which uses the AE-MDB. The alternative offset test was investigated with a simulation analysis regarding fulfillment of the requirements listed in Section 4.2. The evaluation results confirmed the suitability of the AE-MDB for use in the assessment approach of frontal crash compatibility.

The AE-MDB has been developed for side impacts. The application of the AE-MDB in frontal impacts might result in reproducibility and repeatability issues, which did not exist in side impact tests. Since the aim of this study was not to develop a new barrier, the AE-MDB is used as the most similar barrier to our intended concept that enables us to study and develop the whole approach for assessing frontal crash compatibility. Therefore, the AE-MDB should be seen as a barrier concept proposed for further development of the MPDB. The most important characteristics of the AE-MDB that should be considered for further development of the MPDB are as follows:

- More representative geometry and shape for front-end of passenger cars
- More representative force levels and stiffness distribution in deformable blocks
- Limited deformation depth to disclose the misuse potential from aggressive vehicles

5 Assessment Approach[7]

Chapter 4 discussed the test procedures for the assessment of frontal crash compatibility and proposed a set of two test procedures. The objective of this chapter is to complete the assessment approach with criteria for evaluating the test results. These criteria should allow us to draw a statement about the frontal crash compatibility of vehicles based on their performance in the crash tests and post-crash measurements.

Section 5.1 reviews current criteria and approaches for evaluating the test results and discusses their suitability for use in the proposed test procedure presented in Chapter 4. The criteria are categorized into two groups for full-width and offset test procedures and are discussed separately.

Section 5.2 describes the criteria for evaluating the results from both full-width and offset test procedures. Since an alternative offset test is developed, criteria from the state of the art are insufficient; thus, a new criterion should be developed for the offset test. The efficiency of the developed criterion is validated using crash tests and simulations.

Section 5.3 presents the assessment protocol. The fundamental definition model from Chapter 3 is applied to the test procedures presented in Chapter 4 and the assessment criteria from Section 5.2.

Section 5.4 summarizes the results of this chapter and discusses the limitations of the results that can be investigated in future works.

5.1 State of the Art of Assessment Criteria for Crash Compatibility

Generally, the criteria for evaluation of the crash test results can be categorized into two groups: criteria for self-protection and criteria for partner-protection.

For rating the crash performance in terms of self-protection, dummy measurements and injury criteria can be used. There is an agreement on these criteria, and dummy models are continuously being researched in other works (e.g., [149–151]) to improve their capabilities for injury predictions. FIMCAR criticized that the compartment strength cannot be assessed using the dummy criteria alone and suggested [98, p. 113] adding a criterion for displacement of the A-pillar of the test vehicle to be less than 50 mm to demand a strong occupant compartment.

Furthermore, in some crash tests performed in the FIMCAR project, a female dummy was used instead of the common male dummy on the front passenger seat. The objective was to investigate the protection of this group of occupants that had so far been neglected in the crash tests [141, Ch2P2]. Previous crash analysis [91, p. 42] showed that female occupants are exposed to more restraint injuries compared to the male occupants. However, this is because the front passenger seat is more frequently occupied by female occupants (64 % [91, p. 66]) or because of the calibration of the restraint systems for male dummies and consequently male occupants.

In previous works of EEVC WG15, VC-COMPAT, and FIMCAR, the structural interaction and force levels were seen as the decisive parameters for assessing partner-protection.

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[7] This chapter is taken in part from an article [148] published in International Journal of Crashworthiness, September 2016. This article was prepared by Sadeghipour (main author) during his work.

Thus, the criteria for partner-protection are focused on assessing these two requirements. Two approaches were investigated and developed in previous works based on the assessment of exerted loads on the LCW or deformations of the barrier face. These approaches and relevant criteria are discussed in more depth in the following sections.

5.1.1 Criteria Existing for Partner-Protection in Full-Width Tests

The FWRB does not have any deformable blocks, and therefore, the only possibility for assessing partner-protection of a test vehicle is by evaluating the load spreading on the LCW of the barrier. The NHTSA [152, pp. 2-6] developed two criteria in its previous studies on compatibility between passenger cars and light trucks and vans. The criteria are as follows [152, p. 2]:

- AHOF 400: Average height of force (AHOF) delivered by a vehicle in the first 400 mm of crush
- KW 400: Stiffness-related crush energy absorbed by a vehicle in the first 400 mm of crush

The objective of AHOF 400 is to ensure the presence of a crashworthy structure in the common interaction zone to provide an adequate vertical structural interaction. The time window for measuring the forces is limited to a crush depth between 25 mm and 400 mm to avoid influencing the results from the crushing of a relatively soft bumper and the impact of the engine block on the LCW [152, p. 3]. The FWRB test and AHOF 400 can only assess the primary energy absorbing structures (PEAS), and a complementary test is needed to assess the secondary energy absorbing structures (SEAS) [153, p. 16]. Because the SEAS are normally set back from the front bumper, they do not have enough interaction with the LCW to be evaluated with the AHOF 400 (Fig. 5.1).

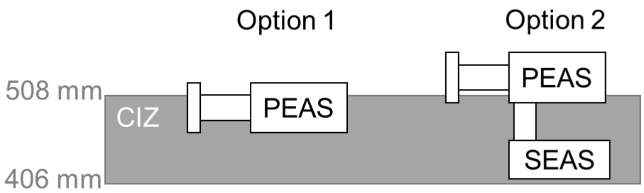


Figure 5.1: FWRB and AHOF 400 cannot detect SEAS adequately in option 2; CIZ = Common Interaction Zone

According to [153, p. 14]

The objective of KW 400 is to harmonize the force levels and avoid heavier vehicles over-crushing lighter vehicles because of the higher strength in their energy absorbing structures.

The principle of an ideal spring is used in KW 400 to calculate and limit the strength of the energy-absorbing structures in the crushing depth of 25 mm to 400 mm, and a lower and an upper limit is defined for KW 400, Eq. (5.1). The crushing depth is limited to disclose the influence of non-crashworthy structures (e.g. soft nose for pedestrian protection).

$$KW\ 400 = \frac{2\int_{25\ mm}^{400\ mm} F dx}{(400^2 - 25^2)} \tag{5.1}$$

Since the crash structures of heavier vehicles have to absorb more kinetic energy in single vehicle collisions, they need a higher strength or a longer deformation zone relative to the lighter vehicles. Therefore, KW 400 results in reducing the self-protection level of heavier vehicles or increasing the length of the vehicles' front. Fig. 5.2 presents the wide range of KW 400 for different vehicle masses. FIMCAR [153, p. 18] claimed that it would be infeasible to apply this requirement over the full range of vehicle sizes due to the side effects of the vehicle design.

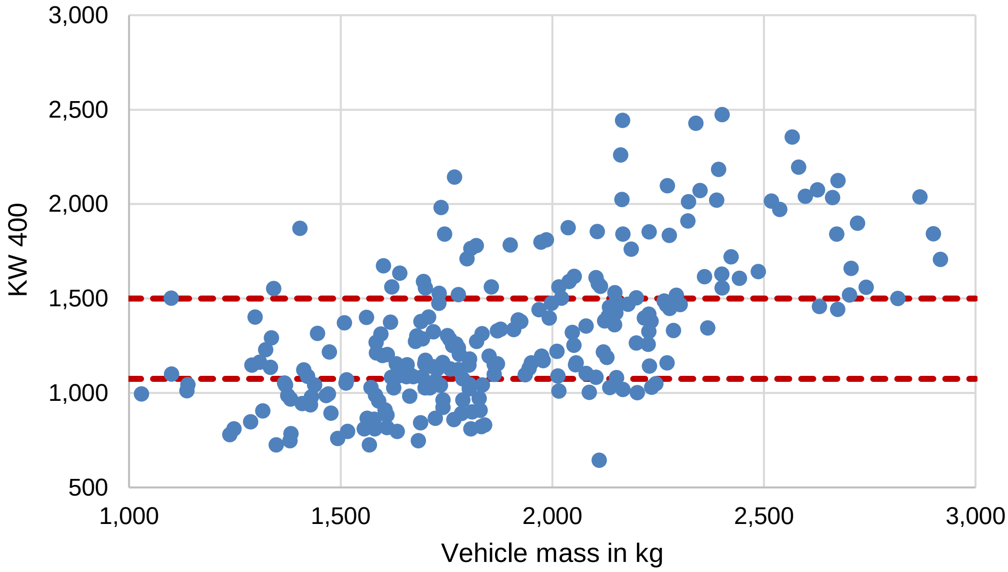


Figure 5.2: KW 400 versus vehicle test mass; red dashes show the defined limits

According to [152, p. 5]

Furthermore, KW 400 assumes a linear force deformation characteristic for the energy-absorbing structures of the vehicles. As described by FIMCAR [153, pp. 19-20], this simplification would result in situations in which the vehicle has to absorb more crash energy in the collision with a vehicle having a lower KW 400. Thus, the over-crushing issue of lighter vehicles would not be solved by limiting KW 400.

Nagoya University has proposed a criterion to evaluate the height of PEAS using load measurements on LCWs [153, pp. 20-21], which is an updated version of AHOF 400. In this criterion, rows three and four of the LCW are assumed as the common interaction zone, covering the height range of 330 mm to 580 mm from the ground. The loads of the third row (F_3) and the fourth row (F_4) are measured when the total measured load on the LCW is equal to 200 kN to assure the load measurement before the engine block impacts the LCW. The measured loads have to fulfill the following requirements:

$$F_4 + F_3 \geq 80 \text{ kN}, \tag{5.2}$$

$$\frac{F_4}{F_4 + F_3} \geq 0.2, \tag{5.3}$$

$$\frac{F_4}{F_4 + F_3} \leq 0.8. \tag{5.4}$$

However, similar to AHOF 400, this criterion cannot evaluate the SEAS in the FWRB test.

The FWDB has a deformable block, which can detect structures set back from the bumper front. Thus, the issue of SEAS detection might not appear in this test procedure. The FIMCAR project adopted Nagoya University's criterion for the FWDB test and developed it further [98, p. 112]. In the FWDB criterion, the load measurements should fulfill the following requirements to assure the vertical structural interaction of the test vehicle:

$$F_4 + F_3 \geq \min\{200\ \text{kN}, 0.4F_{T40}\}, \quad (5.5)$$

$$F_4 \geq \min\{100\ \text{kN}, 0.2F_{T40}\}, \quad (5.6)$$

$$F_3 \geq \min\{100\ \text{kN} - Limit, 0.2F_{T40} - Limit\}, \quad (5.7)$$

where F_{T40} is the maximum of total LCW force up to the time of 40 ms, and $Limit$ is defined with Eq. (5.8).

$$Limit = F_2 - 70\ \text{kN} \quad \text{and} \quad 0\ \text{kN} \leq Limit \leq 50\ \text{kN}, \quad (5.8)$$

where F_2 is the loads of the second row on the LCW. FIMCAR [98, pp. 112-113] validated the FWDB criterion with test results and confirmed the consistency of the LCW data with the structural properties of the test vehicles. However, as described by the FIMCAR consortium, more studies are required to confirm the repeatability and reproducibility of the LCW measurements in the FWDB test.

There is still no criterion for assessing the horizontal structural interaction in the full-width test procedures, and the criteria for assessing partner-protection are limited to evaluation of the vertical structural interaction.

5.1.2 Criteria Existing for Partner-Protection in Offset Tests

As explained in Section 4.1.3, the ODB will bottom out in almost all tests with new generation vehicles. Therefore, the deformation of the barrier face does not include any valuable information for evaluating partner-protection.

EEVC W15 [97, p. 18] developed a criterion for controlling the force levels using LCW data. In this criterion, the peak of the forces is measured in a 10 ms time window (Fig. 5.3). Limiting the measurements to 10 ms intends to filter out the unrealistic additional short duration peak loads on the LCW, e.g., due to the engine impact on the rigid wall.

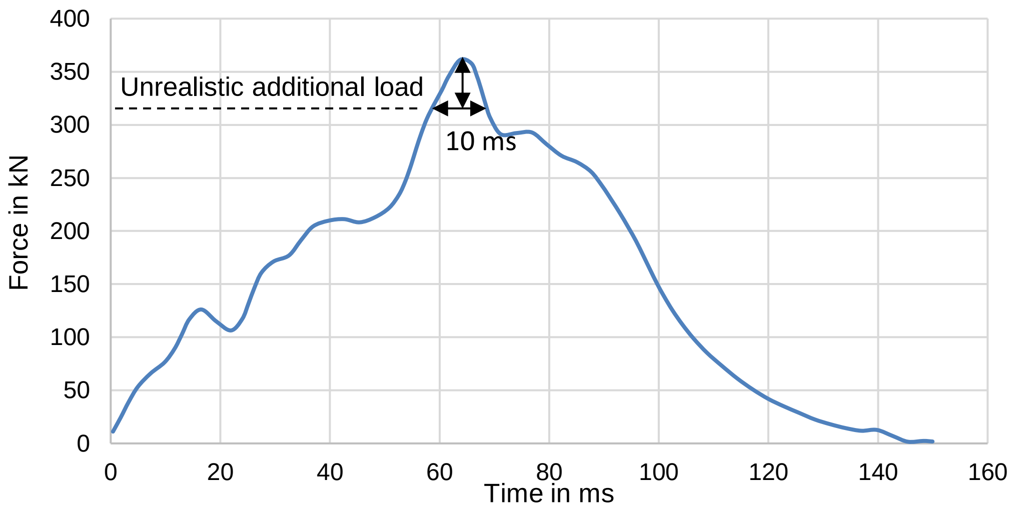


Figure 5.3: LCW data in the ODB test showing the additional load caused by the engine dump

According to [97, p. 18]

The objective of this criterion was to limit the force levels, similar to KW 400, to avoid over-crushing of lighter vehicles in car-to-car collisions with heavier vehicles. The main issue of KW 400 exists also here; thus, applying a limit for force levels in the ODB test reduces the self-protection of heavy vehicles or results in many infeasible side effects for the vehicle design. EEVC WG15 stated that the ODB may deform in different manners in repeated tests with the same vehicle model, resulting in different energy absorption levels in the deformable block [97, p. 35]. Thus, any criterion based on the behavior of the ODB would confront with reproducibility issues.

The LCW data cannot be used in the PDB tests since the high depth deformable block filters the load spreading. However, as described in Section 4.1.4 and Section 4.1.5, the PDB shows stable behavior and the deformations on the barrier face can therefore be used to develop a criterion for partner-protection.

FIMCAR developed a criterion for the PDB to evaluate the load spreading and structural interaction of the test vehicle by assessing deformations on the barrier face. The barrier is divided into three areas (Fig. 5.4) for evaluating the deformations. Significant deformations in the upper areas mean a high risk of override/underride, homogenous deformations in the middle area improve partner-protection, and deformations in the lower area show the existence of SEAS, which improves partner-protection [142, p. 4].

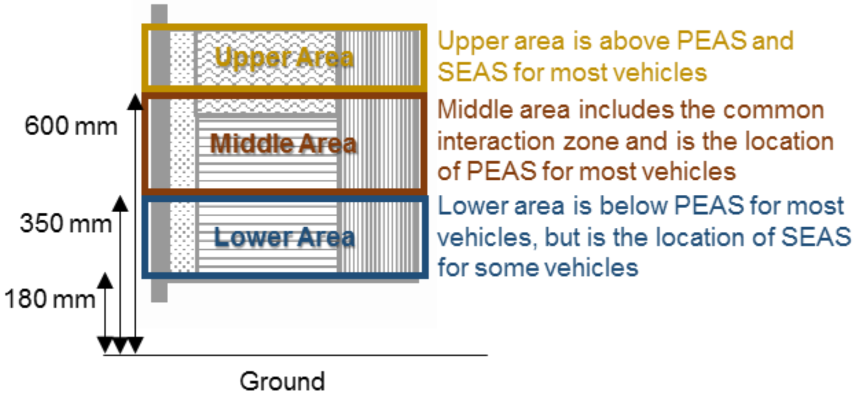


Figure 5.4: Assessment areas of the PDB

According to [142, p. 4]

Del Pozo et al. [142, pp. 5-7] proposed a two-stage criterion for evaluating partner-protection in the PDB tests, which uses a pass/fail concept (Fig. 5.5). The objective is to assure that a load path is present in the common interaction zone and the load spreading is homogenous.

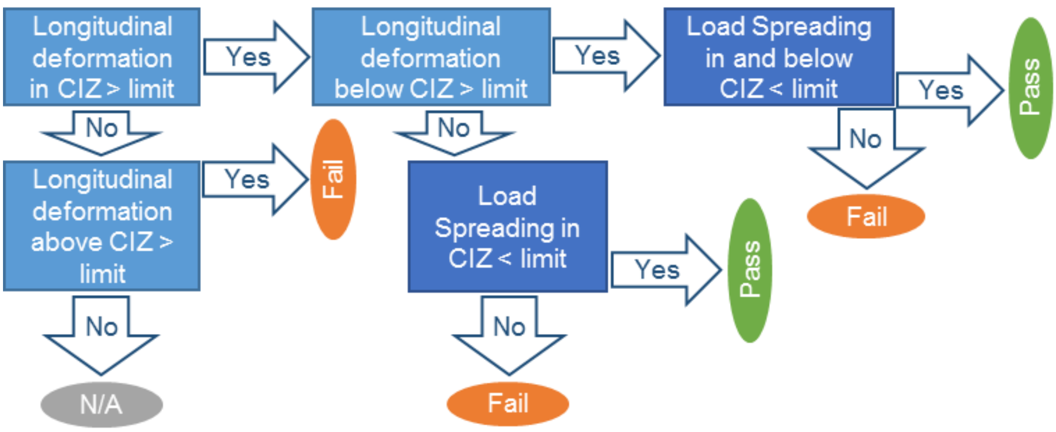


Figure 5.5: Concept of the proposed criterion for the PDB tests; CIZ = Common Interaction Zone

According to [142, p. 5]

In the first stage, the longitudinal deformation is assessed using the criterion (d) (Fig. 5.6), which gives some scores with respect to the deformation depth in different areas. If the deformation depth is in the predefined zones, the load path is detected and this stage is passed. Presence of crashworthy structures in the middle area (i.e. common interaction zone) is considered as more important for crash compatibility and therefore, scores of this area are higher.

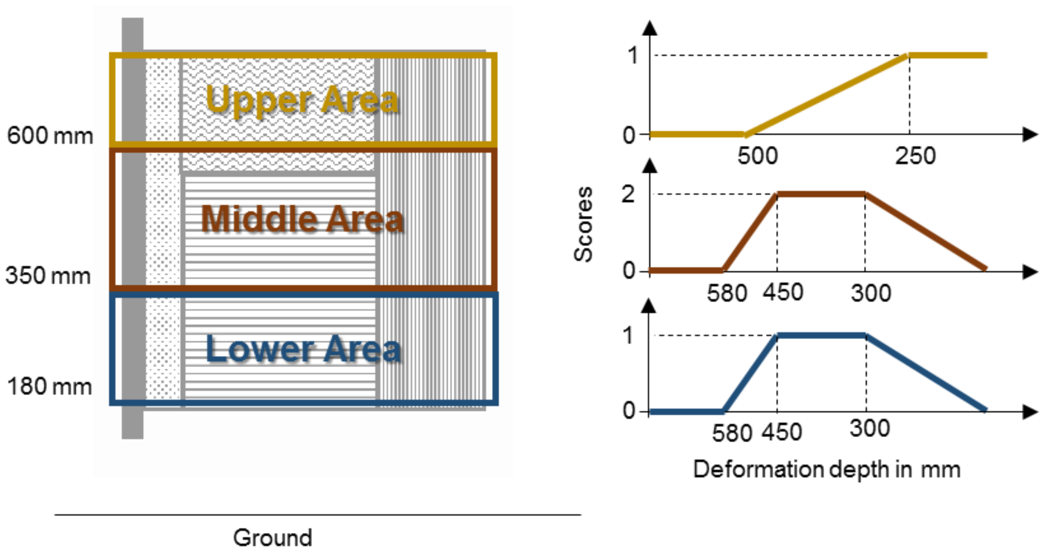


Figure 5.6: Criterion (d) is the sum of scores for evaluating the longitudinal deformations in the first stage of the PDB criterion

According to [142, p. 6]

In the second stage, when the load path is detected in the lower or middle area, the criterion Digital Derivative in Y Direction (DDY) determines the homogeneity of the load spreading. First, the area is divided in N equal subzones, for which the differences in longitudinal deformations are analyzed through the following parameters:

- D_i is the average longitudinal deformation in subzone i.
- $Q\%ile$ is the quantile of the longitudinal deformation in a subzone, e.g., 99%ile means 99% quantile of the longitudinal deformations in a subzone.

The DDY is defined using Eq. (5.9).

$$DDY = \left| \frac{X_{(y,z)} - X_{(y-1,z)}}{size\ of\ the\ subzone} \right|, \tag{5.9}$$

where $X_{(y,z)}$ is the 99%ile longitudinal deformation of the subzone (y,z). Lower values of the DDY correspond to more homogenous load spreading.

Del Pozo et al. [142, pp. 7-9] conducted three car-to-car crash tests and analyzed the results to make a statement about crash compatibility of the test vehicles. The expectations are compared with the PDB test results to validate the proposed criterion. The car-to-car test results showed the following:

- Supermini 1 should acquire a clear pass.
- Supermini 2 should acquire a pass.
- SUV 1 should acquire a clear pass.
- SUV 2 and Small Family Car 1 showed a fork effect and need to be evaluated further.

The DDY values of Supermini 2 and SUV 1 are both below two [142, p. 7], which is a clear pass for the proposed threshold of 3.5 for DDY. However, the DDY value of Supermini 1 is more than nine [142, p. 7], which is a clear fail instead of the expected clear pass. Furthermore, the DDY values of a repeated test for Small Family Car 3 (2.27 for test 35, and 1.27 for test 18 [142, p. 7]) showed repeatability issues with the developed criterion for assessing partner-protection in the PDB tests. The FIMCAR consortium [98, p. 113] stated another issue for the PDB criterion; the rating results show step effects, which are inconsistent when applied to different vehicle models.

The same criterion can be used for the MPDB test results. However, the same issues arise. ADAC modified the MPDB test procedure to reach increased representability of car-to-car collisions [14, pp. 9−13]. ADAC uses a three-stage concept for evaluating the test results:

1. The rating area is 45 % of the vehicle width, 200 mm from the barrier side, and between the height of 250 mm to 650 mm from the ground (Fig. 5.7).
2. The average intrusion depth and standard deviation are evaluated, while the average deformation depth should be between 320 mm and 480 mm [154, p. 20], and the standard deviation should be low.
3. Change in the trolley speed should be equal to or less than 50 km/h, and the test vehicle should absorb kinetic energy in its crumple zone.

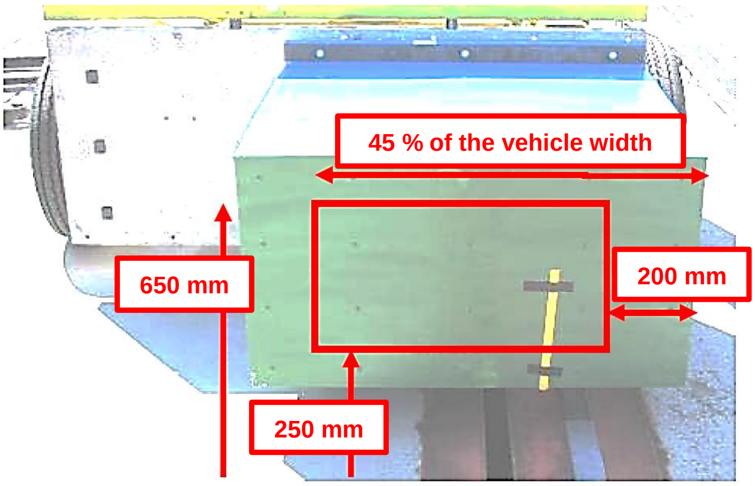


Figure 5.7: Rating area of the ADAC criterion for the modified MPDB [14, p. 12]

Some crash tests from ADAC [154, pp. 18-20] showed that the ADAC criterion can recognize the general compatibility problems. However, limits and weightings of the criteria are not yet finalized (e.g., mechanism of penalizing due to the high deformation depth or the limit for minimum absorbed energy in the crumple zone of the vehicle). Therefore, a comparison of the criterion results with car-to-car test results is not possible, and more investigations are required to confirm the reproducibility and repeatability of the assessment results. Furthermore, since the conducted tests contain vehicles with extreme compatibility issues, more studies are required to ensure the ability of the ADAC criterion for grading the compatible vehicles.

Another issue of the ADAC criterion is limiting the deformation depth. Similar to KW 400, it might be infeasible to apply this limited deformation depth to the whole range of passenger vehicles (up to 3.5 ton) due to the side effects on the vehicle size (longer front-end) and lower self-protection (lower strength).

5.2 Assessment Criteria

The assessment approach in this study is based on the assessment of parameters with a direct influence on injury risks (i.e., intrusions and restraint loads). Other parameters such as structural interaction or force levels are not assessed directly, and only their influence on the intrusion values or restraint loads is evaluated (Fig. 5.8).

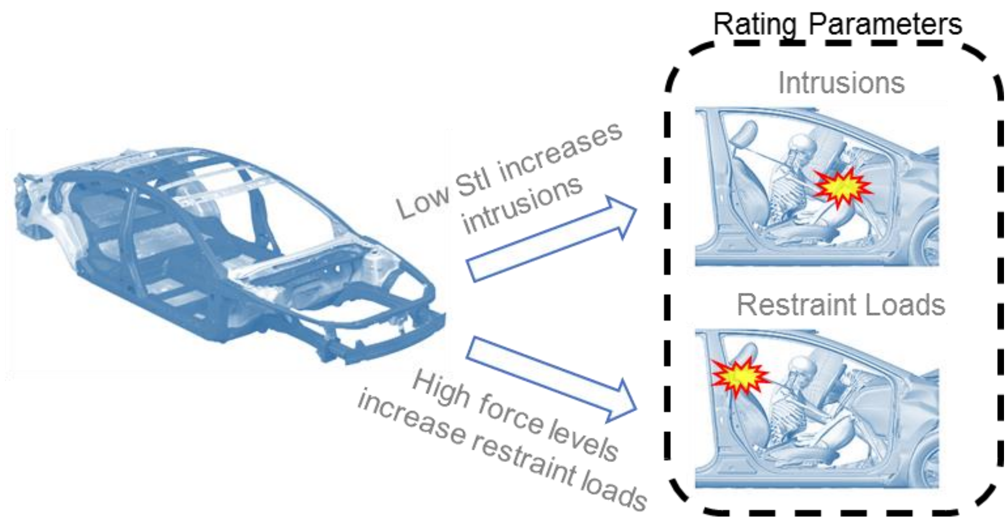


Figure 5.8: Concept of the rating approach; StI = Structural Interaction

Graphics from [155], [156]

Self-protection and partner-protection are assessed using separate criteria, which are described in the following sections.

5.2.1 Criteria for Self-Protection

Self-protection is evaluated in both full-width and offset tests using dummy measurements and intrusions into the occupant compartment of the test vehicle.

To consider both genders, a Hybrid III 50 % male dummy is placed on the driver seat, and a Hybrid III 5 % female dummy is placed on the front passenger seat. The seating positions are consistent with the crash statistics [91, p. 66]; 64 % of front seat passengers with severe injuries are females and 68 % of drivers with severe injuries are males.

To assess self-protection, dummy measurements are evaluated according to the Euro NCAP frontal impact test protocols [157]. These measurements cover different body parts of the dummies: head, neck, chest, abdomen, knee, femur, pelvis, and lower leg. The Euro NCAP test protocols also define a limit for displacement of the pedal and steering column. Besides these criteria, a limit of 50 mm displacement is set for the A-pillar, which is a suggestion from the FIMCAR consortium [98, p. 113] to cover the issue of compartment strength.

5.2.2 Criteria for Partner-Protection

As described in Section 4.2, partner-protection should be assessed only in the offset test with the AE-MDB. Risk of injury due to the restraint loads and intrusions is evaluated using injury measurements taken on a virtual dummy on the moving barrier. Thus, an accelerometer is installed on the center of gravity of the trolley. The acceleration measurements are assessed using the Occupant Load Criterion (OLC) to cover the restraint injuries and Acceleration-Based Criterion for Intrusions (ABC-I) to cover the intrusions' injuries.

5.2.2.1 OLC for Restraint Injuries

The OLC uses the principle physical behavior of the restraint systems to relate the acceleration pulses to the restraint loads on the dummy. Kübler et al. [158, p. 13] described the OLC approach, which assumes that the restraining mechanism consists of two phases. In the free flight phase, the occupant travels a relative distance of 65 mm to the vehicle at its initial velocity without any restraining loads. In the second phase, the restraint system decelerates the occupant with a constant load along a limited distance of 235 mm. After the second phase, the occupant reaches the vehicle's speed and the restraining mechanism is finished (Fig. 5.9).

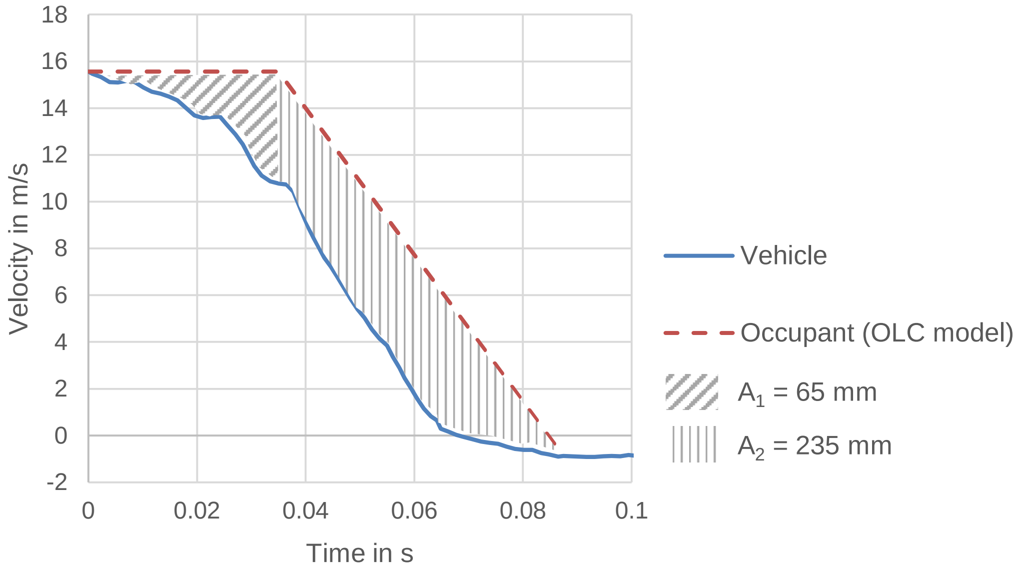


Figure 5.9: Restraining mechanism in the OLC approach

According to [158, p. 13]

The constant deceleration value in the second phase is the OLC value, which represents the severity of the collision for the restraint systems. Kübler et al. [158, p. 14] compared some dummy measurements from crash tests with OLC values and found a correlation between the OLC and the Head Injury Criterion with 36 ms time-window (HIC_{36}). Since the dummy measurements in frontal impacts are normally given in HIC_{15}, the correlation between HIC_{15} and HIC_{36} [159, pp. 2-3] can be used to set the limit of the OLC according to the maximum dummy values. The OLC represents the dummy injuries in a vehicle equipped with an ideal restraint system. Therefore, the HIC_{15} should not be more than 500, which is the limit of the green code in frontal impact Euro NCAP test protocols. Therefore, if the maximum value of the estimated OLC based on the acceleration measurements on the barrier's trolley does not exceed 37 g, the risk of restraint injuries on the partner is low. However, the OLC value of the AE-MDB in an AE-MDB-to-AE-MDB test with 50 % offset and at 90 km/h (i.e., 45 km/h for each party) is about 31 g. Thus, the limit of the OLC for partner-protection is set to 31 g, and any higher OLC values in the AE-MDB test should be penalized.

5.2.2.2 ABC-I for Intrusions' Injuries

The ABC-I has been developed to relate the acceleration measurements of the trolley to the risk of intrusions in the partner vehicle. The objective was to complete the assessment of partner-protection using the acceleration measurements on the MDB. This section describes the theoretical principle, the development approach, and validation of ABC-I summarily, which can be found in more detail in our previous work [148].

The crumple zone of vehicles has normally a progressive deformation force level [6, p. 165]. Thus, any intrusions in the occupant compartment are accompanied by a high deformation force level, which is described by:

$$W = \int F \cdot ds, \tag{5.10}$$

where W is the work in J done by the applied force (F) in N, and s is the intrusion in the occupant compartment in m. Considering Newton's second law, the high force level for deformation of the occupant compartment will result in acceleration peaks, and Eq. (5.10) can be rewritten as:

$$W = m \int a \cdot ds, \tag{5.11}$$

where m is the vehicle mass behind the occupant compartment in kg, and a is the vehicle acceleration in m/s². Eq. (5.11) is used in ABC-I to evaluate the risk of significant intrusions into the occupant compartment in two steps (Fig. 5.10):

1. A limit (α) for the acceleration pulse detects high load peaks, which happen during a high depth crushing and consequently an impact on the occupant compartment;
2. The work done by the identified load peaks is measured and compared with a critical value (β-factor), which represents the capability of the occupant compartment to withstand the loads without any significant intrusions.

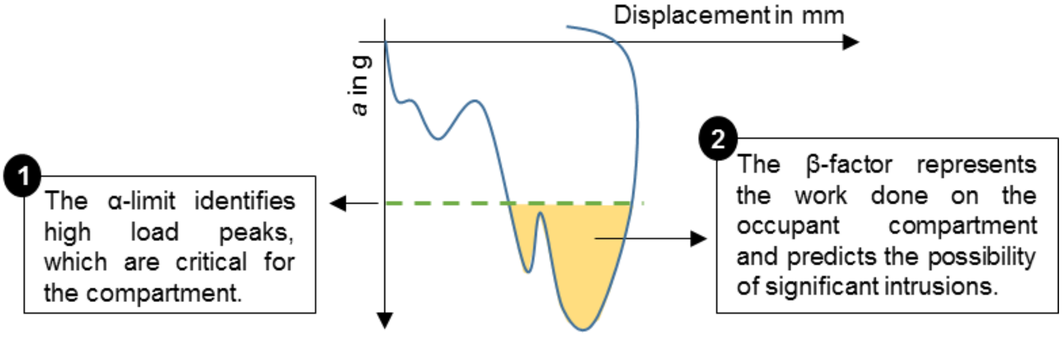


Figure 5.10: Two steps for evaluating ABC-I [148, p. 3]

The limits of these two steps depend on the parameters and characteristics of the vehicles, which are not constant for all vehicles. Since the AE-MDB represents an average vehicle from the passenger car fleet in Europe, the α-limit and β-factor should be calibrated for average vehicles to assess the possibility of intrusions in car-to-car collisions using the acceleration measurements in the AE-MDB test.

The test data from the NHTSA Vehicle Crash Test Database [107] is used to calibrate the α-limit and β-factor for frontal impact tests with moving barriers. The following criteria are used for the data selection to match the vehicle classification, which is represented by a moving barrier in the offset test procedure:

- Vehicles with an approval date of 2000 or later
- Limited vehicle mass to 2500 kg
- Vehicle segment limited to A to F
- Frontal impact tests with an overlap value between 25 % and 50 %

A total of 33 crash tests are used to calibrate the limits, which are described as functions of the vehicle mass by Eq. (5.12) and Eq. (5.13).

$$\alpha_{lim} = 7.297\times10^{-3}\,\frac{\mathrm{g}}{\mathrm{kg}}\times mg - 30.469g \tag{5.12}$$

$$\beta_{lim} = 1.3\times10^{-4}\,\frac{\mathrm{J}}{\mathrm{kg}^2}\times m + 0.335\,\frac{\mathrm{J}}{\mathrm{kg}} \tag{5.13}$$

If the estimated β-factor from the trolley's accelerations exceeds the limit derived from Eq. (5.13), there is a high possibility of significant intrusions (i.e., more than 50 mm as defined by FIMCAR [138, p. 6]) into the occupant compartment of the partner vehicle.

The predictability of ABC-I is investigated with full-scale crash tests and simulation results in our previous work [148, pp. 16-17]. Fig. 5.11 presents the validation results with the maximum intrusion values on the X-axis and the difference between the β-factor and the limit of β-factor on the Y-axis.

X values higher than 50 mm (zones II and III in the diagram) show the vehicles with significant intrusions in their occupant compartment, while positive Y values (i.e., zones I and II) present the prediction of ABC-I for significant intrusions. Thus, values in zones II and IV are consistent with the criterion results, and values in zones I and III show inconsistency between the criterion predictions and the occurred intrusions.

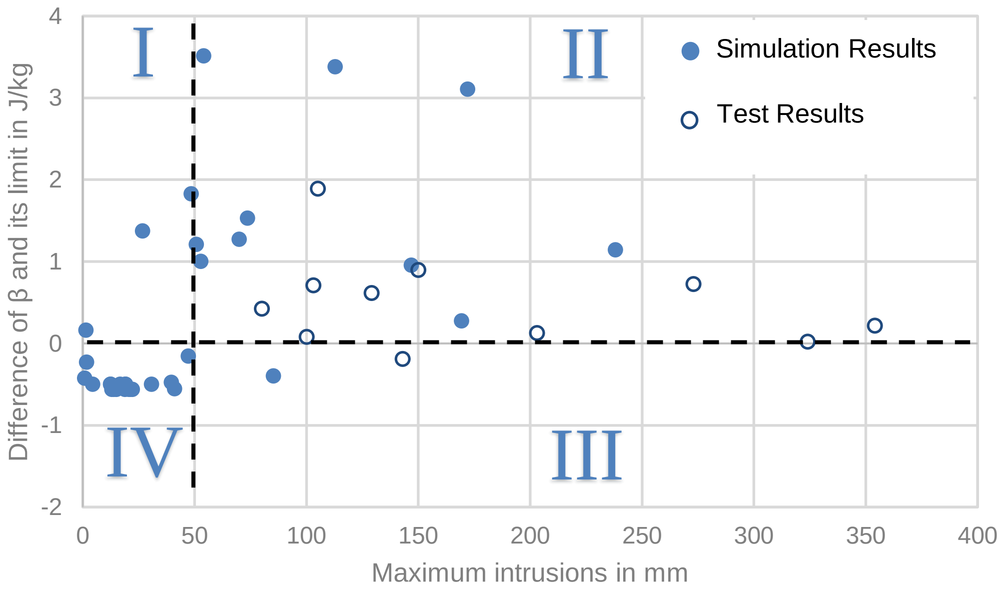


Figure 5.11: Validation results of the criterion ABC-I [148, p. 7]

ABC-I predicted the occurrence of significant intrusions in 86 % of cases, which is a representative predictability for average vehicles. Furthermore, the validation results confirmed the reproducibility of the criterion ABC-I in repeated tests with the same vehicle model [148, p. 8].

According to Eq. (5.13), the critical value of the β-factor for the AE-MDB is 0.45 J/kg. However, the deformation zone of the barrier is not enough to keep this value in an AE-MDB-to-AE-MDB test with 50 % offset and at 90 km/h (i.e., 45 km/h for each party), and the β-factor is about 1.9 J/kg. Therefore, test vehicles with an ABC-I value more than 1.9 J/kg in the AE-MDB test are penalized to reduce risk of intrusions' injuries in partner vehicles.

5.3 New Assessment Protocol

This section summarizes the discussed test procedures and assessment criteria from the previous sections in a new assessment protocol for the frontal crash compatibility of European passenger cars. The test preparations, test parameters, and evaluation steps are described. Notably, this assessment protocol contains general information for the application of this study (i.e., simulation analysis). More information can be found in the full-width frontal impact testing protocol of Euro NCAP [49] and the MPDB testing protocol of FIMCAR [146], which are used as references for the full-width and offset test procedures.

5.3.1 Test Preparations

The vehicle should be unloaded, and its fuel tank must be filled with an amount of water that represents 90 % of the total mass of a full fuel tank. The vehicle's tires should be inflated as described in the manufacturer's instructions for a half load. A mass of 36 kg should be placed in the luggage compartment of the vehicle.

To measure the intrusions, all places described in Tab. 5.1 should be marked. The intrusions are measured relative to a rigid part on the rear of the vehicle (e.g., rear bumper beam) and in the longitudinal direction of the vehicle.

Table 5.1: Positions for intrusion measurements according to [49, pp. 10-11]; [146, pp. 17-19]

Position
Center of the clutch, brake, and acceleration pedals
Center of the top of the steering column
A-pillar on the driver and passenger side, 100 mm above the sill, and 100 mm below the lowest level of the side window
B-pillar on the driver and passenger side, 100 mm above the sill, and 100 mm below the lowest level of the side window
Top and base of the instrument panel as described by FIMCAR [146, pp. 17-18]
Toe-pan intrusions as described by FIMCAR [146, pp. 18-19]

Both front seats should be set to their middle positions. A Hybrid-III 5 % female dummy should be placed on the front passenger seat and a Hybrid-III 50 % male dummy should be placed on the driver seat. The Hybrid dummies should be equipped with appropriate sensors and instruments to measure the listed parameters in Tab. 5.2. The x-axis is the longitudinal direction of the vehicle, the y-axis is the lateral direction of the vehicle, and the z-axis is perpendicular to the ground.

Table 5.2: Dummy instrumentations according to [49, p. 16]

Location	Parameter
Head	Accelerations A_x, A_y, and A_z
Neck	Forces F_x, F_y, and F_z
	Moments M_x, M_y, and M_z
Chest	Accelerations A_x, A_y, and A_z
	Deflection D_{chest}
Pelvis	Accelerations A_x, A_y, and A_z
Iliac Left and Right	Force F_x
	Moment M_y
Lumbar Spine	Forces F_x and F_z
	Moment M_y
Femurs Left and Right	Force F_z
Knees Left and Right	Displacement D_{Knee}
Upper Tibia Left and Right	Forces F_x and F_z
	Moment M_x and M_y
Lower Tibia Left and Right	Forces F_x and F_z
	Moment M_x and M_y

5.3.2 Test Parameters

The assessment approach consists of two test procedures: full-width and offset test (Fig. 5.12).

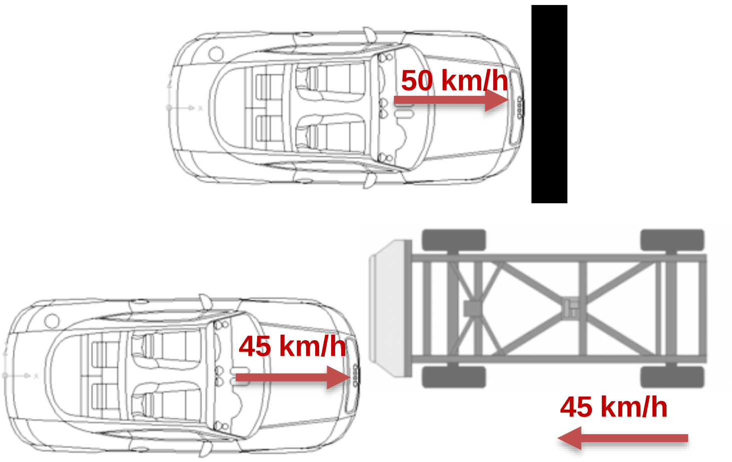


Figure 5.12: Full-width (top) and offset (bottom) test procedures

Using graphics from [123], [160]

The full-width test procedure is conducted as described in the full-width frontal impact testing protocol of Euro NCAP [49, pp. 30-31]. The barrier is a block of reinforced concrete with a minimum size of 3 m in width and 1.5 m in height. The thickness of the barrier should be sized so that its mass is not less than 70 tons. The barrier face should be flat and covered with 20 mm thick plywood boards. The test vehicle should impact the barrier perpendicular to its face at a collision speed of 50 km/h.

The offset test procedure uses the AE-MDB, as described in the Euro NCAP side impact test protocol [145]. The test speed is 90 km/h (i.e., 45 km/h for each party), and the impact angle is 0°. The overlap value is 50 % of the minimum of the AE-MDB's width and the vehicle width, which is measured at the widest points of the vehicle ignoring the mirrors, lamps, and tire pressure indicators. The width of the barrier is 1700 mm, giving a maximum overlap value of 850 mm, if the test vehicle has higher width than the barrier.

5.3.3 Assessment of the Safety Level

The safety level is assessed in the full-width test procedure. The limits of the assessment protocol of Euro NCAP [157, pp. 13-19] are considered to rate the crash performance of the vehicle. If all dummy measurements are within the ranges (Tab. 5.3), the safety level (SL) of the vehicle is equal to the change of the kinetic energy just before and shortly after the impact, as described by Eq. (5.14).

$$SL = \frac{1}{2} m\left(V_{collision}^2 - V_{Reb}^2\right). \tag{5.14}$$

Table 5.3: Dummy criteria for the full-width test according to [157, pp. 13-16]

Body zone	Criterion	Limit
Head	HIC_{15}	500
	a_{3ms}	72 g
Neck	Shear	1.2 kN
	Tension	1.7 kN
	Extension	36 Nm
Chest	Compression	18 mm
	Viscous criterion	0.5 m/s
Femur	Compression	2.6 kN

The estimated safety level is modified (i.e., multiplied by a penalty factor of 0.9) for each of the following issues that occur:

- **Intrusions into the test vehicle:** significant intrusions into the occupant compartment, i.e., more than 100 mm for pedals or steering columns and more than 50 mm in other positions listed in Tab. 5.1, or one or more doors open during the impact, or the doors cannot be opened after the impact with limited force (i.e., less than 100 N).
- **Restraint injuries:** any of the dummy measurements exceed the defined limits (Tab. 5.3).

5.3.4 Assessment of the Compatibility Rate

The compatibility rate (CR) is assessed in the offset test procedure. The limits in the assessment protocol of Euro NCAP [157, pp. 4-6] are considered to rate the crash performance of the vehicle. If all the dummy measurements are within the determined ranges (Tab. 5.4), the change of the kinetic energy of the vehicle and the barrier just before and shortly after the impact are used to estimate the compatibility rate:

$$CR = \frac{\frac{1}{2}\left[m_{car}\left(V_{car}^2 - V_{Reb-car}^2\right) + m_{barrier}\left(V_{barrier}^2 - V_{Reb-barrier}^2\right)\right] - 40\ kJ}{SL} \tag{5.15}$$

40 kJ is the average value of the absorbed energy in the deformable blocks of the AE-MDB, which is based on the simulation analysis presented in Section 4.4.2. The rebound velocity (V_{Reb}) is measured shortly after separation of the test vehicle and the barrier. The rotational kinetic energy is low and therefore, is neglected for simplification of measurements.

Table 5.4: Dummy criteria for the offset test according to [157, pp. 4-6]

Body zone	Criterion	Limit
Head	HIC_{15}	500
	a_{3ms}	72 g
Neck	Shear	1.9 kN at 0 ms, 1.2 kN at 25 ms to 35 ms, and 1.1 kN at 45 ms
	Tension	2.7 kN at 0 ms, 2.3 kN at 35 ms, and 1.1 kN at 60 ms
	Extension	42 Nm
Chest	Compression	22 mm
	Viscous criterion	0.5 m/s
Femur	Compression	3.8 kN
Knee	Compressive displacement	6 mm
Tibia	Index	0.4
	Compression	2 kN

The estimated compatibility rate is modified (i.e., multiplied by a penalty factor of 0.9) for each of the following issues:

- **Intrusions in the partner vehicle:** β-factor of the barrier, estimated by means of a_x in the gravity center of the trolley, exceeds 1.9 J/kg.
- **Intrusions in the test vehicle:** significant intrusions into the occupant compartment of the test vehicle, i.e., more than 100 mm for pedals or steering columns and more than 50 mm in other positions listed in Tab. 5.1, or one or more doors open during the impact, or the doors cannot be opened after the impact with limited force (i.e., less than 100 N).
- **Restraint injuries in the test vehicle:** any of the dummy measurements exceeds the defined limits (Tab. 5.4).
- **Restraint injuries in the partner vehicle:** the OLC value of the barrier, estimated by means of v_x in the gravity center of the trolley, exceeds 31 g.

5.4 Summary and Discussion

Section 5.1 reviewed and discussed current criteria and approaches for evaluating the test results. While dummy and intrusion measurements can be used to assess self-protection of the test vehicle, the assessment of partner-protection is still an unresolved problem. Current assessment criteria are limited to an evaluation of structural interactions, which does not result in a comprehensive assessment approach.

Section 5.2 described the criteria for evaluating the results from both full-width and offset test procedures. Self-protection can be assessed, as in the state of the art, using dummy and intrusion measurements on the test vehicle in both full-width and offset tests. Partner-protection was assessed using a new method in the offset test with the moving barrier. Risk of injuries was broken down into restraint injuries and intrusions' injuries. The OLC was used to assess the restraint injuries in the partner vehicle using the acceleration measurements on the moving barrier. An acceleration-based criterion for intrusion (ABC-I) measurements was developed and validated with full-scale crash tests and simulation analysis. ABC-I gave a qualitative statement about the possibility of significant intrusions into the occupant compartment of the partner vehicle, announcing a high risk for intrusions' injuries.

Section 5.3 presented an assessment protocol for frontal crash compatibility. The fundamental definition model presented in Chapter 3 was implemented in the test procedures given in Chapter 4 and assessment criteria presented in Section 5.2.

There is a difference between implementing the fundamental definition in the assessment protocol and in the Euro NCAP frontal impact tests for validating the definition model (Section 3.3). In Section 3.3, dummy measurements were used to record the occurrence moment of intolerable injuries, and the change of kinetic energy values were used to estimate the safety level and compatibility rate.

However, there is a concern with regard to the misuse of this approach in the assessment protocols. The restraint systems could be designed so that high dummy measurements happen later, and consequently a later occurrence moment of intolerable injuries, which does not necessarily mean better occupant protection. Since the analysis conducted in Section 3.3 was on previously conducted crash tests, the restraint systems were not adapted for acquiring the maximum points. However, car manufacturers would use the new assessment protocol to optimize their systems. Therefore, the assessment of dummy measurements should be based on outcome from the crash test, applying penalty factors for poor performances.

The assessment protocol uses penalty factors for modifying the safety level and compatibility rate. The value of this factor is set to 0.9 in this study, which is based on various simulation analyses to penalize aggressive vehicles. However, the penalty factor should be investigated in future works using full-scale crash tests and dummy measurements. It is also possible to determine different penalty factors for the issues mentioned in Sections 5.3.3 and 5.3.4 or increase the factor if the dummy or intrusion measurements exceed the limits to a large extent. However, this work focuses on the concept of an assessment approach, and calibration of the details is not within the scope.

Hybrid dummies are used in the new assessment protocol. Currently a new Test device for Human Occupant Restraint (THOR) is under development and discussion [149], which should replace Hybrid dummies in future tests protocols. THOR represents the human body and its biofidelic kinematic better and is more sensitive to new restraint systems [150, p. 1]. Since the injury limits of THOR dummy were not yet finalized during this work, Hybrid dummies are used in the new assessment protocol. However, substitution of the Hybrid dummies with the THOR dummies should be considered in future works on further development of the new assessment protocol.

6 Validation of the New Assessment Approach

The previous chapters developed an approach for assessing frontal crash compatibility. During the development, full-scale crash test results from other works were analyzed and reevaluated and simulation analyses were used to validate the approach in each step. The aim of this chapter is to validate the assessment approach as a whole to ensure it benefits the crash compatibility of passenger cars.

Section 6.1 reviews previous works and investigates the validation approaches used in other studies. The objective is to find the deficiencies of other approaches, which should be addressed in this study.

Section 6.2 explains the validation approach used in this study, which consists of two steps. The first step validates whether the assessment results correlate with the crash performance of vehicles in car-to-car collisions. The second step investigates whether optimization of vehicles for better assessment results improves the crash compatibility of vehicles in car-to-car collisions. The objective is to investigate whether the assessment approach required special designs that are not crashworthy and would improve the crash compatibility of the vehicle in car-to-car collisions.

Section 6.3 presents the validation results and shows the efficiencies and deficiencies of the developed assessment approach for improving the crash compatibility of vehicles in frontal car-to-car collisions.

Section 6.4 summarizes the results of this chapter and discusses the limitations of the results that can be investigated in future works.

6.1 State of the Art of Validation Approaches

Both EEVC WG-15 [97, c3 - c4] and VC-COMPAT [94, p. 19] used the same approach to validate the candidate test procedures and approaches for assessing frontal crash compatibility. They conducted car-to-car tests to identify important vehicle characteristics, which can improve the vehicles’ crash performance, and then conducted car-to-barrier tests to ascertain whether the beneficial characteristics can be adequately identified and evaluated in the candidate test procedures, i.e., the PDB and the FWDB tests. Furthermore, the repeatability and reproducibility of the assessment results have been investigated with repeating crash tests.

However, the variations in the conducted car-to-car tests were limited to different scenarios for vehicles with and without secondary energy-absorber structures, which was assumed to be an influential characteristic for the crash compatibility of vehicles. Notably, full-scale crash tests are expensive, but for this validation study, 12 car-to-car tests were conducted.

The used validation approach showed several imperfections, as the VDA [101], particularly Volkswagen, Audi, and Daimler, criticized the proposed PDB test procedure for substituting the ODB test procedure in ECE R94. The VDA used validated simulation models and varied some vehicle characteristics (e.g., stiffness of the energy absorbers) to highlight the deficiency of the PDB in the assessment of aggressive designs.

FIMCAR [98, pp. 109-110] extended the approach of the previous studies and created a list of compatibility requirements, based on the results of previous works and the accident analyses. The different test procedures and the assessment criteria were investigated using simulation analyses, full-scale tests, and component tests to assess their capability in fulfilling the established requirements. Furthermore, FIMCAR used full-scale crash tests with the same vehicle model to investigate the repeatability and reproducibility of the assessment approaches.

Del Pozo et al. [142, pp. 8-9] used a different approach to validate their proposed assessment criteria and test procedure. They conducted several car-to-car tests and identified vehicles with incompatibility issues based on the engineering knowledge of crash experts. The vehicles with incompatibility issues had to fail the car-to-barrier test to assure the validity of the proposed assessment approach. In total, only three car-to-car tests were conducted for this validation analysis, for which the focus was on different structural interactions and their relevant compatibility issues.

ADAC [14, pp. 8−19] has yet to validate its assessment approach. However, ADAC experts used an explorative method to develop its assessment approach. A vehicle model was tested in a car-to-car test with a mass ratio of about 1:1 and a car-to-barrier test. The test results were compared. The barrier and test speed were then modified and three car-to-barrier tests were conducted. ADAC experts analyzed the vehicle structures and compared the assessment results with their expectations to control the efficiency of their assessment approach for improving the crash compatibility of vehicles in frontal car-to-car collisions.

6.2 Approach for Validation

The developed assessment approach in this study comprises three main cores: the definition model (Chapter 3), the test procedure (Chapter 4), and the assessment criteria (Section 5.2). Each of these topics is validated in Chapters 3, 4 and 5 with full-scale tests and simulation models (Fig. 6.1).

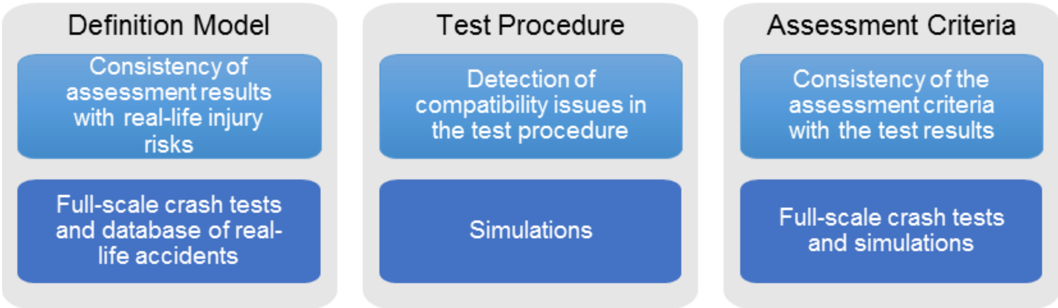


Figure 6.1: Validation topics (top) and validation tools (bottom)

As can be seen, the validation approach used in EEVC-WG15, VC-COMPAT, and FIMCAR has already been implemented in the test procedures and criteria. Furthermore, the repeatability of the criteria's results was investigated in Section 5.2.2.2. To complete the validation and exclude the effect of unconsidered compatibility issues in the previous steps, the developed assessment approach is validated as a whole for the following issues:

- **Correlation:** The assessment results should correlate with the crash performance of the vehicles in relevant scenarios of car-to-car collisions. I.e., vehicles with a better rating should show a better crash performance.
- **Efficiency:** Optimizing the vehicle design for acquiring better assessment results should improve the crash performance of the vehicle in relevant

scenarios of car-to-car collisions. I.e., optimized vehicles with a better rating should show a better crash performance.

Both validation analyses are done using virtual testing for three reasons:

1. Full-scale crash tests are expensive, thus limiting the number of tests and negatively affecting the completeness of the validation analysis.
2. Results of the full-scale crash tests are influenced by the reproducibility and repeatability of the vehicle structures.
3. Optimization of the vehicle's structures is not feasible in full-scale crash tests, as any changes in the vehicle structure should be considered in the manufacturing process and production line. Any manipulation of the vehicle structure to implement the optimized design would lead to many side effects that influence the test results.

The trustworthiness of the simulation results is ensured through the requirements described in Appendix A and the use of validated simulation models described in Appendix B.

6.2.1 Correlation of the Assessment Results

The validation approach for correlating the assessment results with crash performances in car-to-car collisions comprises the following three steps:

1. Four validated vehicle models that represent a wide range of the passenger car fleet from heavy quadricycles to SUVs are rated using the developed assessment approach.
2. The rated vehicles are tested in car-to-car crash scenarios.
3. The crash performance of the vehicles in different scenarios is compared with their rating results from the assessment approach.

The assessment approach is considered validated if the crash performance of the vehicles in car-to-car collisions correlates with the assessment results.

6.2.1.1 Assessment of the Vehicles

Five vehicle models (Tab. 6.1) are selected to be assessed by the proposed protocol presented in Section 5.3.

Table 6.1: Selected vehicle models for validating the rating's efficiency

Vehicle Model	Model Year	Vehicle Segment	Test Mass
Generic Microcar	2015	Heavy quadricycle	704.7 kg
Toyota Yaris	2010	Supermini	1220.2 kg
Toyota Camry	2012	Large family car	1626.4 kg
Chevrolet Silverado	2007	Large off-road	2495.9 kg

The vehicle models do not include dummies and restraint systems and represent only the vehicle structure and its crash performance. Dummy injuries can be assessed in separated models from the vehicle compartment and with calibrated restraint systems. However, as mentioned in the FIMCAR project [141, p. 12], the restraint systems are not yet calibrated for the MDB test mode and therefore, the restraint systems would not perform as intended in tests with moving barriers (e.g., the airbag deployment could delay). To consider the real crashworthiness potential of the vehicle, the restraint systems should be optimized, and thereafter the dummy measurements should be rated. For this study, the dummy measurements described in Tab. 5.3 and Tab. 5.4 are associated with the OLC to provide a common level for comparing all vehicles' crash performance regarding the crash pulse and crash severity for the restraint systems.

For intrusion measurements, various points are marked on the vehicle models as described in Table 5.1. However, none of the vehicle models have pedals and two of them (generic microcar and Silverado) do not have an instrument panel. Thus, to keep the comparability between intrusion measurements, the holding structure behind the instrument panel is used for intrusion measurements at the top and bottom of the instrument panel. The locations of the intrusion measurements are presented in Appendix D.

6.2.1.2 Car-to-Car Collisions

The baseline situation of the AE-MDB test is a car-to-car collision with a collision speed of 90 km/h (i.e., 45 km/h for each party) and an overlap value of 50 % of the involved vehicles' minimum width. Therefore, the assessed vehicles are tested against each other to provide a database for comparing their crash performance with the assessment results. Tab. 6.2 presents the test scenarios.

Table 6.2: Test matrix for car-to-car collisions

	Generic Microcar	Yaris	Camry	Silverado
Generic Microcar	X	X	X	X
Yaris	-	X	X	X
Camry	-	-	X	X
Silverado	-	-	-	X

Ten scenarios are simulated. It is expected that the vehicles with better safety level and compatibility rate have better self-protection and partner-protection in car-to-car collisions.

6.2.2 Efficiency of the Assessment Approach

The validation approach for evaluating the efficiency of the assessment approach for improving the crash compatibility of vehicles in frontal car-to-car collisions consists of three steps:

1. The generic simulation model of microcars is optimized to acquire better results in the proposed assessment approach.
2. The optimized model is simulated in different car-to-car collision scenarios, as described in Tab. 6.2.
3. The crash performance of the optimized vehicle is compared with the crash performance of the original model.

The assessment approach is considered validated if the crash performance of the optimized vehicle is better in different car-to-car collisions.

6.2.2.1 Optimization of the Generic Microcar

Development of a parametric reduced-order model from the FE model is investigated in a series of TUM internal studies [161–164], and a parametric reduced-order model

(Fig. 6.2) is created using beam elements and reduced shell elements from the generic microcar. The parametric model is validated for several parameter variations. The validation results show the consistency of the parametric model with the original FE model with respect to the acceleration pulse and qualitative trends of intrusions by changing the parameters.

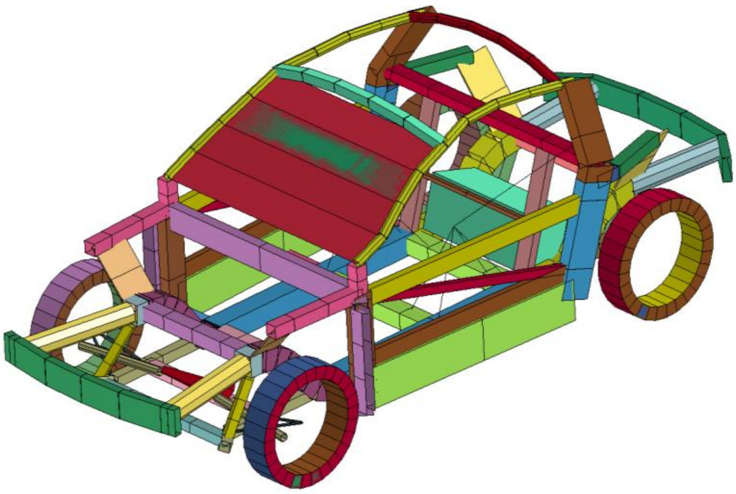


Figure 6.2: The parametric reduced order model of the generic microcar, which is based on the Visio.M car [165]

A catalogue of parameters is created, including both geometric and topology changes of the vehicle structure. To ensure the feasibility of the optimization, the parameter ranges are limited to be compatible with the Visio.M car. A list of parameters and their variation ranges can be found in Appendix E.

The main scenario for the assessment approach is the AE-MDB test. Thus, a reduced-order model for the AE-MDB is created and validated with certification tests for the barrier. Crash performance of the vehicle in the FWRB test is also considered to avoid a one-sided optimized design. Furthermore, to avoid any changes in the vehicle concept, which would make it incompatible with other components (e.g., suspension systems), changes in bending and torsion stiffness of the structure are also considered in the optimization.

The parametric model is optimized by means of an equally weighted multi-objective genetic algorithm with regard to the OLC and ABC-I of the vehicle in the AE-MDB test as the optimization objectives. To consider partner-protection, some limits are set for the OLC and ABC-I of the moving barrier and for the OLC of the vehicle in the FWRB test as the optimization constraints. Furthermore, changes in the bending stiffness and torsion stiffness of the vehicle structure are constrained to a pre-defined tolerance range to ensure compatibility of the optimized structure with the suspension systems. The change in the vehicle mass is constrained to the tolerance of the vehicle mass for the market approval in Europe. Fig. 6.3 illustrates the optimization structure, which is implemented in LS-OPT V5.2 [166].

The genetic algorithm is based on the Darwinian principle of "survival of the fittest" [166, p. 538]. Stander et al. [166, pp. 538-548] described how the genetic algorithm is implemented in LS-OPT. First, in the sampling step, a number of parameters' combinations (population) are generated randomly. The whole population is simulated in the defined scenarios and their responses are evaluated to identify the best results (the fittest individual). The fittest individual is introduced to the next sampling step to define new parameters' combinations from the best samples (children of the fittest individual). This process is conducted for a pre-defined number of generations (in this case, max. 150) and the best results are presented as the optimized model.

The advantage of the genetic algorithm is the global optimization that discloses the selection of local optima as the result [166, p. 538]. However, the computational costs are high, which have been kept in the acceptable range using the parametric reduced-order model.

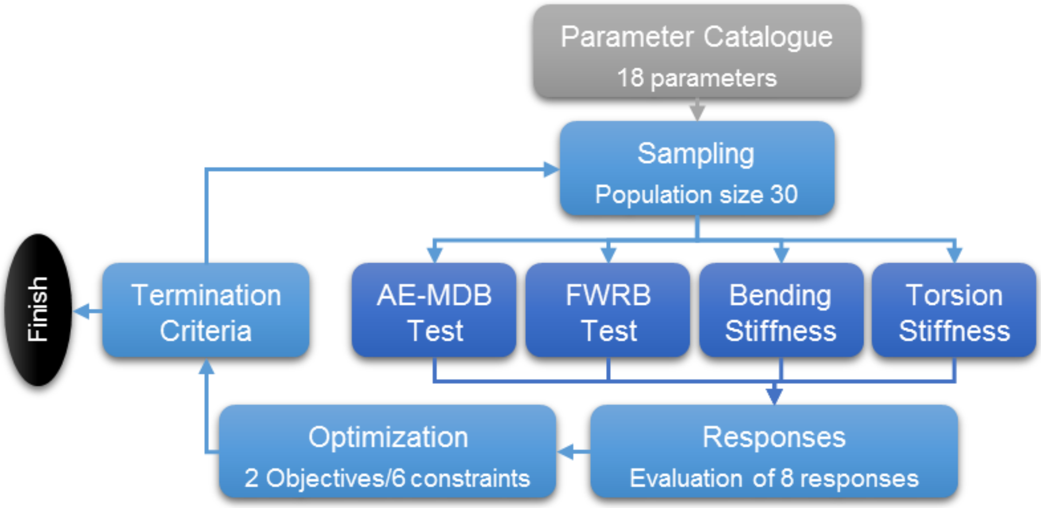


Figure 6.3: Optimization structure of the parametric model

6.2.2.2 Car-to-Car Collisions

The optimized set of parameters is implemented in the FE model of the generic microcar to create an optimized microcar. The optimized microcar is tested in the same crash scenarios of the generic microcar from Tab. 6.2, and its crash performance is compared with the crash performance of the generic microcar. Efficiency of the assessment approach is considered validated if the optimized model shows a better crash performance than the original model in the relevant car-to-car crash tests.

6.3 Results

The simulation results (Appendix F) were analyzed with regard to the energy values, mass increases, and trustworthiness of the graphical results to disclose the effect of numerical errors on the results. All simulations showed correct results and fulfilled the discussed requirements for trustworthy simulations from Appendix A.

6.3.1 Correlation of the Assessment Results

Tab. 6.3 presents the FWRB test results and the estimated safety levels for each vehicle model. A higher safety level presents a higher safety potential, which could be interpreted as a better self-protection. As expected, heavier vehicles have higher safety levels, representing their higher level of self-protection.

Less rebound velocity (v_2) means a higher energy absorption in the crash structures of the vehicle that correlates with OLC values. As can be seen, the generic microcar has a high level of energy absorption due to the lack of engine block and rigid components in the crash zone of the vehicle, which reduces the deformation zone and consequently increases the crash pulse for other vehicles (i.e. Yaris and Camry). Silverado has also a long deformation zone, which is due to the special geometry of the SUV.

Table 6.3: Safety level (SL) of the vehicle models regarding the performance in the FWRB test

Vehicle Model	Test mass in kg	v_2 in m/s	Max. intrusion in mm	OLC in g	SL in kJ
Generic Microcar	704.7	1.37	1.4	26.5	67.3
Yaris	1220.2	1.95	87.9	31.3	103.8
Camry	1626.3	1.53	73.4	28.5	139.5
Silverado	2495.9	1.39	3.9	24.3	238.3

Tab. 6.4 presents the AE-MDB test results and the estimated compatibility rates for each vehicle model. The compatibility rate corresponds to the capability of the vehicle to use its safety potential in car-to-car collisions and allows other vehicles to use their safety potential. Lighter vehicles (i.e., with a mass ratio of less than 1:1 in the AE-MDB test) have a compatibility rate greater than 100 %, which shows that these lighter vehicles absorb more crash energy than their allowed safety level and thus reduce the partner's collision severity. These vehicles would be over-crushed in car-to-car collisions. A lower compatibility rate shows lower partner-protection and aggressiveness of the test vehicle.

Table 6.4: Compatibility rate (CR) of the vehicle models regarding performance in the offset test

Vehicle Model	v_2 of car in m/s	v_2 of barrier in m/s	Max. intrusion in mm	OLC of car in g	ABC-I of barrier in J/kg	OLC of barrier in g	CR
Generic Microcar	3.91	3.08	25.5	27.9	0.55	14.9	156%
Yaris	2.54	2.35	110.0	27.9	2.29	27.6	117%
Camry	2.62	4.60	96.1	21.4	1.94	31.8	88%
Silverado	2.86	5.67	14.1	14.8	2.07	35.1	77%

Fig. 6.4 illustrates the OLC values of different vehicle models with different safety levels in car-to-car tests against partners with different compatibility rates.

The crash performance of the vehicles depends also on particular structural issues occurring in a specific car-to-car collision. Two incompatible vehicles might have a compatible collision, since their incompatibilities (e.g. height of the load path) are similar and compensate their influences. Thus, for discussion of the results, focus should be on the qualitative trend of values with changing compatibility rates and safety levels, rather than the comparison of values in each case. E.g. generally Yaris's OLC increases as the compatibility rate of the partner decreases, but there is an exception against Silverado (lower OLC values than against Camry) that is due to the compensation of incompatibilities (in-line load paths).

As can be seen, the OLC values (i.e., risk of restraint injuries) decrease (solid arrow) as the compatibility rate of the partner increases, thus confirming the efficiency of the ratings regarding the assessment of partner-protection. Furthermore, the general OLC values of the vehicles decrease (dashed arrow) as their safety levels increase, which confirms the efficiency of the ratings regarding the assessment of self-protection.

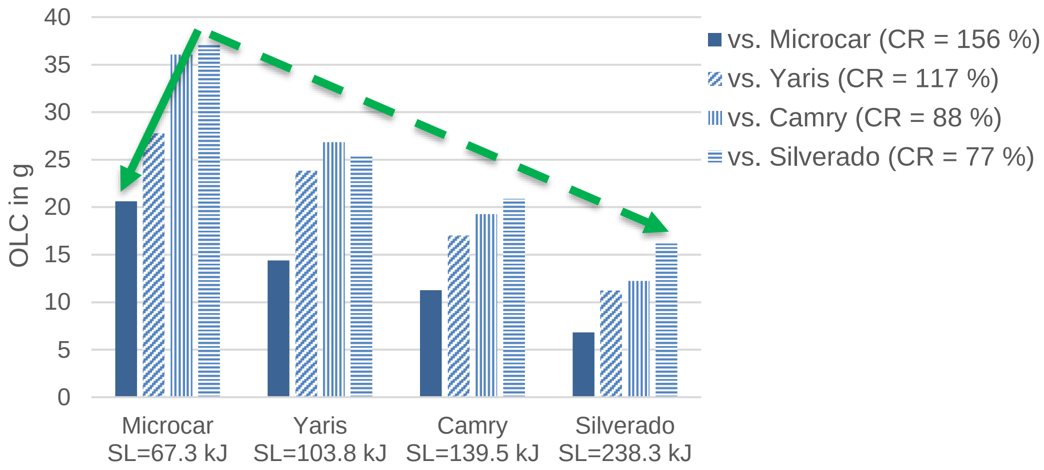


Figure 6.4: OLC values of the vehicles with different safety levels (SL) in car-to-car tests against partners with different compatibility rates (CR)

Fig. 6.5 illustrates the maximum intrusions into the occupant compartment of different vehicle models with different safety levels in car-to-car tests against partners with different compatibility rates.

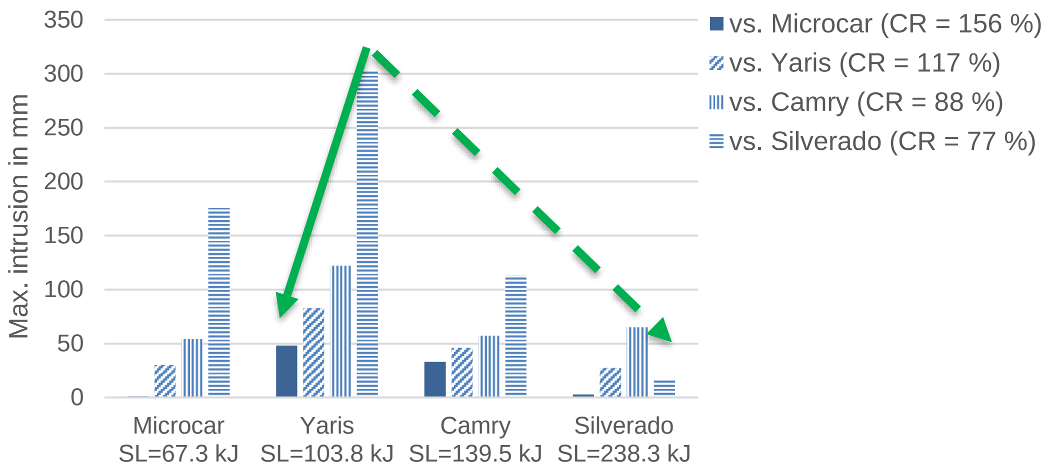


Figure 6.5: Maximum intrusions into the occupant compartment of vehicles with different safety levels (SL) in car-to-car tests against partners with different compatibility rates (CR)

The generic microcar has generally lower intrusion values than other vehicle models. It is among others due to fewer details in the microcar than in other vehicle models. E.g., the generic microcar does not have a firewall that receives the displacements of other components (e.g., transmission block) and translates them into intrusions into the occupant compartment. Furthermore, the generic microcar is an electric vehicle with fewer rigid components in the front section that would reduce the available deformation length in other vehicle models.

Intrusions are measured in different locations of the vehicles and are not, therefore, directly comparable. While in a crash constellation, the maximum intrusion might happen in the toe-pan, the maximum intrusion of the same vehicle model might be on the instrument panel in another crash constellation. Thus, the trends of the maximum intrusions are not as clear as those of the OLC values. However, the same trend as for the OLC values can be recognized for the intrusion values. Intrusions (risk of intrusions' injuries) decrease (solid arrow) as the compatibility rate of the partner increases, thus confirming the efficiency of the ratings regarding the assessment of partner-protection. Furthermore, the general intrusion values into the occupant compartment of the vehicles decrease (dashed arrow) as their safety levels increase, which confirms the efficiency of the ratings regarding self-protection.

6.3.2 Efficiency of the Assessment Approach

The reduced-order parametric model uses a simplified beam model with a pre-defined deformation-force history for the energy absorbers, which represents the deformation of these components in the FE model. The parametric model cannot represent different deformation modes of the energy absorbers, and consequently, variations in the main load path would give unrepresentative results. To optimize the energy absorbers and the main load path of the vehicle, other models with more details are required.

Therefore, the number of parameters is limited in the optimization process. Eleven parameters are used to optimize the OLC and ABC-I of the vehicle with equal weights in the AE-MDB test with regard to six constraints (OLC and ABC-I of the barrier, mass of the vehicle, bending and torsion stiffness of the vehicle, and OLC of the vehicle in the FWRB test).

The optimization is terminated after 22 generations. Fig. 6.6 presents the best results in each generation during the optimization. As can be seen, the optimum parameter set is found in the sixth generation and the following generations failed to obtain better results. Repeated optimizations resulted in similar optima.

The chosen genetic algorithm of LS-OPT uses a method called elitism to keep the high fitness parameter sets (children) in the new generations [166, pp. 542-543]. In each sampling step, the worst parameter sets are replaced by the elite parameter sets from the last generation to avoid the optimum results getting lost during the optimization. However, the genetic algorithm continues with the optimization to ensure that the elite parameter set is as close as possible with the restricted computational time to the global optimum. Therefore, the optimum is not further improved after the sixth generation. The parameter sets of each optimization's generation are presented in Appendix G.

The optimization objectives (i.e., OLC and ABC-I of the vehicle in the AE-MDB test) have to be reduced. The OLC is reduced by 18.5 % and the ABC-I is reduced by 17.6 %. This shows better crash performance in the AE-MDB test. Partner-protection was improved, which can be observed from the reduced values for the OLC and ABC-I of the AE-MDB. The OLC of the barrier was reduced by 2.7 %, and ABC-I of the barrier was reduced by 47.4 %. Furthermore, the OLC of the car in the FWRB test also decreased by 1.8 %.

The vehicle mass was constrained to avoid any changes greater than 5 %. During the optimization, the vehicle mass showed small changes and was reduced by 0.6 %. The torsion and bending stiffness were constrained to prevent any changes greater than 10 %. A side effect of the optimization was the reduction of the vehicle stiffness, i.e., reduction of torsion stiffness by 4.3 % and reduction of bending stiffness by 5.2 %.

The parameter changes from the reduced order parametric model have been implemented in the FE model, and an optimized vehicle model is created. The reduced-order parametric model represents the trends of values by parameter variations qualitatively. Therefore, the FE model does not show exactly the same values as shown in Fig. 6.6. However, it is expected that both self-protection and partner-protection of the optimized vehicle increase slightly in line with the parameters implemented in the FE model. The optimized microcar is simulated in the FWRB test to estimate its safety level (Tab. 6.5).

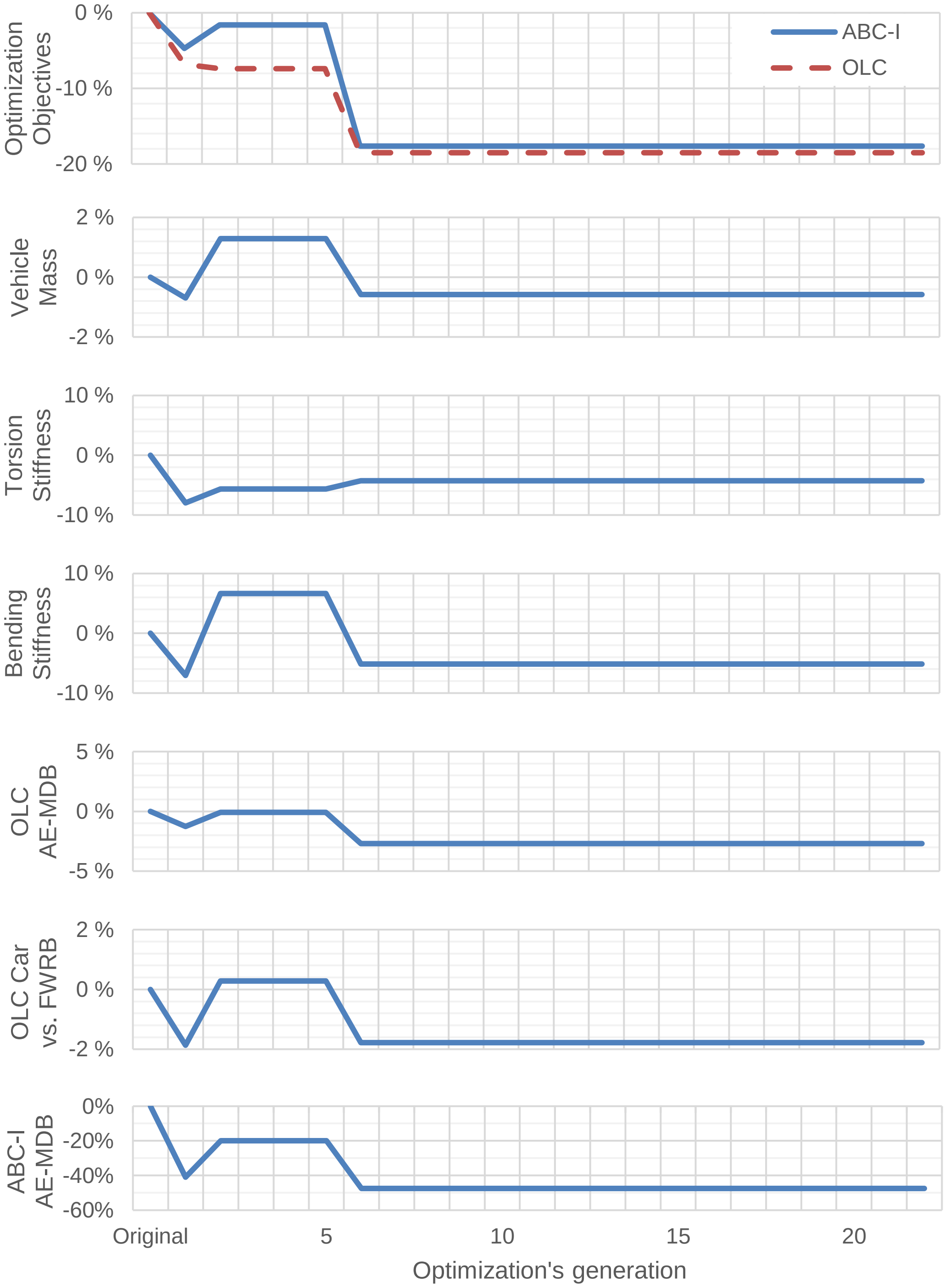


Figure 6.6: Comparison of the optimization results with the original model

Table 6.5: Safety level of the original and optimized model regarding the performance in the FWRB test

Vehicle Model	Test mass in kg	v_2 in m/s	Max. intrusion in mm	OLC in g	SL in kJ
Generic Microcar	704.7	1.37	1.4	26.5	67.3
Optimized Microcar	702.1	1.16	2.2	27.4	67.2

The vehicle mass is reduced by 0.36 %, resulting in a lower safety level due to lower kinetic energy. However, the safety level is reduced by only 0.09 %, which indicates higher energy absorption in the vehicle structure. Lower rebound velocity (v_2) confirms a better performance of the optimized vehicle in the FWRB test, which is masked by the decrease of the vehicle mass. The maximum intrusion and OLC of the optimized model increased slightly, but stayed under the critical limit. The optimized microcar is simulated in the AE-MDB test to estimate its compatibility rate (Tab. 6.6).

Table 6.6: Compatibility rate of the original and optimized model regarding the performance in the AE-MDB test

Vehicle Model	v_2 of car in m/s	v_2 of barrier in m/s	Max. intrusion in mm	OLC of car in g	ABC-I of barrier in J/kg	OLC of barrier in g	CR
Generic Microcar	3.91	3.08	25.5	27.9	0.55	14.9	156%
Optimized Microcar	3.78	3.21	35.2	28.0	0.12	14.5	156%

Again, the reduction of vehicle mass masks the better performance of the optimized model and therefore, the compatibility rates are equal. However, a lower rebound velocity (v_2) for the vehicle, despite the reduced mass, indicates a better crash performance. The OLC and ABC-I of the barrier are reduced, which shows a better partner-protection in the AE-MDB test. The changes in the OLC and maximum intrusion of the vehicle are small and under the critical limit.

Although the safety level and compatibility rate have not really changed, the general performance of the optimized microcar brings the expectation of a slightly better crash performance in car-to-car collisions. Fig. 6.7 compares the OLC results of the optimized and original model in car-to-car collisions against different vehicle models.

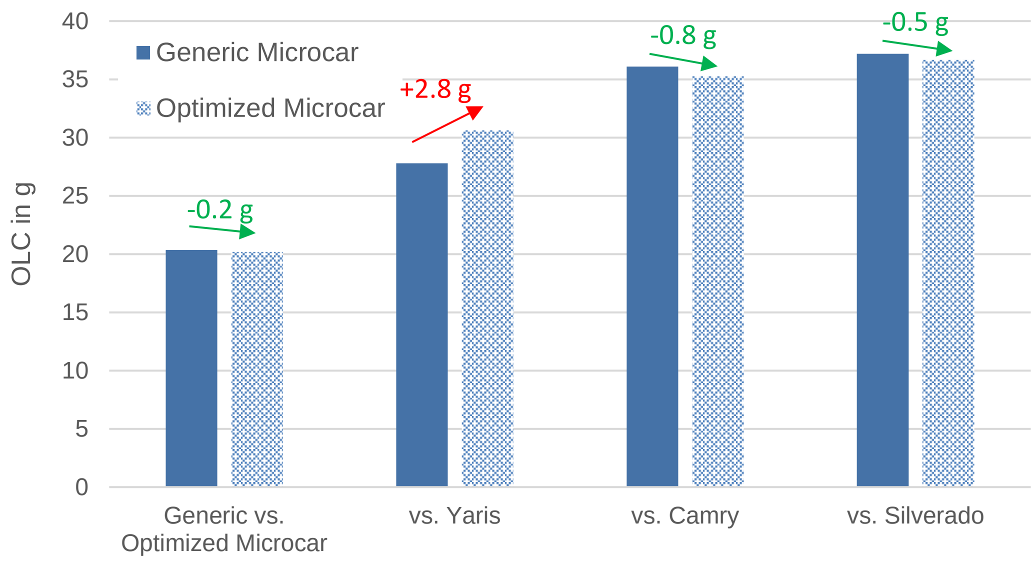


Figure 6.7: OLC values of the generic and optimized microcar in car-to-car collisions

Generally, the optimized model shows lower OLC values and consequently a lower risk of restraint injuries in car-to-car collisions. The original model only had a lower OLC value in the test against the Toyota Yaris that is due to the particular compatibility between the generic microcar and Toyota Yaris. However, intrusion values should also be considered for evaluating the general crash performance. Fig. 6.8 compares the intrusions into the occupant compartment of the optimized and original model.

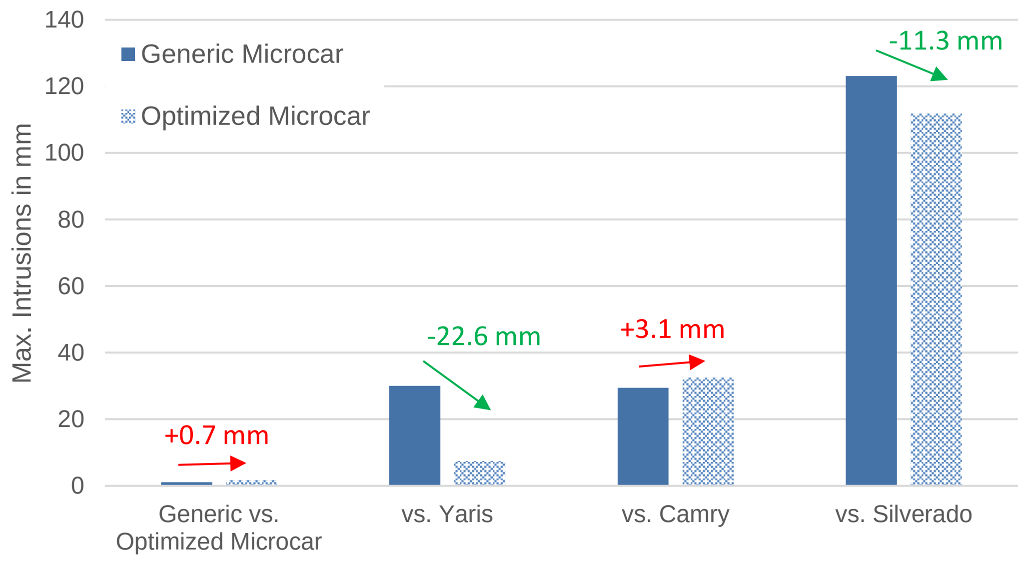


Figure 6.8: Maximum intrusions of the generic and optimized microcar in car-to-car collisions

Generally, the optimized model shows lower intrusions in car-to-car collisions. In the test against the Toyota Camry and the original model, the maximum intrusions of optimized microcar were slightly higher than the generic microcar. However, the differences are small (i.e., less than 3.1 mm) and might be within the tolerance of the model's precision.

The OLCs and maximum intrusions of the partner vehicles remained almost constant. Therefore, the optimized microcar has shown better crash performance in car-to-car collisions and confirmed the efficiency of the developed assessment approach for improving the crash compatibility of vehicles in frontal car-to-car collisions.

6.4 Summary and Discussion

Section 6.1 reviewed the validation approaches of previous works and discussed the efficiency of the previous approaches. Owing to high testing costs, the validation approaches were supported with only a few crash tests, which limits their efficiency and causes a dependency of results on the specifications of the used vehicle models.

Section 6.2 presented the validation approach in this study. The assessment approach consisted of three main cores (i.e., fundamental definition, test procedure, and assessment criteria), the efficiency and correlation of which were validated with test results and simulation analyses in the previous sections. The whole assessment approach needed to be validated to ensure validity of the assessment results, as these three main cores interact with each other. The validation approach comprised two steps: correlation of the assessment results with crash performance of vehicles, and efficiency of the assessment approach for improving crash compatibility.

To validate the assessment's correlation, four vehicle models were assessed according to the protocol presented in Section 5.3. Then, these vehicles were tested in car-to-car collisions and their crash performances were compared with respect to the assessment results. The results confirmed a correlation between the safety level and compatibility rate with self- and partner-protection of the test vehicles regarding the risk of injuries.

To validate the assessment's efficiency, the generic microcar was optimized for better results in the AE-MDB test. A reduced-order parametric model was created from the FE model to represent the crash pulse and intrusions of the FE model qualitatively. The parametric model was optimized using a genetic algorithm for better OLC and ABC-I in the AE-MDB test. The OLC of the vehicle in the FWRB test and the OLC and ABC-I of the barrier in the AE-MDB test were constrained to consider all relevant issues for the assessment of the safety level and compatibility rate. Furthermore, the parameters' range, vehicle mass, and its bending and torsion stiffness were constrained to avoid changing the vehicle concept or unfeasible designs during the optimization.

The optimized design was implemented in the FE model, and an optimized microcar was created. The optimized microcar was assessed according to the protocol presented in Section 5.3 and tested in car-to-car collisions against other vehicle models. The crash performances of the generic and optimized microcar were compared. It should be noted that in car-to-car collisions, compatibility of the partner vehicle is also influential, and two generally incompatible vehicles would thus obtain better results in a car-to-car collision than in the case of a compatible vehicle against an incompatible vehicle. The lower OLC value of the generic microcar against the Toyota Yaris can also be interpreted as a special compatible constellation between these two vehicles. The overall results confirmed an improved crash performance for the optimized vehicle in car-to-car collisions.

Notably, the generic microcar uses a vehicle structure, which is already optimized in previous works of Wehrle [167, pp. 81-115]. Thus, further optimization has not improved the crash performance of the vehicle significantly. Furthermore, the use of the OLC instead of dummy measurements and modeling simplifications in the vehicle model dampened the difference in the crash performances of the generic and optimized microcar, meaning that changes have not be observed in the safety level and compatibility rate of the vehicles. However, the objective of this work was to investigate whether the assessment approach required special designs that are not crashworthy and would improve the crash compatibility of the vehicle in car-to-car collisions.

An optimization strategy can be derived from the optimization results of the generic microcar, which is applicable to microcars:

- The crash structure of the vehicle should have a multiple load path, which is connected with deformable elements. Furthermore, side rails should be extended to increase the potential of energy absorption in the vehicle structure.
- Crushing strength of each deformable element in the crash structure should be set in a manner, not to limit the deformation of other components and to allow a homogeneous deformation along the front section.
- The occupant compartment should have a high strength, particularly high strength A-pillars to prevent intrusions in the toe-pan of the vehicle.

7 Conclusion

The aim of this work was to propose an assessment approach for the frontal crash compatibility of European passenger cars, which can be applied as a safety regulation for market approval or for optimizing the vehicles’ structures.

7.1 Summary

Chapter 2 reviewed the state of the art of crash compatibility. Section 2.1 described the most important classifications for European passenger cars and reviewed the safety regulations for their market approval in Europe. M1 car classification uses frontal impact tests that were developed in the 1980s and 1990s and therefore seems to be no longer effective for the modern vehicle fleet. The L7e classification does not require a crash test for market approval, and therefore heavy quadricycles without adequate safety could be approved for the market. Section 2.2 reviewed the current safety on the roads and highlighted the issue of correlation between the frontal impact tests and injury risks in real-life accidents. This confirmed the necessity for new assessment approaches for the frontal crash compatibility of passenger cars. Furthermore, studying the vehicle structure of several microcars highlighted the necessity for crash tests for this car classification to avoid the market approval of vehicles with inadequate safety. Section 2.3 reviewed the previous works on crash compatibility and described their results and deficiencies to be addressed in this study. Methods and tools for use in this work were described, and the requirements for trustworthiness of the FE simulations were discussed as a main tool in this study. Section 2.4 derived the research question of the work addressing four topics: the definition of crash compatibility, test procedures for assessing crash compatibility, assessment criteria for the test results, and validation of the assessment approach.

Chapter 3 proposed a definition model for crash compatibility that served as the basis for the discussion of different assessment approaches. Section 3.1 reviewed the literature and described different definitions for crash compatibility. Although there is a common understanding of crash compatibility, some conflicts and disagreements arise as experts discuss this topic. Points of agreement and disagreement were discussed and some requirements were set for a fundamental definition of crash compatibility. Section 3.2 described an alternative definition model comprising two parts: safety level, which represents the safety potential of the vehicle, and compatibility rate, which represents the capability of the vehicle to use its safety potential in different crash constellations. Section 3.3 applied the alternative definition model to the Euro NCAP frontal impact test protocols and created an assessment model. The results of the NHTSA Crash Test Database were used to assess the safety level and the compatibility rate of 60 vehicles, the crash performance of which were studied in 34 real-life frontal car-to-car accidents retrieved from the NASS Crashworthiness Data System. The results showed the correlation of the evaluation results with injury risks in real-life accidents. Hence, the fundamental definition model is valid and can be applied to different test procedures to develop an assessment approach.

Chapter 4 proposed a test procedure to assess frontal crash compatibility. Section 4.1 reviewed the literature for existing test procedures and summarized the characteristics of different test procedures (i.e., ODB, PDB, MPDB, FWRB, and FWDB). Section 4.2

discussed the approach and requirements for evaluating the test procedures for assessing frontal crash compatibility with respect to the developed fundamental definition model. Section 4.3 studied the efficiency of the current test procedures from previous projects to fulfill the requirements. The evaluation results showed that an alternative offset test procedure is required to assess the compatibility rate of the vehicles. Section 4.4 introduced an alternative test procedure with the AE-MDB for the assessment of frontal crash compatibility. This alternative offset test was analyzed using FE simulations and validated in terms of fulfilling the requirements of test procedures presented in the previous sections.

Chapter 5 proposed some criteria for rating the results of the proposed test procedure detailed in Chapter 4 to complete the assessment approach of frontal crash compatibility. Section 5.1 reviewed the literature for rating approaches in previous works and highlighted the issue pertaining to the assessment of partner-protection that remains unresolved. Section 5.2 introduced an alternative rating approach for the assessment of self-protection and partner-protection in tests with moving barriers. Furthermore, an assessment criterion was developed and validated to predict the high risk of intrusions' injuries using acceleration measurements on the moving barrier. Section 5.3 described the assessment protocol that is based on the proposed definition model presented in Chapter 3, the proposed test procedure from Chapter 4, and the assessment criteria detailed in Section 5.2.

Chapter 6 validated the whole assessment approach. Section 6.1 reviewed the state of the art and explained the approach of validation in previous works. Owing to high testing costs, the validation approaches were supported with few crash tests, which limits their efficiency and leads to a dependency of results on the specifications of the used vehicle models. Section 6.2 described the validation approach of this study. The fundamental definition, developed test procedure, and developed assessment criteria had already been validated using test results and simulation analyses in the previous sections. However, the whole assessment approach has to be validated to ensure the validity of the results, as these three main cores interact with each other. The validation approach consisted of two topics: correlation of the assessment results with injury risks in car-to-car collisions and efficiency of the assessment approach for improving the crash performance of vehicles in car-to-car collisions. Section 6.3 presented the validation results. To validate the assessment's correlation, four vehicle models were assessed. These vehicles were tested in car-to-car collisions and their crash performances were compared with the assessment results. To validate the assessment's efficiency, a vehicle model was optimized for better results in the AE-MDB test. The optimized design was assessed according to the protocol of Section 5.3 and tested in car-to-car collisions against other vehicle models. The crash performances of the original and optimized models were compared. The validation results confirmed the correlation of the assessment results with injury risks and the efficiency of the assessment approach in improving the vehicle's crash compatibility.

7.2 Discussion

The novelty of this work is the methodology used to develop an assessment approach. This work attempted to conduct a comprehensive study starting with a definition of crash compatibility, giving a general approach to assessments, and ending with a validation of the assessment approach, which has not been done in this form until now. The main result of this work is this methodology rather than the proposed assessment protocol. However, to show the efficiency of the developed method, it was implemented and described using an assessment protocol that contains some assumptions (e.g., value of the modification factor in the assessment protocol). The general method can be used to further develop other assessment protocols (e.g., MPDB test of Euro NCAP), which are already under discussion. It is understandable that consumer and test organizations want to finalize an assessment approach for frontal crash compatibility, and they might not be able to study new test procedures. Nevertheless, the general method of this work (e.g., the fundamental definition model and assessment criteria) can also be implemented in other types of test procedures (e.g., MPDB test) to solve the problems.

Owing to the limited budget available for this work, it was not possible to conduct any physical crash tests, and the analysis was limited to FE simulations. However, validated simulation models were used to assure the trustworthiness of the analyses conducted in this study. Simulation results are controlled with various requirements to avoid influential numerical errors and to disclose that the interpretations are affected by simulations errors. In limited number of cases, simulation models were used that have insufficient representability of the vehicle model (e.g., Ford Taurus, Geo Metro, and Dodge Neon from NCAC). However, these simulation models did not have to represent a real vehicle model and were only used as a feasible variation of the vehicle structures or concepts.

Furthermore, test results from previous projects and the NHTSA crash database were used to support the analyses. It should be noted that the NHTSA test results are for vehicles sold in the American market. Owing to differences in the safety regulations and requirements for market approval, car manufacturers modify the vehicles' structures and restraint systems for sale in different markets. Therefore, the test results of the NHTSA might differ from the European tests (e.g., Euro NCAP test results). However, the test results are used to study the phenomena and issues of compatibility, and to validate whether the results of the developed models and criteria are feasible. Therefore, the analyses should not necessarily be performed in a European crash test database.

This study developed the concept of an assessment protocol. However, this assessment protocol is not appropriate to be implemented directly as a safety regulation and should be modified in some aspects. The used offset barrier (i.e., AE-MDB) was developed for side impacts and might show irreproducibility issues in frontal impacts with higher severity and consequently deformations. However, this might be solved by modifying the barriers' components (e.g., cladding sheets or strength of the deformable blocks). Since this modification requires crash tests and cannot be studied in simulation analyses, further studies are necessary.

The modification factor of 0.9 in the assessment protocol should also be investigated in real crash tests and modified to improve the ranking of the assessment results.

The validation approach used in this work is unique. Other works used experts' opinions, which could differ and could be based on different interpretations of crash compatibility. Through implementation of the fundamental definition, this work could serve as a standard for interpreting the crash compatibility of vehicles, which made the validation results reproducible and independent from personal interpretations.

For validation, the OLC values are used instead of the dummy measurements. The assessment protocol should be validated with dummy measurements in real crash tests to assure its suitability in assessing frontal crash compatibility.

7.3 Outlook

During this work, several new topics arose that could not be studied in detail within the scope of this work. To avoid dispersion of the results, the new topics are studied roughly to isolate the relevant issues and their influence on the results. However, these new issues could be studied in future works:

- The fundamental definition model has the capability to integrate both active and passive safety in a collective safety value, which is based on the kinetic energy. This might be helpful for the development and efficiency measurements of new safety features and particularly integral safety.
- The AE-MDB is used as an MDB for frontal impacts. Since the barrier is developed for side impacts with lower crash severity, the deformation depth of the barrier might be extended to be more representative of the front-end of passenger cars.
- The developed criterion ABC-I is implemented in the assessment protocol with the AE-MDB. Since this assessment criterion is developed for moving barriers, it could be calibrated for use in the MPDB test.
- The validation is performed using simulation analysis of four different vehicles. Besides physical crash tests, it is suggested to use different vehicles with similar mass ranges to validate the assessment approach. This is because the mass of the vehicle is an influential parameter, which might blend the deficiency of the assessment approach regarding other compatibility parameters.
- The optimization methods used in this work were compatible with available tools and models. Beam elements are used in the reduced order models, which have a limited predictability. To confront with this problem, applications of macro-elements have been studied in [163]. However, the method of macro-elements is not as mature as beam or finite element methods and needs more progress to be used in optimization algorithms.

Appendices

Appendix A: Verification and Validation

Tab. A.1 lists the requirements for verification of the model.

Table A.1: Requirements for model verification [112, pp. 19-21]

Discretization and integration of the model:
The elements' type and size should have the ability to correctly reproduce the stress-strain distribution and rupture, and should fit the geometry details.
The mesh quality should be in the acceptable range to prevent numerical errors and distortions.
The time step should be low enough that the simulation model reaches a convergence. The mass scaling should not increase the model's mass to more than 1 % [168, p. 15].
Material and joint models
The material models should be able to reproduce the static and dynamic mechanical behavior in different deformation modes.
The kinematics and stiffness of the joints should be modeled in a realistic way.
The rigid joint models might have the ability to reproduce rupture
Contact models
Large penetrations, perforations, and hookings should be avoided.
The contact behavior should be stable.
An adequate friction model should be implemented.
The contact energy should be kept under control.
External load models
The gravity field and external loads should be modeled correctly.
The initial and boundary conditions should be applied correctly (location, direction, magnitude, and time).
Physical principles
The calculation should end without any error messages or warning messages.
The energy values should be under control and physically realistic. The energy ratio should remain close to 1.0, and the hourglass energy should be less than 10 % of peak internal energy [168, p. 15].
The kinematics and deformations should be realistic and set according to the problem considerations.
Different platforms
When run on different platforms with different numbers of processors or with different versions of the solver code, it should get similar results.
Variation
Small variations in the input should yield small variations in responses.

Tab. A.2 lists the requirements for validation of the analysis.

Table A.2: Requirements for analysis validation [112, pp. 21-22]

Kinematics
The model should have the ability to correlate displacements and rotations of low deformable bodies.
Deformations
The model should correlate elastic/plastic deformations and ruptures.
Time history signals
The model should correlate sensor signals (accelerometers, potentiometers, load cells, etc.).
Injury criteria
The model should correlate peak and injury criteria values calculated from sensor signals.
Robustness
The model should correlate multiple test cases simultaneously and keep a common set of values and functions for the calibration parameters used within a model under different design variables and test conditions.
Level of representability
Following calibration efforts are needed to get a predictable model: • Material characterization tests • A set of subsystem tests • A set of full assembly tests
Level of predictability
The level of predictability of the model should be checked: • What is the level of similarity between the predicted results from simulation and further validation test results? • Is the model able to predict tendencies in the right direction? • Would the model be able to predict results out of the range of conditions in which it was calibrated?

Appendix B: Simulation Models

In this work, two groups of simulation models are used to investigate the frontal crash compatibility: vehicle models and barrier models.

Vehicle models

Seven simulation models are selected to be used in this work. Tab. B.2 presents these models, their validation scenarios, and their application in this work.

Table B.1: Vehicle simulation models used in this work

Model	Developer	Validation Scenarios	Application
Generic Microcar	TUM	Frontal full-width and offset test	Section 3.3, Section 4.4.2, Section 4.4.3, Section 5.2.2.2 and Section 6.3
Toyota Yaris	NCAC	Frontal full-width and offset test	Section 3.3, Section 4.3, Section 4.4.2, Section 4.4.3, Section 5.2.2.2 and Section 6.3
Toyota Camry	NCAC	Frontal full-width test	Section 4.4.2, Section 4.4.3, and Section 6.3
Chevrolet Silverado	NCAC	Frontal full-width and offset test	Section 4.4.2, Section 4.4.3, and Section 6.3
Ford Taurus	NCAC	Frontal full-width and offset test	Section 3.3, Section 4.4.3, and Section 5.2.2.2
Geo Metro	NCAC	Frontal full-width test	Section 4.4.3
Dodge Neon	NCAC	Frontal full-width test	Section 4.4.3

The generic microcar has been developed in our previous work [165] and is described briefly in this section: generic microcar has a vehicle concept that is based on the project MUTE [169] and its successor Visio.M [72]. This model uses a Lightweight Extruded Aluminum Frame developed by Wehrle [167] as a parameterized demonstrator for structural design optimization. The generic microcar is developed for frontal impact scenarios, and therefore only relevant components are assembled in the model. For non-structural components of the front section (e.g., steering components, heating, ventilation, and air conditioning) and important non-structural components of the rear section (e.g., battery pack, e-motor), reduced models are used, which represent their geometry, stiffness, and mass effectively. The relevant exterior parts for frontal impacts are modeled with steel sheets and are welded to the vehicle structure. A dummy structure is used for the doors, which represents their structural stiffness and the load paths through the door under frontal impact. All other vehicle components that are not relevant for frontal impacts are represented by mass points and added mass to their neighboring structural parts. The mass in running of the generic microcar is 692 kg, including a battery pack with 92 kg and two dummies with 150 kg. Fig. B.1 presents an exploded view of the generic microcar.

The generic microcar is verified and validated [165] for frontal impact tests against ODB at 64 km/h and against FWRB at 56 km/h that covers both full-width and overlap scenarios. The crash performance of the simulation model was similar to the crash performance of light passenger cars, and it showed trustworthy responses in regard to the velocity-time-history, acceleration-time-history, and deformations. Furthermore, a robustness analysis confirmed the stability of the generic microcar for other frontal impact scenarios with higher severities.

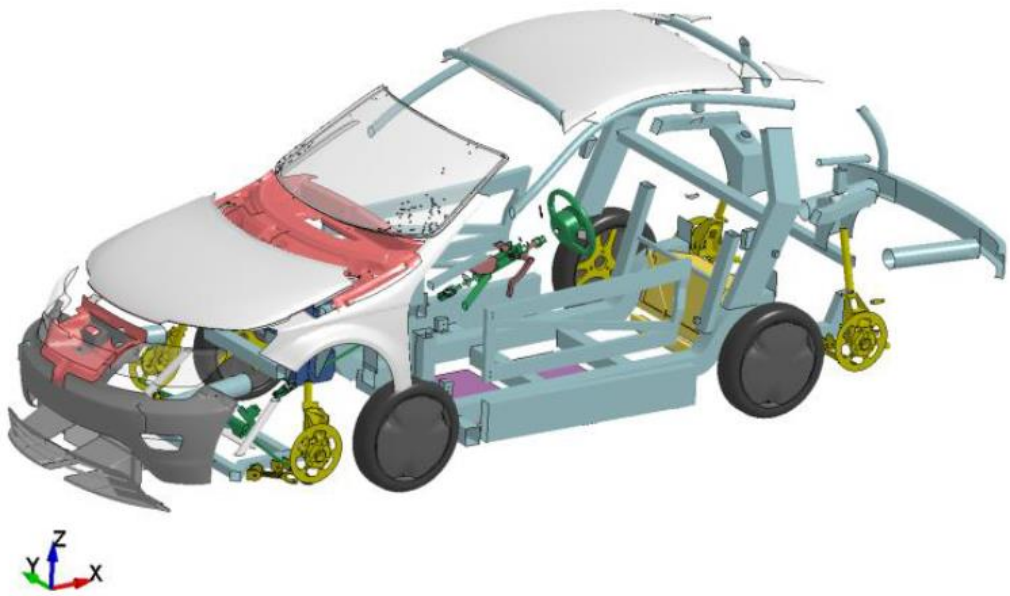


Figure B.1: Exploded view of the generic microcar [165]

The National Crash Analysis Center (NCAC)[8] of the George Washington University developed several FE simulation models using reverse engineering. As described by NCAC [143, p. 1], vehicle models are bought, disassembled, and scanned part by part to record the geometries and material types. Some samples of the vehicle components are tested to develop some material models. The generated geometries are meshed and set with the developed material models to create an FE model. FE models of the suspension and steering systems are constructed in details and could represent the crash behavior of the vehicle.

All vehicle models are verified and validated in some crash scenarios [143, 171–177]. The vehicle models have different levels of prediction, which should be considered for use in the simulation analysis. E.g., only simulation models that are validated for both full-width and offset frontal impact can be used in validation (Section 6.3) of the assessment approach. Therefore, for validation analysis, three vehicle models from different segments (Toyota Yaris, Toyota Camry, and Chevrolet Silverado) are selected from the NCAC FE model archive, as they show stability and have more details than other vehicle models.

The predictability of the NCAC simulation models and their simulation techniques were investigated in an internal study at TUM [178] based on some car-to-car crash tests from the NHTSA crash database with the Toyota Yaris model and Ford Taurus model. The results showed that the NCAC models are also valid for car-to-car frontal impacts and represent the acceleration-time-history and velocity-time-history along the vehicle length in real crash tests. However, the deformations might vary from the real values in low overlap scenarios. The tires of the NCAC simulation models are constructed with simple

[8] Unfortunately, the NCAC website and their archive of FE models are offline since summer 2016. The author has not succeeded in knowing, if this is a decision from NCAC to end sharing their FE models or a technical problem. The simulation models are currently available on the website of NHTSA [170].

airbags, which can model the wheels' stiffness and their role as one of the load paths; however, in low overlap scenarios, the wheels are the main load path and the tire would fail, which cannot be modeled with simple airbags. Therefore, the application of the NCAC simulation models is limited to frontal impacts with overlap values higher than 20 %.

Barrier models

Five simulation models of different barriers are necessary for this work (Tab. B.2).

Table B.2: Barrier simulation models necessary for this work

Barrier	Name	Developer
Full-Width Rigid Barrier	FWRB	NCAC
Full-Width Deformable Barrier	FWDB	TUM
Offset Deformable Barrier	ODB	LSTC
Progressive Deformable Barrier	PDB	TUM
Advanced European Mobile Deformable Barrier	AE-MDB	LSTC

The FWRB can be modeled as a rigid wall, which is constrained in all directions. This type of barrier is used in many validation analyses, e.g., the validation of NCAC simulation models, and showed trustworthy results.

The barrier model of FWDB was constructed in an internal study [133, pp. 78-79] at the Technical University of Munich during the Visio.M project. The simulation model of FWDB was verified and validated using a sled test. The results showed good consistency with the force-deformation-history of real test results (Fig. B.2).

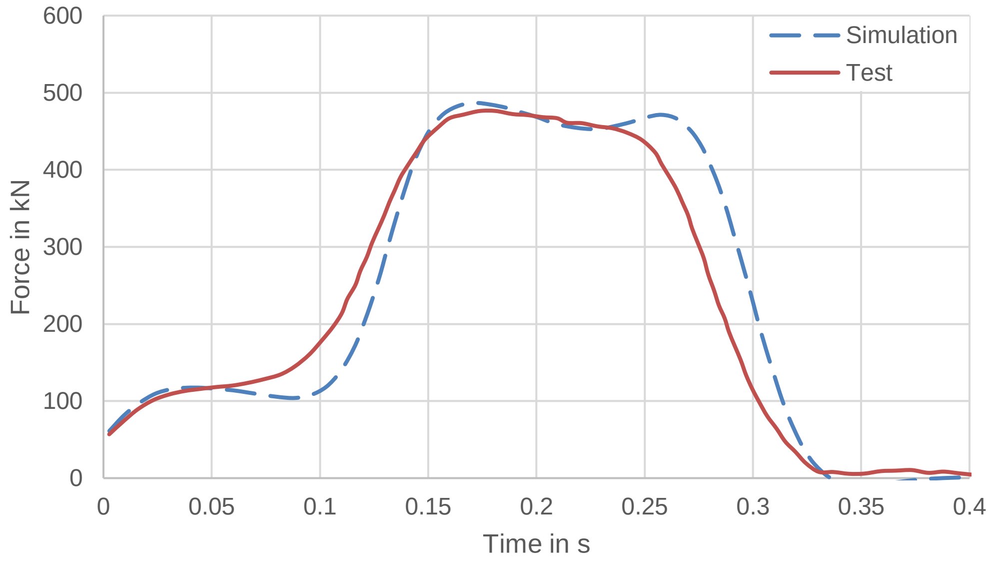
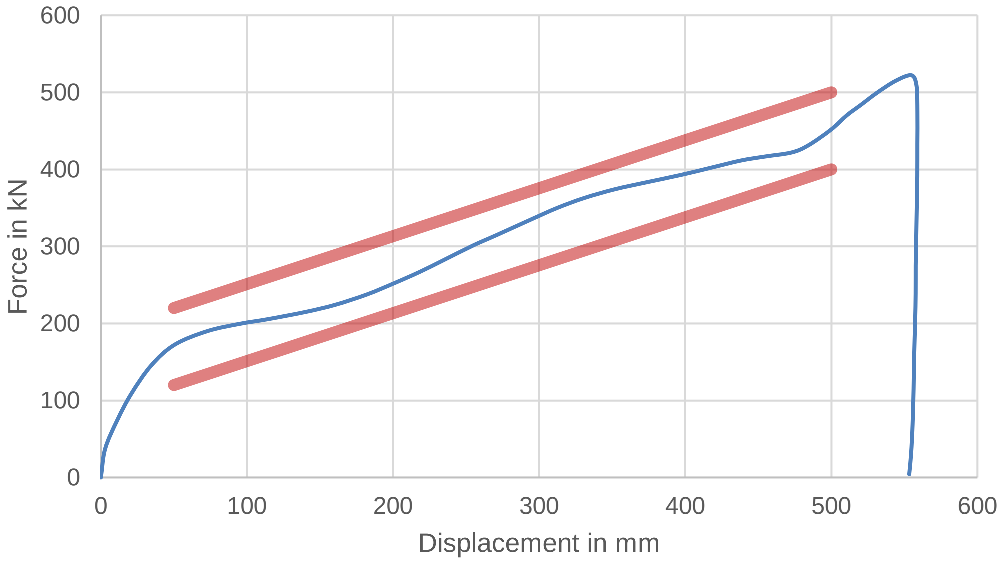


Figure B.2: Validation results for FWDB

[133, p. 79] for the test result

Livermore Software Technology Corporations (LSTC) developed a set of ODB models, which are verified and validated with a test series in [179]. The results showed good consistency with the force-deformation-history of real test results.

The barrier model of PDB was constructed in an internal study [139] at the Technical University of Munich. The simulation model of the PDB was verified and validated with two sled tests [138, pp. 49-54]. The results showed good consistency with the force-deformation-history of real test results and were within the pre-defined corridors (Fig. B.3).



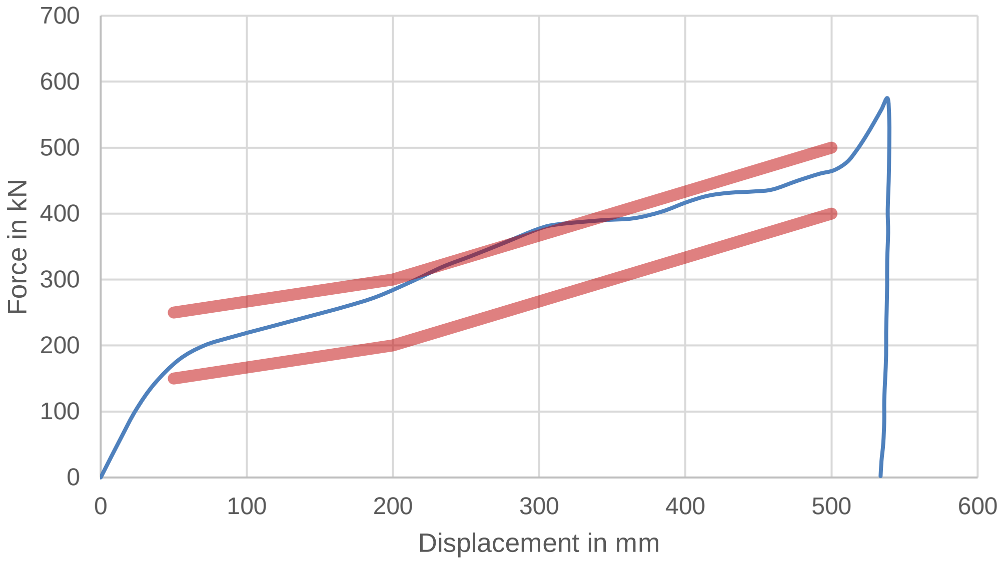


Figure B.3: Validation results and corridors for the PDB model; Certification Test 1 (Top) and Certification Test 2 (Bottom)

[139, pp. 27-28]

LSTC developed a simulation model for AE-MDB according to the described geometry and properties of the barrier (Section 4.4.1). The simulation model was validated in a dynamic test against FWRB at 35 km/h, and the results showed good consistency with the pre-defined corridors for the force-deformation-histories of the whole barrier and single blocks (Fig. B.4).

This barrier model was designed for side impacts, whereby the honeycomb would deform by about 50 % [180]. Thus, the validation test would not ensure the trustworthiness of the FE model for frontal impacts in which the deformable blocks bottom out. However, this model is used to investigate the concept of a MDB similar to AE-MDB for the assessment of frontal crash compatibility. The AE-MDB should be modified for this application according to the results of this work, and the current FE model could be used as a reference for the modifications.

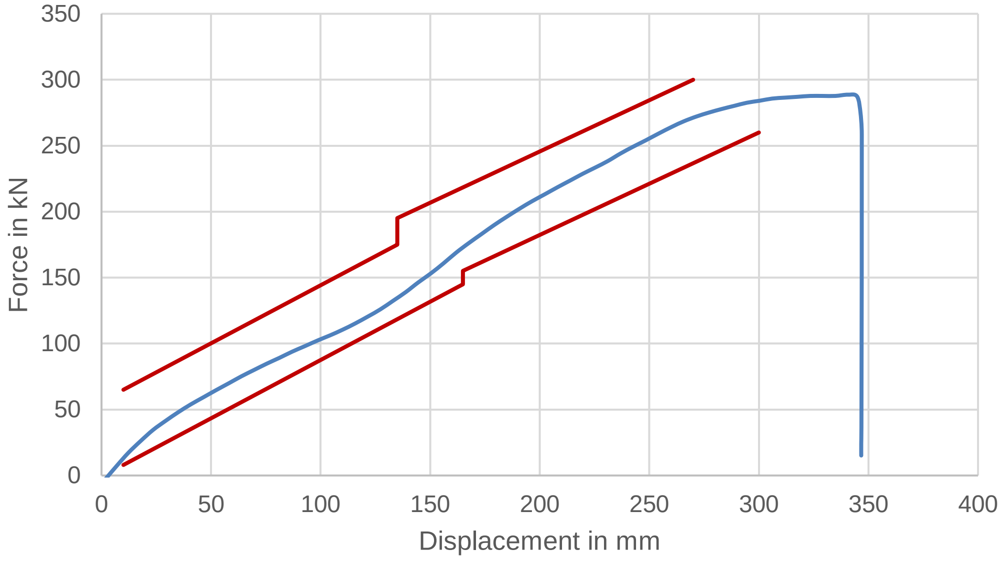


Figure B.4: Validation results for the full barrier

[181, p. 4]

Appendix C: Validation Results for the Proposed Definition Model

Tab. C.1 presents the studied NASS data, which are used to validate the proposed definition model. Case IDs are colored regarding the prediction of the proposed definition model. Green means consistent, yellow means inconsistent but comprehensible, red means inconsistent and gray means too much or insufficient severity. Injuries are presented as Abbreviated Injury Score (AIS), by which one is minor injuries and six is fatal injuries.

Table C.1: NASS crash scenarios and the validation results [182, Appendix B]

Case ID[1]	Car 1				Car 2			
	Model	Safety Level in kJ	Compatibility Rate	AIS Code	Model	Safety Level in kJ	Compatibility Rate	AIS Code
159010724	Honda Civic 1997	122.0	60.1%	4	Jeep Wrangler 1997	155.2	76.7%	2
179008751	Nissan Sentra 1997	128.6	60.3%	3	Chevrolet S-10 1997	137.7	56.4%	2
174010059	Honda Civic 2000	122.0	60.1%	3	Nissan Sentra 1998	128.6	60.3%	1
149006672	Honda Odyssey 2001	232.0	75.6%	1	Toyota Sienna 1998	203.7	58.6%	3
102004984	Ford Escort 1999	129.7	16.6%	1	Dodge Neon 1998	107.6	50.9%	1
178008643	Ford Ranger 2000	154.4	49.8%	1	Chevrolet S-10 1996	137.7	56.4%	2
169007974	Saturn SL2 1996	69.5	135.3%	2	GMC SONOMA 1996	137.7	56.4%	1
149009383	Saturn SL2 1995	69.5	135.3%	2	Chevrolet S-10 1999	137.7	56.4%	2
175004151	Ford Taurus 1999	185.7	71.8%	2	Chevrolet S-10 2000	137.7	56.4%	1

773014556	BMW 3 Series 2006	176.8	97.4%	1	Chevrolet S-10 2002	137.7	56.4%	2
179007394	Acura RL 1996	169.7	70.0%	1	Chevrolet S-10 1999	137.7	56.4%	2
212005750	Honda Civic 1999	122.0	60.1%	2	Lexus RX300 2002	216.1	71.3%	1
360002687	Chevrolet Impala 2003	165.2	96.5%	1	Chevrolet Malibu 2001	141.2	60.0%	1
163007936	Chrysler LHS 1999	132.7	66.4%	1	Buick Lesabre 2002	224.8	90.8%	1
777013898	Chevrolet Malibu 2005	141.2	60.0%	1	Dodge Inteprid 2001	152.0	93.7%	1
195011008	Ford Taurus 2000	185.7	71.8%	5	Buick Park Avenue 2000	200.9	107.0%	6
174007124	Ford Taurus 2003	185.7	71.8%	3	Jeep Cherokee 2003	167.0	66.9%	2
162008880	Buick Park Avenue 1999	200.9	107.0%	3	Jeep Cherokee 2000	167.0	66.9%	3
780010838	Jeep Cherokee 2000	167.0	66.9%	2	Ford Taurus 2006	185.7	71.8%	3
910003512	Chevrolet S-10 1998	137.7	56.4%	1	Pontiac Grand 2003	148.8	61.9%	1
168007321	Isuzu Rodeo 1998	199.3	86.2%	3	Chevrolet Malibu 2001	141.2	60.0%	1
768011617	Buick Park Avenue 1997	200.9	107.0%	1	Chevrolet Malibu 2002	141.2	60.0%	2
180008817	BMW 3 Series 2001	176.8	97.4%	1	Jeep Cherokee 1999	167.0	66.9%	1

180007207	Toyota Avalon 2001	163.9	85.6%	1	Hyundai Elantra 2002	164.0	74.7%	1
210222165	GMC SONOMA 1998	137.7	56.4%	4	Nissan Maxima 2001	155.0	81.3%	3
769011191	Dodge Intrepid 2003	152.0	93.7%	1	Nissan Maxima 2002	155.0	81.3%	3
437010128	Nissan Maxima 2003	155.0	81.3%	1	Jeep Cherokee 2000	167.0	66.9%	2
162008259	Ford Taurus 2001	185.7	71.8%	1	Jeep Cherokee 2002	167.0	66.9%	1
149006631	Kia Sportage 2001	183.6	79.0%	-	Honda Civic 2000	122.0	60.1%	6
195006249	Honda Civic 1998	122.0	60.1%	1	Kia Sportage 2001	183.6	79.0%	3
770011850	Honda Accord 2001	151.9	72.0%	1	Honda CR-V 1998	184.2	62.0%	2
168005839	Subaru Forester 1998	161.9	66.8%	3	Chevrolet Malibu 1999	141.2	60.0%	3
183004172	Isuzu Trooper II 2000	193.4	76.0%	1	Subaru Forester 1999	161.9	66.8%	1
178010622	Mazda Protege 1995	125.7	74.5%	6	Chevrolet Malibu 2003	141.2	60.0%	6

[1] **Green and bold**: consistent results
Yellow and italic: inconsistent but comprehensible results
Red and underlined: inconsistent results
Gray: too much or insufficient severity

Appendix D: Location of Intrusion Measurements

Fig. D.1 illustrates the location of intrusion measurements for the generic microcar.

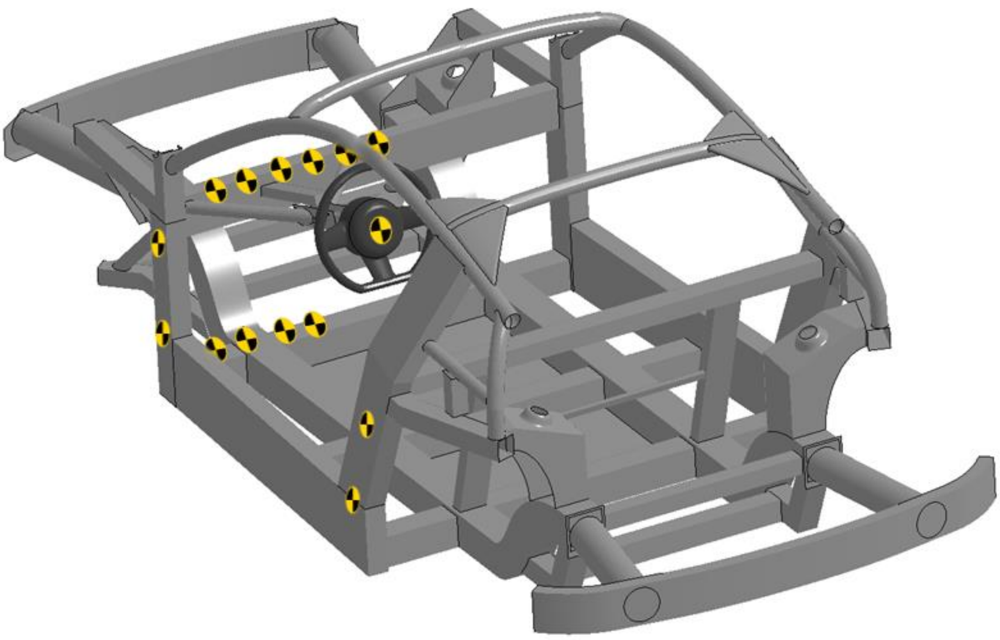


Figure D.1: Location of intrusion measurements (instrument panel, steering wheel, toe-pan, A-pillar, and B-pillar) into the occupant compartment of the generic microcar

Other components are hidden for better visibility

Fig. D.2 illustrates the location of intrusion measurements for Toyota Yaris.

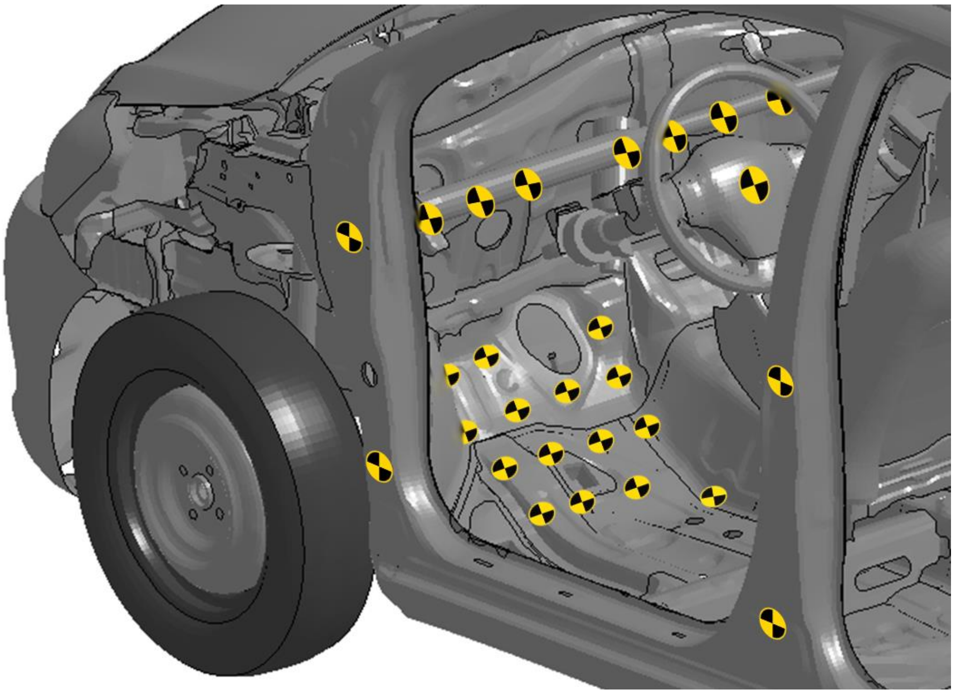


Figure D.2: Location of intrusion measurements (instrument panel, steering wheel, toe-pan, A-pillar, and B-pillar) into the occupant compartment of Toyota Yaris

Other components are hidden for better visibility

Fig. D.3 illustrates the location of intrusion measurements for Toyota Camry.

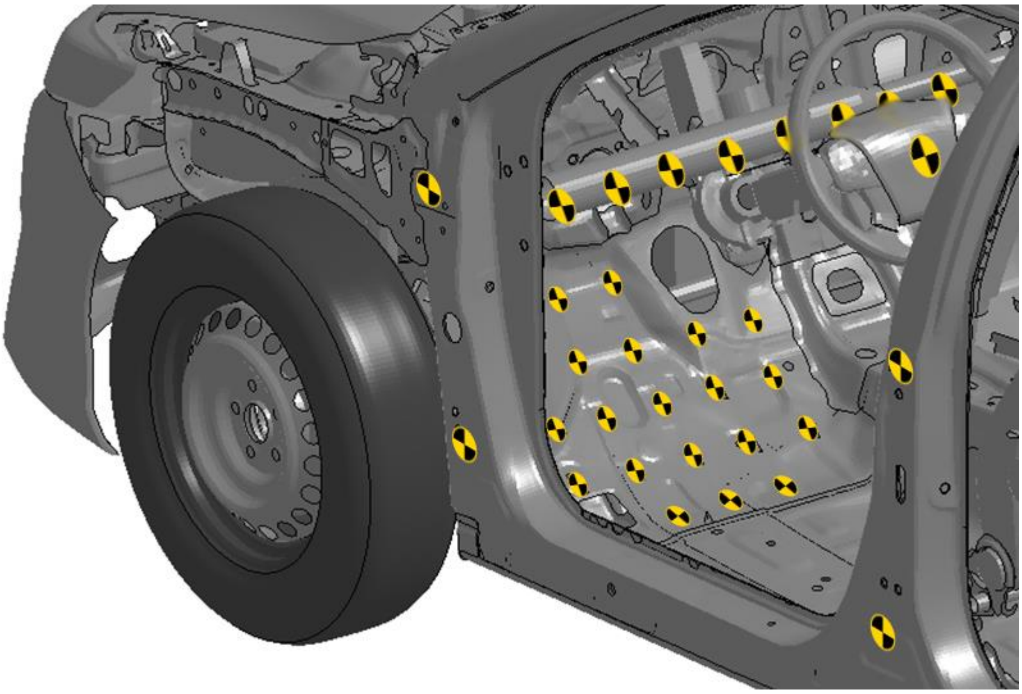


Figure D.3: Location of intrusion measurements (instrument panel, steering wheel, toe-pan, A-pillar, and B-pillar) into the occupant compartment of Toyota Camry

Other components are hidden for better visibility

Fig. D.4 illustrates the location of intrusion measurements for Chevrolet Silverado.

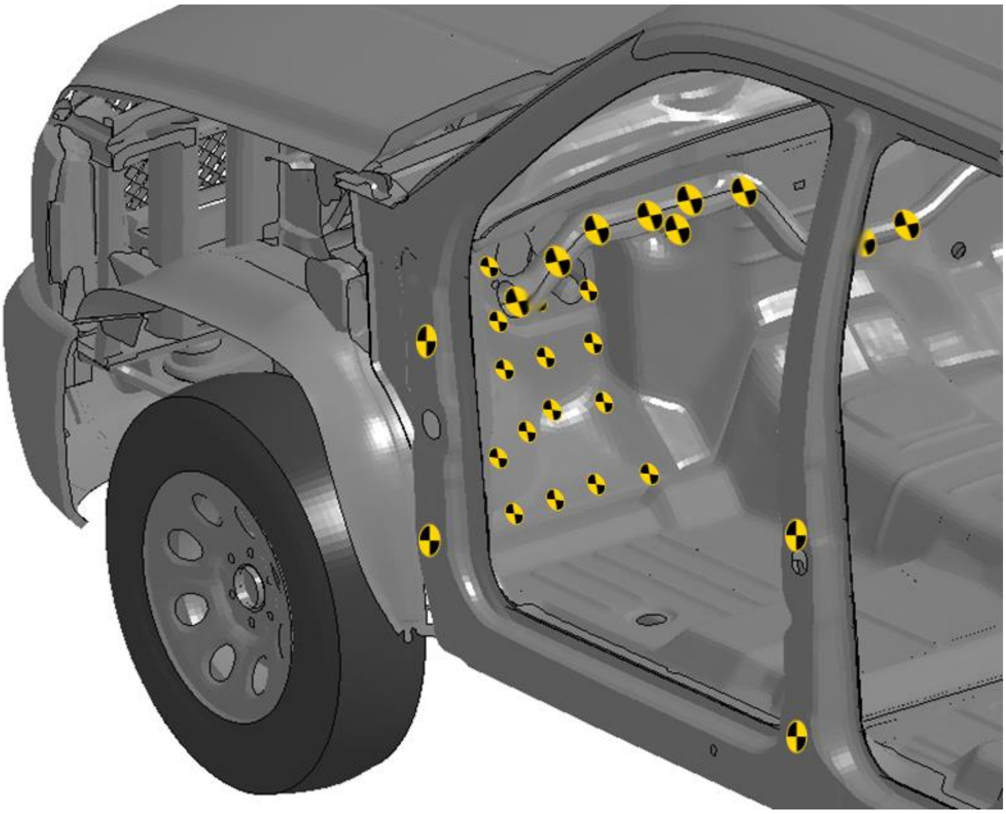


Figure D.4: Location of intrusion measurements (instrument panel, steering wheel, toe-pan, A-pillar, and B-pillar) into the occupant compartment of Chevrolet Silverado

Other components are hidden for better visibility

Appendix E: Parameters and their Variation Ranges

The reduced-order model has the capability to represent the variation of 18 parameters in the front-end of the vehicle, which could influence different issues of crash compatibility. Fig. E.1 illustrates the relevant components.

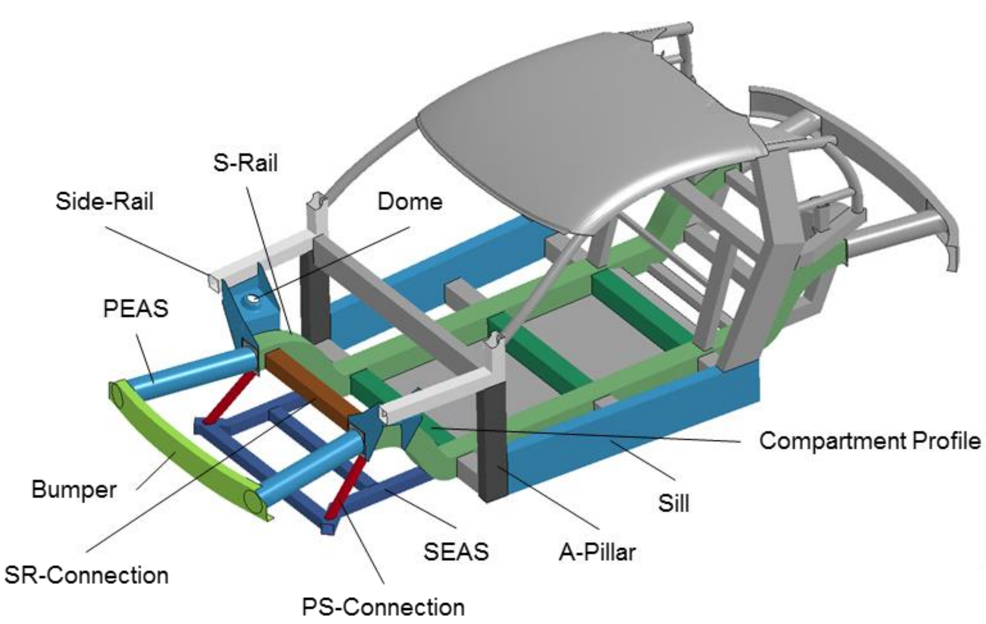


Figure E.1: Relevant components in the front-end of the generic microcar for parameters

The parameters can be categorized into two groups of size and shape parameters. Size parameters represent the change of profile thicknesses of different components (Tab. E.1), while shape parameters represent the change of height or length of the components (Tab. E.2).

Table E.1: Size parameters according to [164, xiii]

Name	Description
t_sf	Thickness of Bumper
t_vst	Thickness of SR-Connections
t_ul	Thickness of SEAS
t_st	Thickness of S-Rails
t_qtu	Thickness of Compartment Profile
t_s	Thickness of Sills
t_qto	Thickness of SR-Connections
t_slt	Thickness of Side-Rails
t_as	Thickness of A-Pillars
ri-lt	Inner radius of PEAS' profiles
ri_vl	Inner radius of PS-Connection's profiles
t_af	Thickness of Domes

Table E.2: Shape parameters according to [164, xiv]

Name	Description
bf	Ground clearance of the vehicle
hlt	Height of PEAS
lul	Length of SEAS
llt	Length of PEAS
sll	Extension of Side-Rails after Domes
sfl	Length of Bumper

The reduced-order parametric model uses beam elements, which cannot represent the complicated deformation mode of PEAS (e.g., buckling). Thus, the number of parameters is reduced to have a representative parametric model for optimizations. Tab. E.3 lists these parameters with their initial values and variation ranges.

Table E.3: Used parameters for the optimization of the generic microcar

No.	Name	Initial value	Variation range
1	ri_vl	18 mm	17–19 mm
2	sll	0 mm	0–170 mm
3	t_af	8 mm	4–12 mm
4	t_as	4 mm	2–6 mm
5	t_qto	2 mm	1–3 mm
6	t_qtu	2 mm	1–3 mm
7	t_s	4 mm	2–6 mm
8	t_sf	3 mm	1.5–4.5 mm
9	t_slt	3 mm	1.5–4.5 mm
10	t_ul	2 mm	1–3 mm
11	t_vst	2 mm	1–3 mm

Appendix F: Simulation Results of the Validation Study

Fig. F.1 presents the simulation results of the generic microcar against the FWRB at 50 km/h for assessing the safety level.

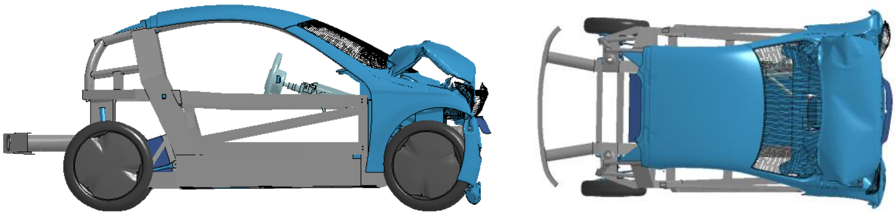


Figure F.1: Deformations of the generic microcar against the FWRB at 50 km/h after 200 ms

Fig. F.2 illustrates the simulation results of the generic microcar and AE-MDB in the offset test at 90 km/h (i.e. 45 km/h for each party) for assessing the compatibility rate.

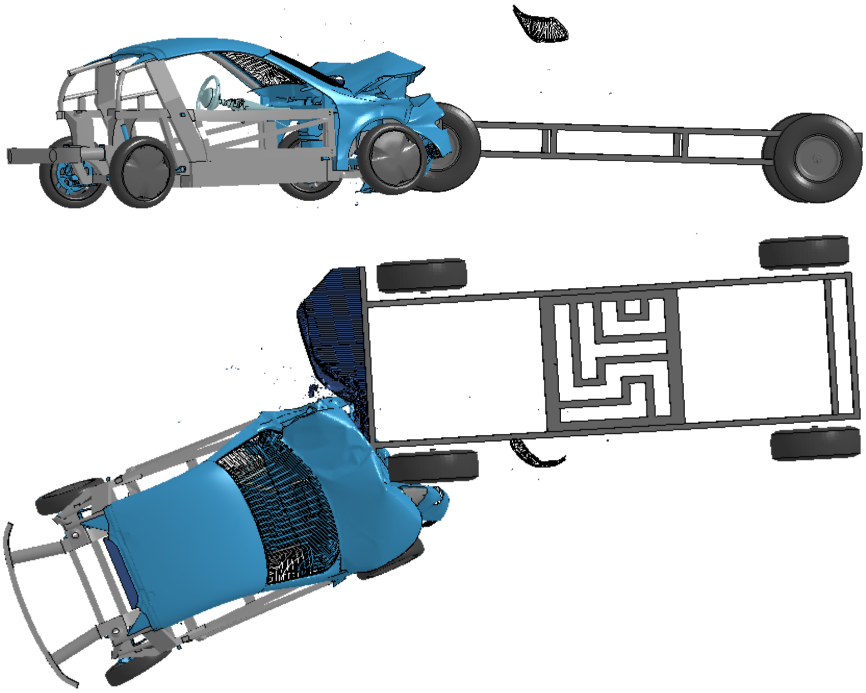


Figure F.2: Deformations of the generic microcar and AE-MDB in the offset test at 90 km/h after 200 ms

Fig. F.3 presents the simulation results of Toyota Yaris against the FWRB at 50 km/h for assessing the safety level.

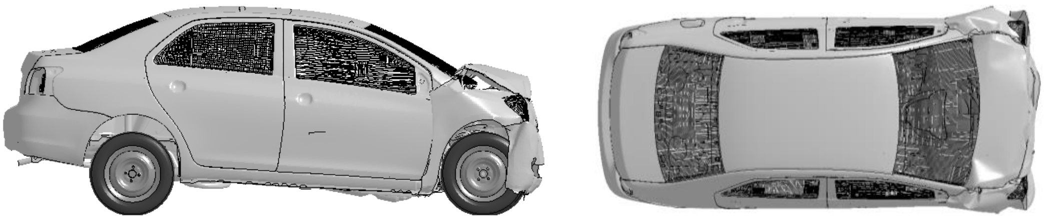


Figure F.3: Deformations of Toyota Yaris against the FWRB at 50 km/h after 200 ms

Fig. F.4 illustrates the simulation results of Toyota Yaris and AE-MDB in the offset test at 90 km/h (i.e. 45 km/h for each party) for assessing the compatibility rate.

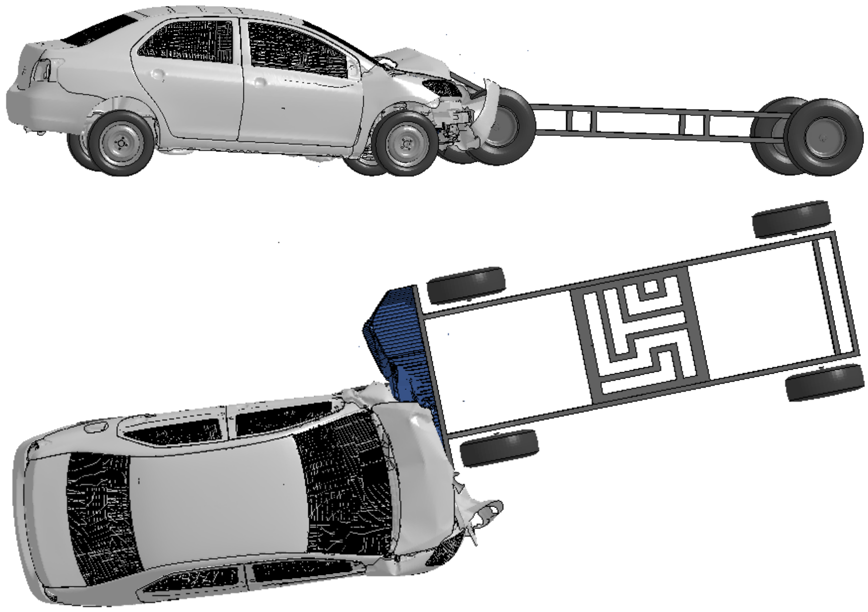


Figure F.4: Deformations of Yaris and AE-MDB in the offset test at 90 km/h after 200 ms

Fig. F.5 presents the simulation results of Toyota Camry against the FWRB at 50 km/h for assessing the safety level.

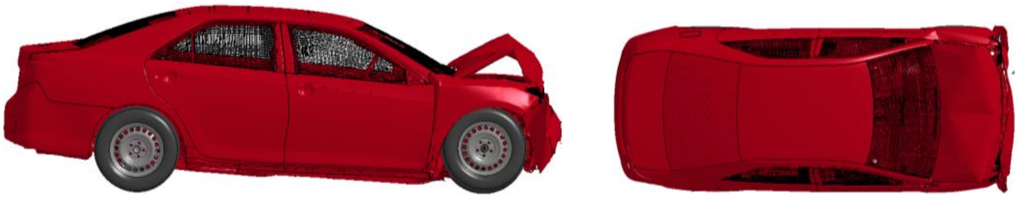


Figure F.5: Deformations of Toyota Camry against the FWRB at 50 km/h after 200 ms

Fig. F.6 illustrates the simulation results of Toyota Camry and AE-MDB in the offset test at 90 km/h (i.e. 45 km/h for each party) for assessing the compatibility rate.

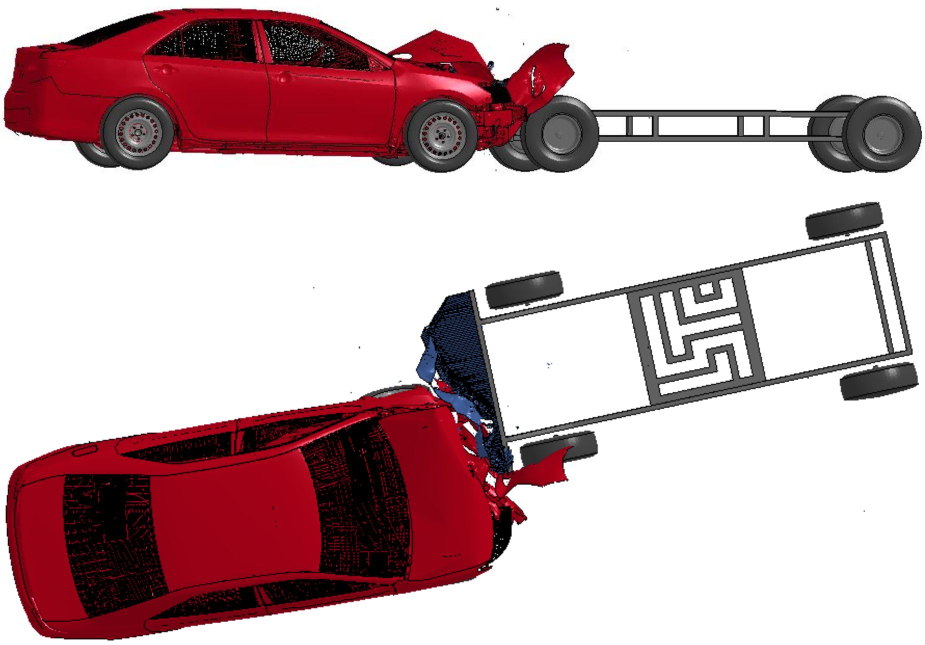


Figure F.6: Deformations of Camry in the offset test at 90 km/h after 200 ms

Fig. F.7 presents the simulation results of Chevrolet Silverado against the FWRB at 50 km/h for assessing the safety level.

Figure F.7: Deformations of Chevrolet Silverado against the FWRB at 50 km/h after 200 ms

Fig. F.8 illustrates the simulation results of Chevrolet Silverado and AE-MDB in the offset test at 90 km/h (i.e. 45 km/h for each party) for assessing the compatibility rate.

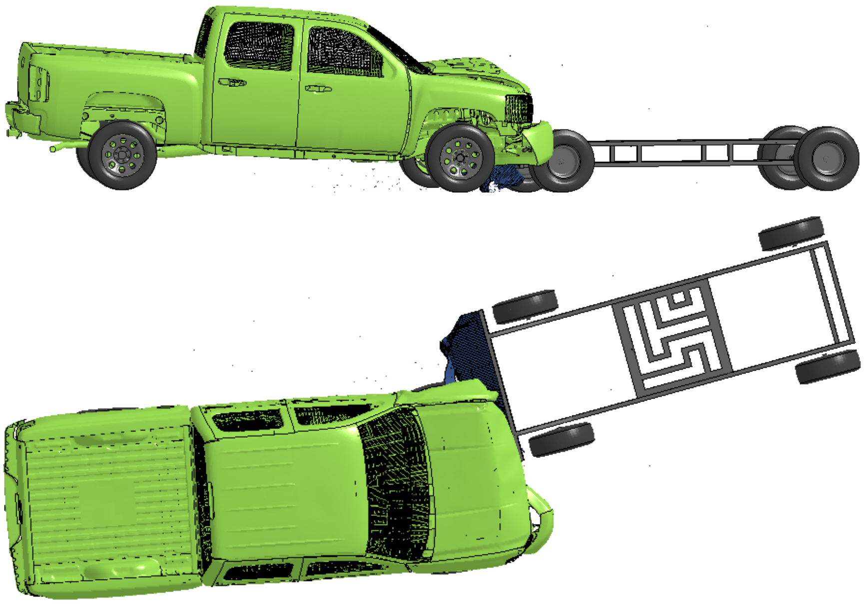


Figure F.8: Deformations of Silverado and AE-MDB in the offset test at 90 km/h after 200 ms

Fig. F.9 and Fig. F.10 present the simulation results of the car-to-car test between two generic microcar models at 90 km/h (i.e. 45 km/h for each party).

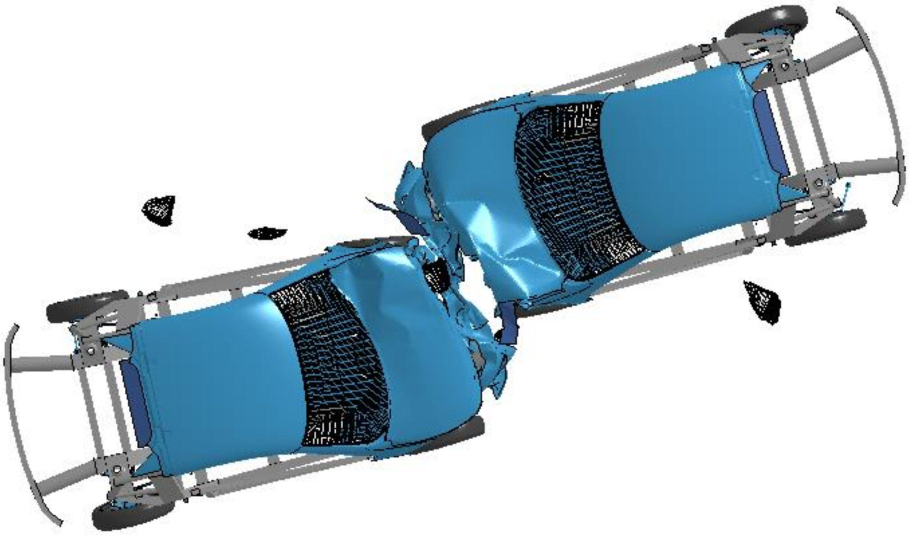


Figure F.9: Deformations of two generic microcars in the car-to-car test at 90 km/h after 250 ms

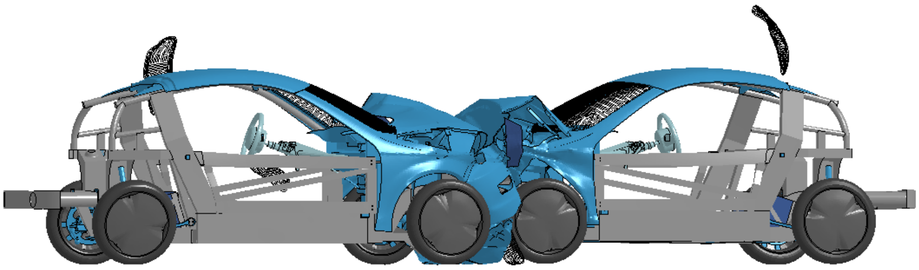


Figure F.10: Deformations of two generic microcars in the car-to-car test at 90 km/h after 250 ms

Fig. F.11 presents the simulation results of the car-to-car test between the generic microcar and Toyota Yaris at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

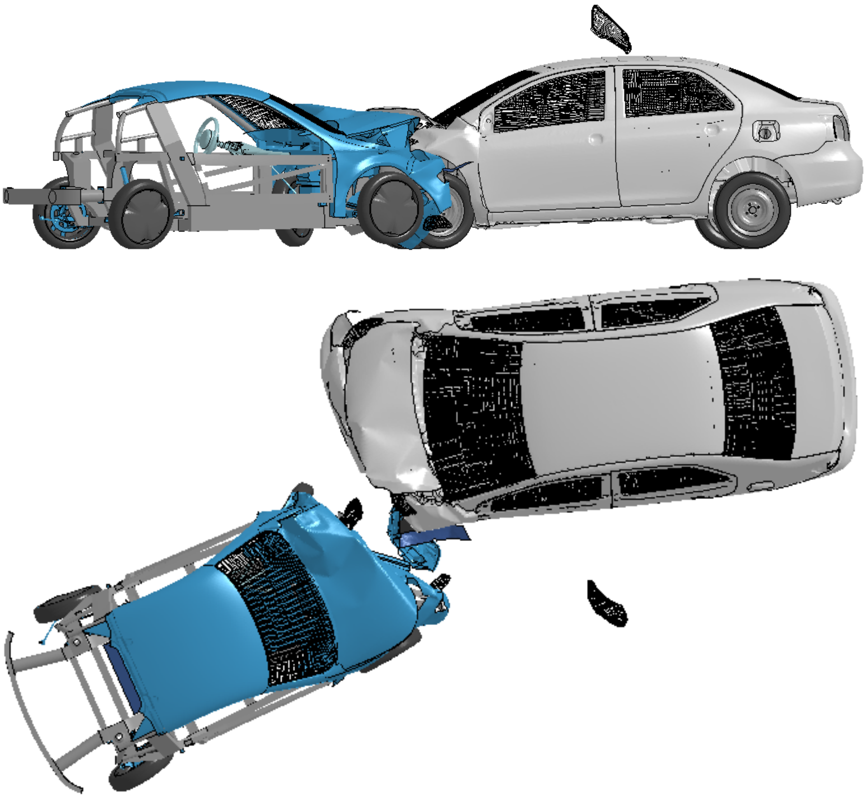


Figure F.11: Deformations of the generic microcar and Yaris in the car-to-car test at 90 km/h after 250 ms

Fig. F.12 and Fig. F.13 present the simulation results of the car-to-car test between the generic microcar and Toyota Camry at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

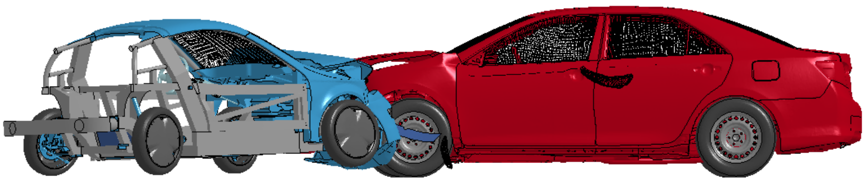


Figure F.12: Deformations of the generic microcar and Camry in the car-to-car test at 90 km/h after 250 ms

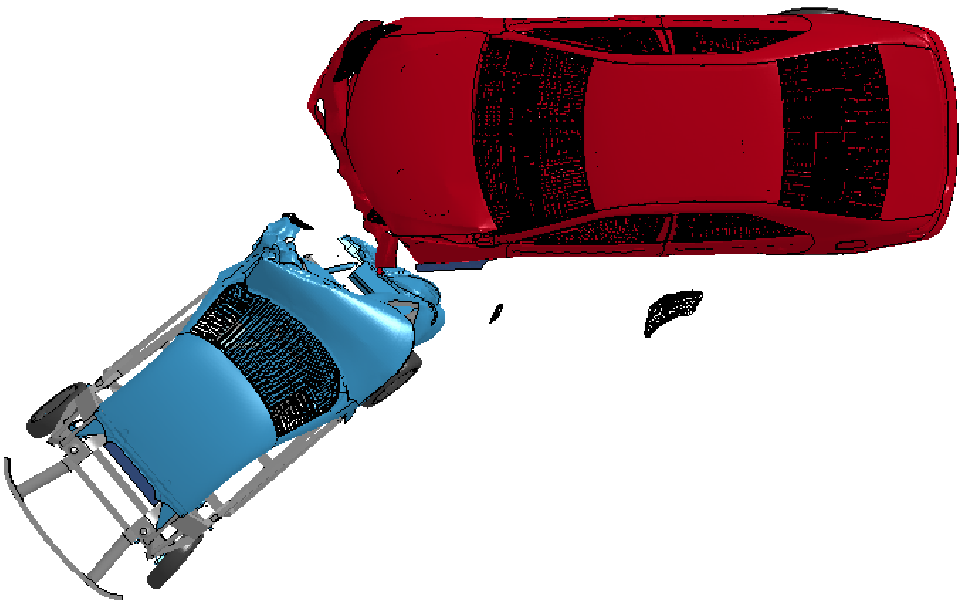


Figure F.13: Deformations of the generic microcar and Camry in the car-to-car test at 90 km/h after 250 ms

Fig. F.14 presents the simulation results of the car-to-car test between the generic microcar and Chevrolet Silverado at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

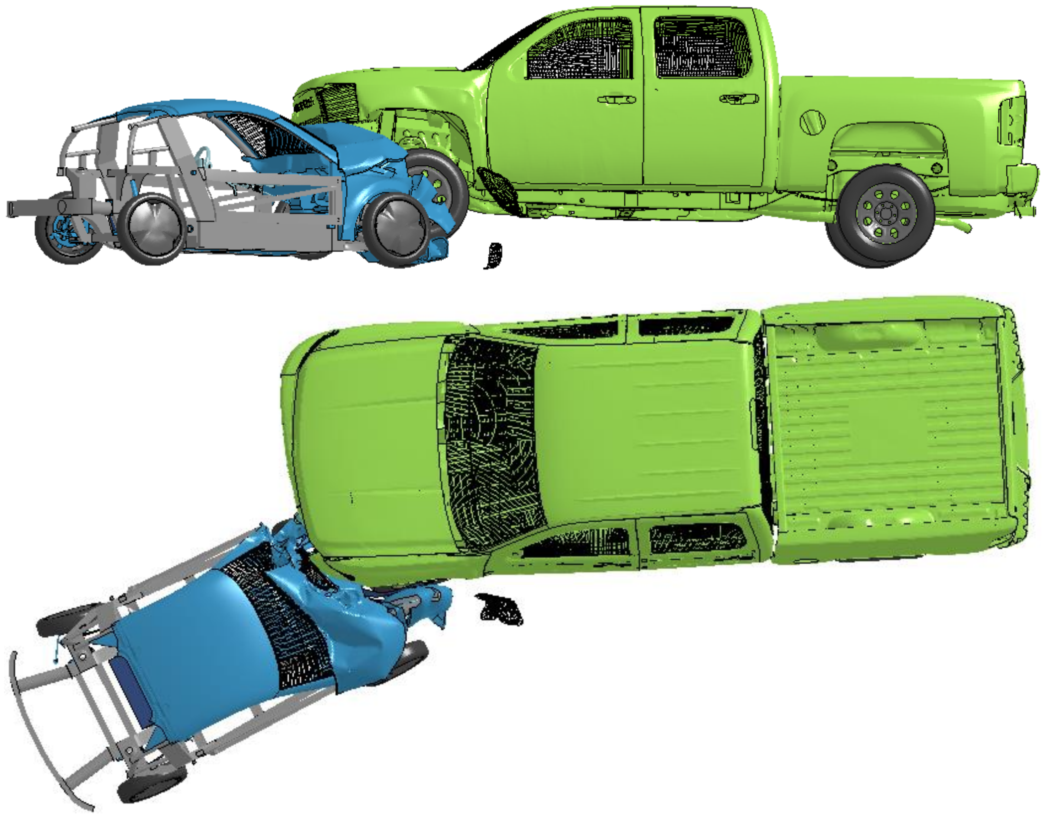


Figure F.14: Deformations of the generic microcar and Silverado in the car-to-car test at 90 km/h after 250 ms

Fig. E.15 presents the simulation results of the car-to-car test between two Toyota Yaris models at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

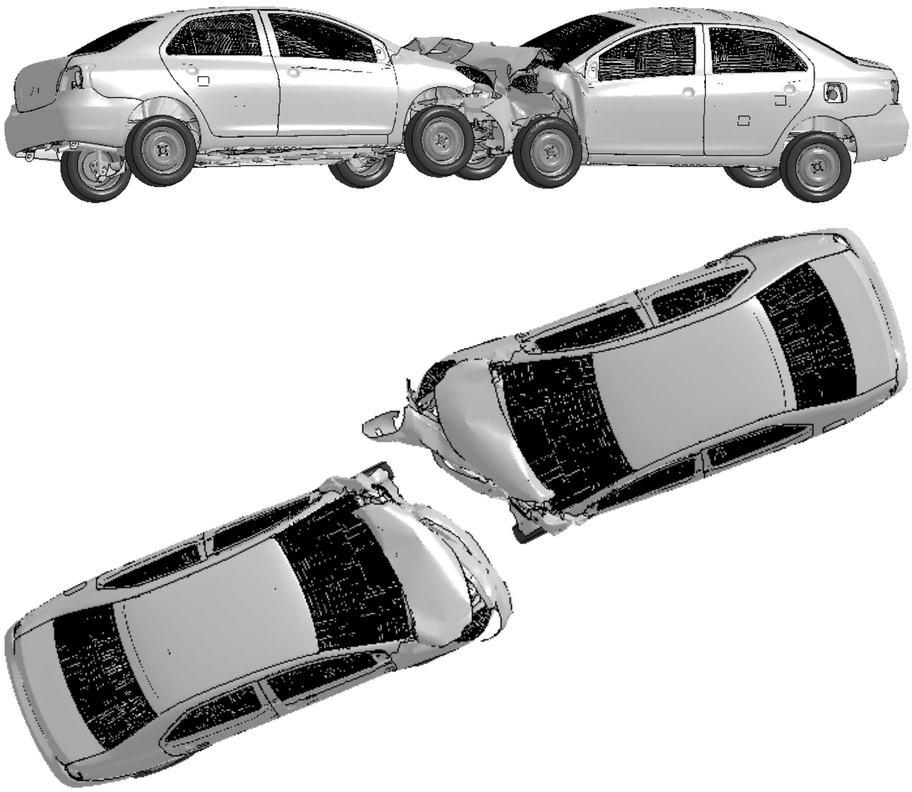


Figure F.15: Deformations of two Yaris models in the car-to-car test at 90 km/h after 250 ms

Fig. F.16 presents the simulation results of the car-to-car test between Toyota Yaris and Toyota Camry at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

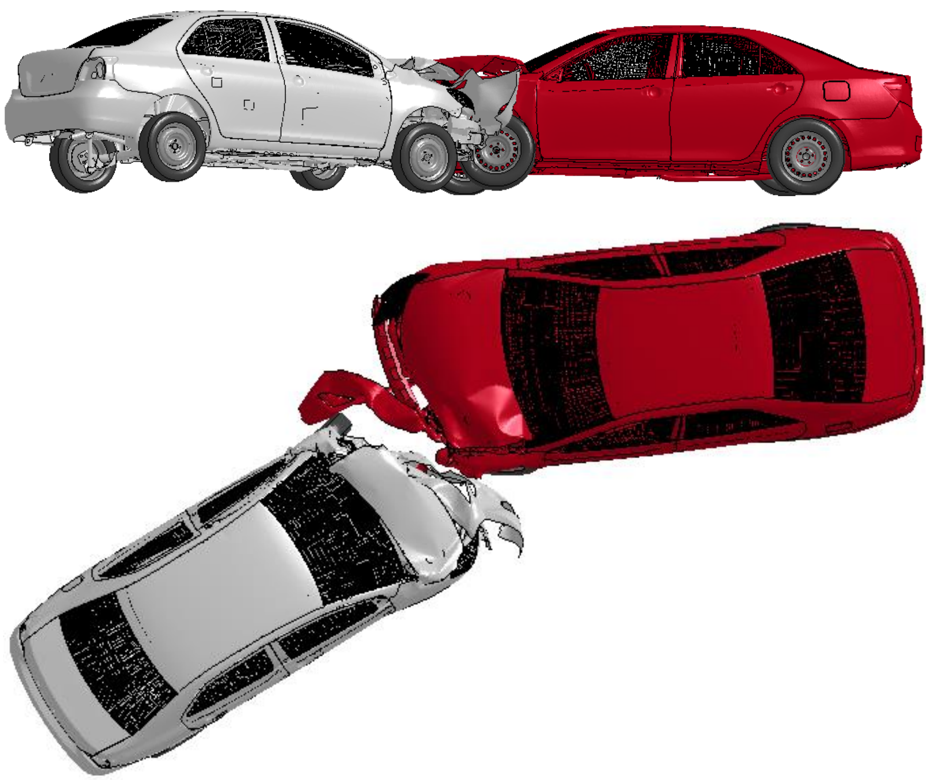


Figure F.16: Deformations of Yaris and Camry in the car-to-car test at 90 km/h after 250 ms

Fig. F.17 presents the simulation results of the car-to-car test between Toyota Yaris and Chevrolet Silverado at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

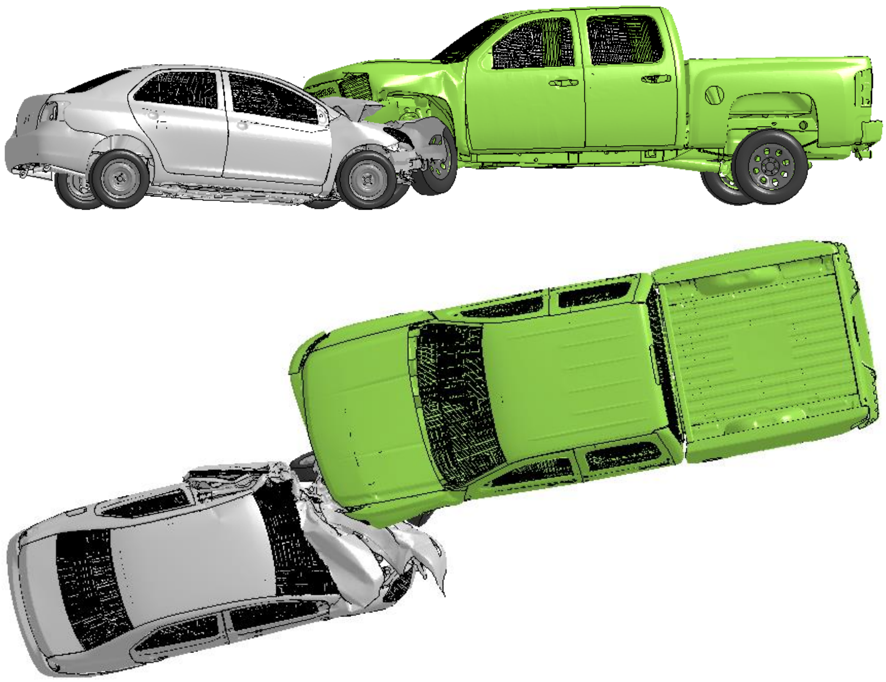


Figure F.17: Deformations of Yaris and Silverado in the car-to-car test at 90 km/h after 250 ms

Fig. F.18 presents the simulation results of the car-to-car test between two Toyota Camry models at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

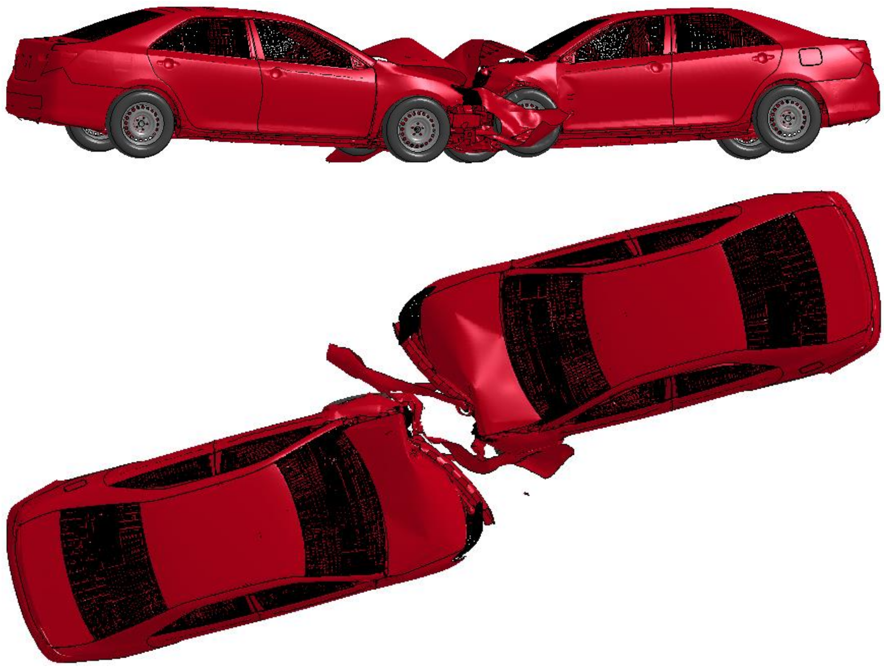


Figure F.18: Deformations of two Camry models in the car-to-car test at 90 km/h after 250 ms

Fig. F.19 presents the simulation results of the car-to-car test between Toyota Camry and Chevrolet Silverado at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

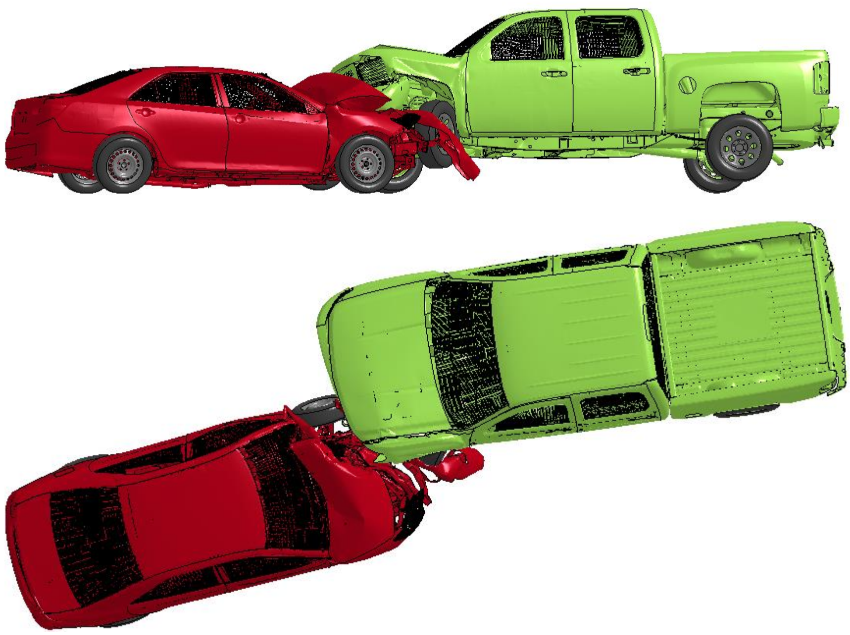


Figure F.19: Deformations of Camry and Silverado in the car-to-car test at 90 km/h after 250 ms

Fig. F.20 presents the simulation results of the car-to-car test between two Chevrolet Silverado models at 90 km/h for comparing with the assessment results.

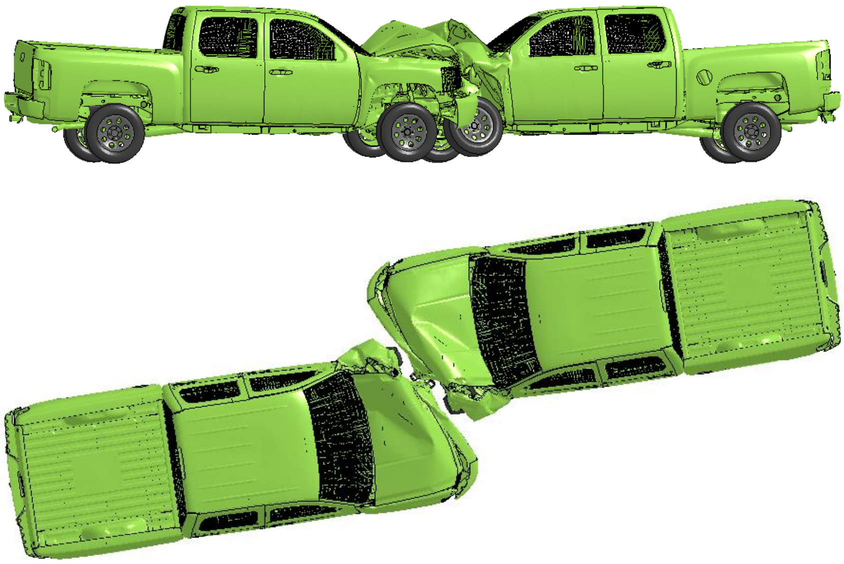


Figure F.20: Deformations of two Silverado models in the car-to-car test at 90 km/h after 250 ms

Fig. F.21 presents the simulation results of the optimized microcar against the FWRB at 50 km/h for assessing the safety level.

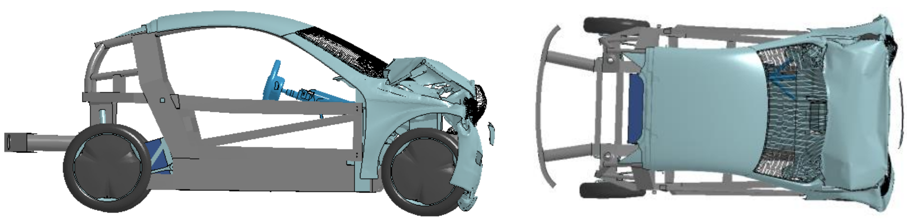


Figure F.21: Deformations of the optimized microcar against the FWRB at 50 km/h after 200 ms

Fig. F.22 illustrates the simulation results of the optimized microcar and AE-MDB in the offset test at 90 km/h (i.e. 45 km/h for each party) for assessing the compatibility rate.

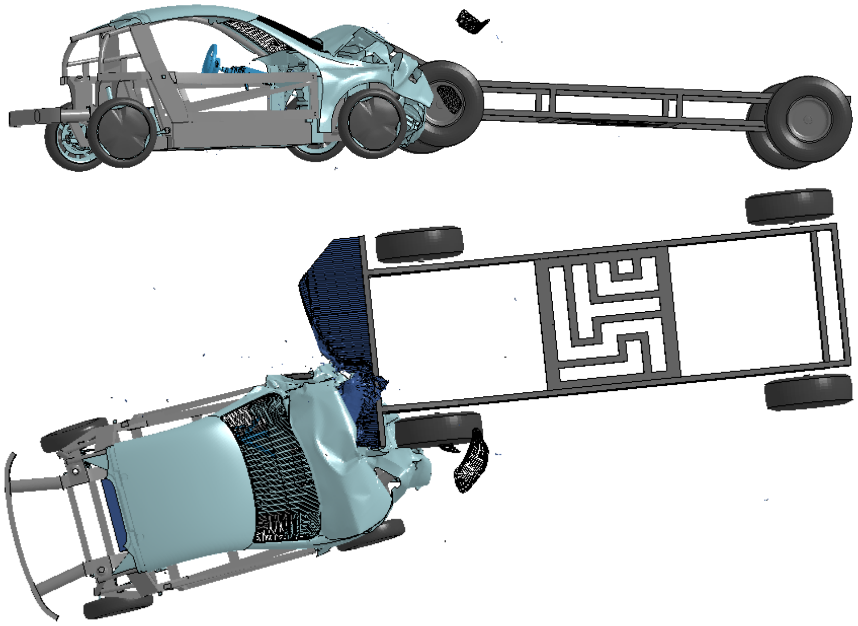


Figure F.22: Deformations of the optimized microcar and AE-MDB in the offset test at 90 km/h after 200 ms

Fig. F.23 presents the simulation results of the car-to-car test between the generic microcar and the optimized microcar at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

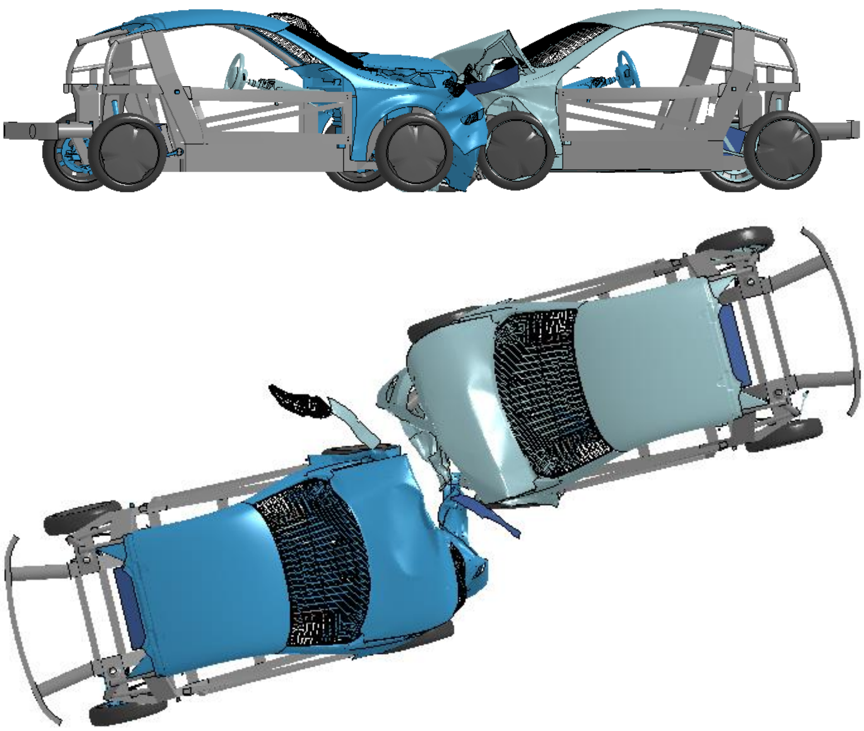


Figure F.23: Deformations of the generic microcar (left) and the optimized microcar (right) in the car-to-car test at 90 km/h after 250 ms

Fig. F.24 presents the simulation results of the car-to-car test between the optimized microcar and Toyota Yaris at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

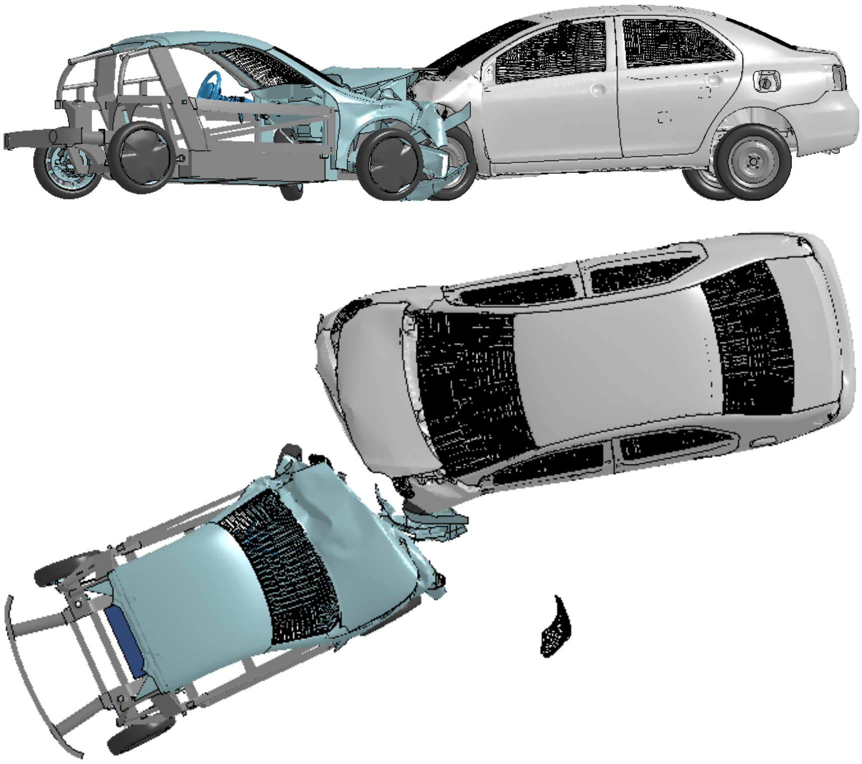


Figure F.24: Deformations of the optimized microcar and Yaris in the car-to-car test at 90 km/h after 250 ms

Fig. F.25 presents the simulation results of the car-to-car test between the optimized microcar and Toyota Camry at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

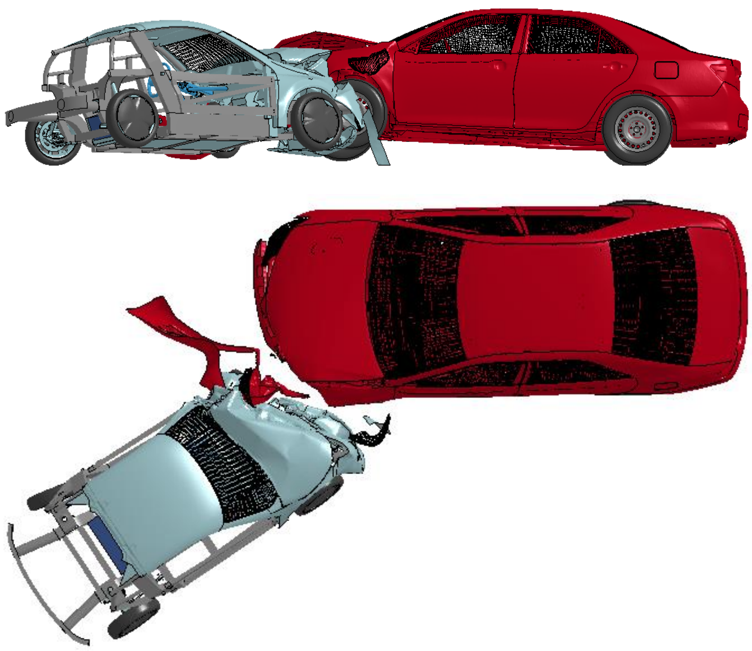


Figure F.25: Deformations of the optimized microcar and Camry in the car-to-car test at 90 km/h after 250 ms

Fig. F.26 presents the simulation results of the car-to-car test between the optimized microcar and Chevrolet Silverado at 90 km/h (i.e. 45 km/h for each party) for comparing with the assessment results.

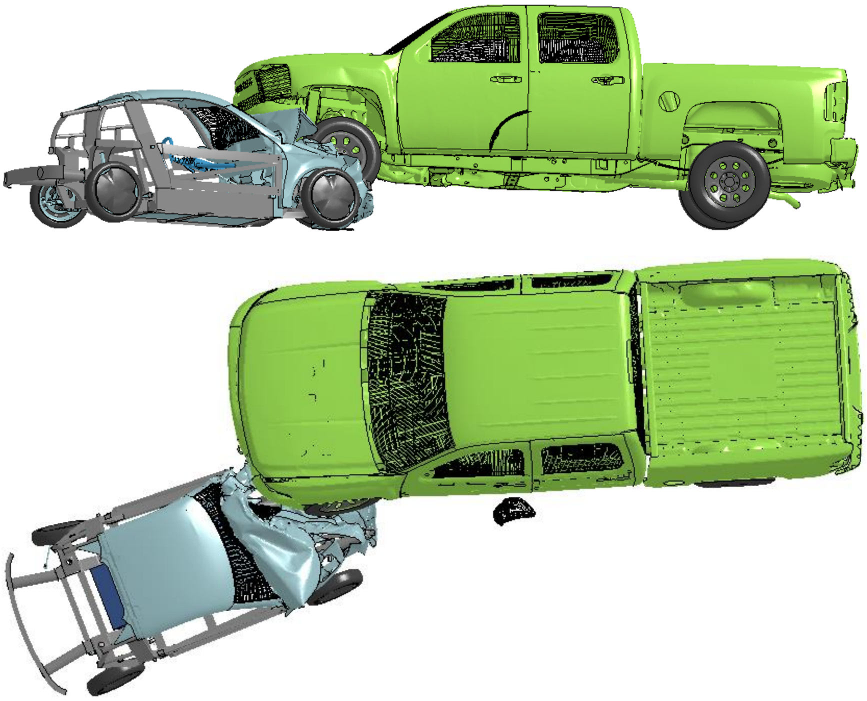


Figure F.26: Deformations of the optimized microcar and Camry in the car-to-car test at 90 km/h after 250 ms

Appendix G: Parameters of the Optimization's Generations

Tab. G.1 presents the parameter values of the optimum model in each generation.

Table G.1: Parameter values of the optimum model in each generation

No. of Parameter	Name of Parameter	Parameter values in mm						
		Original	Generation 1	Generation 2	Generation 3	Generation 4	Generation 5	Generations 6 to 22
1	ri_vl	18	18.1	18.8	18.8	18.8	18.8	18
2	sll	0	110	75	75	75	75	110
3	t_af	8	4	12	12	12	12	5
4	t_as	4	5.4	5.6	5.6	5.6	5.6	5.4
5	t_qto	2	2.6	1	1	1	1	2.6
6	t_qtu	2	1.8	2	2	2	2	1.8
7	t_s	4	3.4	5.8	5.8	5.8	5.8	3.6
8	t_sf	3	1.6	3.2	3.2	3.2	3.2	1.6
9	t_slt	3	1.6	2.2	2.2	2.2	2.2	1.5
10	t_ul	2	2.3	3	3	3	3	1.9
11	t_vst	2	2.8	1	1	1	1	2.8

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List of Abbreviations

ABC-I	Acceleration-Based Criterion for Intrusions
ADAC	In German: Allgemeiner Deutscher Automobil-Club In English: General German Automobile Club
AE-MDB	Advanced European Mobile Deformable Barrier
AHOF	Average Height of Forces
AIS	Abbreviated Injury Score
ASME	American Society of Mechanical Engineers
BASt	In German: Die Bundesanstalt für Straßenwesen In English: The German Federal Highway Research Institute
CCIS	Cooperative Crash Injury Study
CG	Center of Gravity
CR	Compatibility Rate
DDY	Digital Derivative in Y Direction
ECE	Economic Commission for Europe
EES	Energy Equivalent Speed
EEVC	European Enhanced Vehicle-Safety Committee
EEVC WG15	Enhanced European Vehicle-safety Committee Working Group 15
Euro NCAP	European New Car Assessment Program
FE	Finite Element
FIMCAR	The project Frontal Impact and Compatibility Assessment Research
FMVSS	Federal Motor Vehicle Safety Standard
FWDB	Full-Width Deformable Barrier
FWRB	Full-Width Rigid Barrier
GDV	In German: Gesamtverband der Deutschen Versicherungswirtschaft In English: The German Insurance Association
GIDAS	German In-Depth Accident Study
HIC	Head Injury Criterion
LCW	Load Cell Wall
LSTC	Livermore Software Technology Corporation
MDB	Moving/Mobile Deformable Barrier
MPDB	Moving Progressive Deformable Barrier
NASS	National Automotive Sampling System

NCAC	National Crash Analysis Center
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
ODB	Offset Deformable Barrier
OLC	Occupant Load Criterion
OR	Odds Ratio
PEAS	Primary Energy Absorbing Structures
PDB	Progressive Deformable Barrier
SafeEV	The project Safe Small Electric Vehicles through Advanced Simulation Methodologies
SEAS	Secondary Energy Absorbing Structures
SI	In English: international system of units
SL	Safety Level
StI	Structural Interaction
SUV	Sport Utility Vehicle
TNO	In English: The Netherlands organization for applied scientific research
TRL	Transport Research Laboratory of the United Kingdom
TUM	Technical University of Munich
UNECE	United Nations Economic Commission for Europe
VC-COMPAT	The project Vehicle Crash Compatibility
VDA	In German: Verband der Automobilindustrie In English: The German Association of the Automotive Industry
VDI	In German: Verein Deutscher Ingenieure In English: The Association of German Engineers

List of Symbols

Symbol	Unit	Description
a	g	Acceleration
α	g	Alpha (limit of the ABC-I)
β	J/kg	Beta (limit of the ABC-I)
bf	mm	Ground clearance of the vehicle
E_k	J	Kinetic energy
CR	%	Compatibility rate
CR_{act}	%	Active compatibility rate
F	N	Force
g	m/s²	Standard Gravity
hlt	mm	Height of PEAS
k	-	Coefficient of Restitution
llt	mm	Length of PEAS
lul	mm	Length of SEAS
M	Nm	Moment
m	kg	Mass
N	-	Population of a statistical analysis
ri-lt	mm	Inner radius of PEAS' profiles
ri_vl	mm	Inner radius of PS-Connection's profiles
s	mm	Displacement
SL	J	Safety level
sfl	mm	Length of Bumper
sll	mm	Extension of Side-Rails after Domes
t_af	mm	Thickness of Domes
t_as	mm	Thickness of A-Pillars
t_qto	mm	Thickness of SR-Connections
t_qtu	mm	Thickness of OC-Profile
t_s	mm	Thickness of Sills
t_sf	mm	Thickness of Bumper
t_slt	mm	Thickness of Side-Rails
t_st	mm	Thickness of S-Rails
t_ul	mm	Thickness of SEAS

Symbol	Unit	Description
t_vst	mm	Thickness of SR-Connections
v	km/h	Speed
v_2	m/s	Rebound velocity in a test
VC	m/s	Viscous compression
W	J	Work
x	mm	Displacement in X-direction

List of Supervised Student Research Projects

Multiple student research projects were supervised during the completion of this dissertation. Listed below are the student research theses relevant to this dissertation. Many thanks to all the involved persons for their extensive support in this research project.

[128] K. Wang, “Untersuchung und Validierung einer Auswertungsmethode für die aktive Sicherheit: In English: Investigation and validation of an evaluation method for active safety,” Semesterarbeit, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[139] M. Fischer, “Entwicklung eines Simulationsmodells der PDB und Durchführung einer Sensitivitätsanalyse: Development of a simulation model from PDB and conducting a sensitivity analysis,” Semesterarbeit, Chair of Automotive Technology, Technical University of Munich, Germany, 2014.

[161] D. Vietze, “Erstellung und Validierung eines parametrischen Modells mit Balkenelementen für ein Elektrokleinfahrzeug: In English: Creation and validation of a parametric model with beam elements for an electric Microcar,” Bachelor's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[162] T. Zuchtriegel, “Erstellung und Validierung eines parametrischen Modells mit überwiegend Diskreten-Elementen für Elektro-Kleinstfahrzeuge: In English: Creation and validation of a parametric model with mainly discrete elements for an electric microcar,” Bachelor's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[163] M. Huber, “Erstellung und Validierung eines parametrischen Modells zur Optimierung der Crash-Kompatibilität von E-Kleinstfahrzeugen mit Hilfe der Makroelement-Methode: In English: Development of a parametric macroelement-model for optimizing crash-compatibility of e-microcars,” Master's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2016.

[164] M. Fischer, “Untersuchung der Auswirkungen von sicherheitsrelevanten Optimierungsparametern auf das Fahrzeugkonzept: In English: Studying the effect of safety-related optimization parameters on the vehicle concept,” Master's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2016.

[178] H. Willmann, “Untersuchung der Güte von validierten Simulationsmodellen für neue Crash-Konstellationen: In English: Investigation of the quality of validated simulation models for new crash configurations,” Semesterarbeit, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[182] A. Bilic, “Verifizierung und Weiterentwicklung eines Definitionsmodels für die Sicherheit und Crash-Kompatibilität: In English: Verification and further development of a definition model for passive safety and crash

compatibility," Semester's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[183] R. Aranda Marco, "Sensitivity analysis of PDB test approach for crash compatibility with geometrical parameters of the test vehicle," Master Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2013.

[184] R. Ciardiello, "Sensitivity analysis of Advanced European Mobile Deformable Barrier using FE-Simulations," Master's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2014.

[185] E. Panaro, "Investigation on criteria for partner-protection in test with Mobile Deformable Barrier," Master's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2014.

[186] T. Herzog, "Crashanalyse über Kompatibilität der Elektro-Kleinstfahrzeuge: In English: Statistical analysis on crash compatibility of micro cars," Bachelor's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2014.

[187] A. Koch, "Analyse der Strukturvarianten für Elektrokleinstfahrzeuge: In English: Analysis of electric micro cars' structures," Bachelor's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2014.

[188] C. Mijatov, "Entwicklung und Validierung eines generischen Simulationsmodells von einem E-Kleinstfahrzeug: In English: Development and validation of a generic simulation model of an e-microcar," Master's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2015.

[189] B. Danquah, "Analyse von Crash-Pulsen und Identifikation deren Merkmale bei Kollisionen mit Kompatibilitätsproblemen: In English: Analysis of crash pulses and identification their characteristics in collisions with compatibility problems," Semester's Thesis, Chair of Automotive Technology, Technical University of Munich, Germany, 2016.

List of Own Publications in Context of this Thesis

During the preparation of this thesis, following publications are established under substantial scientific, technical and substantive guidance of the author. The results incurred are partially taken up in the present work. Thanks to all involved persons for their support in this research project.

[113] E. Sadeghipour, A. Bilic, and M. Lienkamp, "Proposal of a Fundamental Definition for Crash Compatibility," in *Fahrzeugsicherheit - Sicherheit 2.0: 10. VDI-Tagung: Berlin, Germany, 25. and 26. November*, 2015, pp. 23-35.

[129] E. Sadeghipour, F. Duddeck, and M. Lienkamp, "Crash Compatibility of Microcars: A Study on Current Test Approaches," in *crash.tech*, Munich, Germany, 2014.

[130] E. Sadeghipour, R. Ciardiello, M. Fischer, F. Duddeck, and M. Lienkamp, "Critical Review of the Current Assessment Approaches for Frontal Crash Compatibility Regarding the Evaluation of Structural Interaction," in *24th ESV*, Gothenburg, Sweden, 2015.

[148] E. Sadeghipour, B. Danquah, and M. Lienkamp, "Acceleration-based criterion for intrusions in frontal impacts," *International Journal of Crashworthiness*, pp. 1–12, 2016.

[165] E. Sadeghipour, E. J. Wehrle, and M. Lienkamp, "An Approach for the Development and the Validation of Generic Simulation Models for Crash-Compatibility Investigations," *SAE Int. J. Trans. Safety*, vol. 4, no. 2, 2016.

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[13] M. Edwards, M. Wisch, C. Pastor, J. Price, J. Broughton and T. Adolph, “D1.2: Report detailing an estimation of the costs and benefits of improved car-to-car compatibility on a national and European scale,” EU Research Project FIMCAR, 2012.

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