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FIMCAR

I - Summary Report



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EXECUTIVE SUMMARY

The goal of the FIMCAR (Frontal Impact and Compatibility Assessment Research) project was to propose a frontal impact assessment approach addressing self- and partner protection. Research strategies and priorities were based on earlier research programs and the FIMCAR accident data analysis looking at modern cars. The identified real world safety issues – such as structural interaction (especially under-/override), high acceleration loading of the occupant especially in large overlap accidents and insufficient horizontal and vertical load spreading were used for evaluating the different test candidates. In addition to the issues mentioned above, the FIMCAR accident analysis suggested that frontal force compartment integrity matching is less of an issue as originally expected.

FIMCAR developed a car-to-car test program that investigated the performance of vehicle structures. Results of the test program show that the presence of a lower load path contributes to a more robust performance of the vehicle. The rearward offset of a lower load path could be reviewed and used to quantify when a lower structure design can contribute to structural interaction in both frontal and side impact configurations.

In addition to the car crash test programme, numerical models of actual cars and barriers were developed and used. As car-to-car simulations with models of different car manufacturers are almost impossible because of confidentiality, Parametric Car Models (PCM) and Generic Car Models (GCM) were developed. Due to the parametric design of the PCMs it is possible to modify the models in an easy and fast way. The GCMs model virtual cars which represent an average real car of the respective category in a comparable way to the OEM models.

Within the FIMCAR project, different frontal impact test candidates were analysed regarding their potential for future frontal impact legislation. The research activities focused on car-to-car frontal impact. Test procedures were developed with both a crash test programme and numerical simulations.

This analysis resulted in the combination of the Full Width Deformable Barrier test (FWDB) with compatibility metrics and the existing Offset Deformable Barrier (ODB) as described in UN-ECE Regulation 94 with additional cabin integrity requirement as being proposed as the FIMCAR assessment approach. The advantages of the FWDB compared to the rigid wall are the more representative pulse and deformation pattern as well as the better assessment of load paths. The introduction of a (M)PDB without compatibility metrics (that FIMCAR was unable to deliver in time) was considered as not being appropriate.

The proposed frontal impact assessment approach addresses many of the issues identified by the FIMCAR consortium (impact alignment, high acceleration pulse loading, maintenance of compartment strength requirements, etc.) but not all frontal impact and compatibility issues could be addressed (load spreading). A benefit analysis estimated the benefit of the following three options: no change, introduction of full width test with compatibility assessment in addition to current ECE R94 and introduction of full width test with compatibility assessment and replacement of current ODB test by PDB test with load spreading metric. The comparison of calculated break even costs for option 2 with estimated costs for achieving the benefit from previous projects suggests a positive cost benefit ratio.

1 PROJECT CONTEXT AND MAIN OBJECTIVES

Crash compatibility has long been promoted as a key component in improving vehicle safety. Although compatibility has received worldwide attention for many years, no final assessment approach has been defined. FIMCAR (Frontal Impact and Compatibility Assessment Research) was a research project to address compatibility test procedures. The objective of the project was to answer the remaining open questions identified in earlier projects (such as understanding the advantages and disadvantages of force based metrics and barrier deformation based metrics, confirmation of specific compatibility issues like structural interaction, investigation of force matching) and to finalise the test procedures required to assess compatibility. Within the project, the research activities focused on car-to-car frontal impact accidents. However, other configurations such as lateral impact, car-to-HGV accidents etc. were also considered to ensure that changes made to cars to improve their compatibility in frontal impacts are not detrimental for other impact types.

Improvement of road safety is one of the major aims of road authorities, vehicle manufacturers, rescue organisations and research organisations amongst others. Measures to improve safety are historically divided into the area of active/primary safety (measures that help to avoid the occurrence of accidents) and passive/secondary safety (measures that help to reduce the consequences of accidents).

In the 27 EU member states, road fatalities are still a major cause of death although important safety improvements have reduced the number of killed people since 1990, see Figure 1.1. It should be noted that almost 50% of the 2008 road fatalities of the 27 EU member states were car occupants (Figure 1.2).

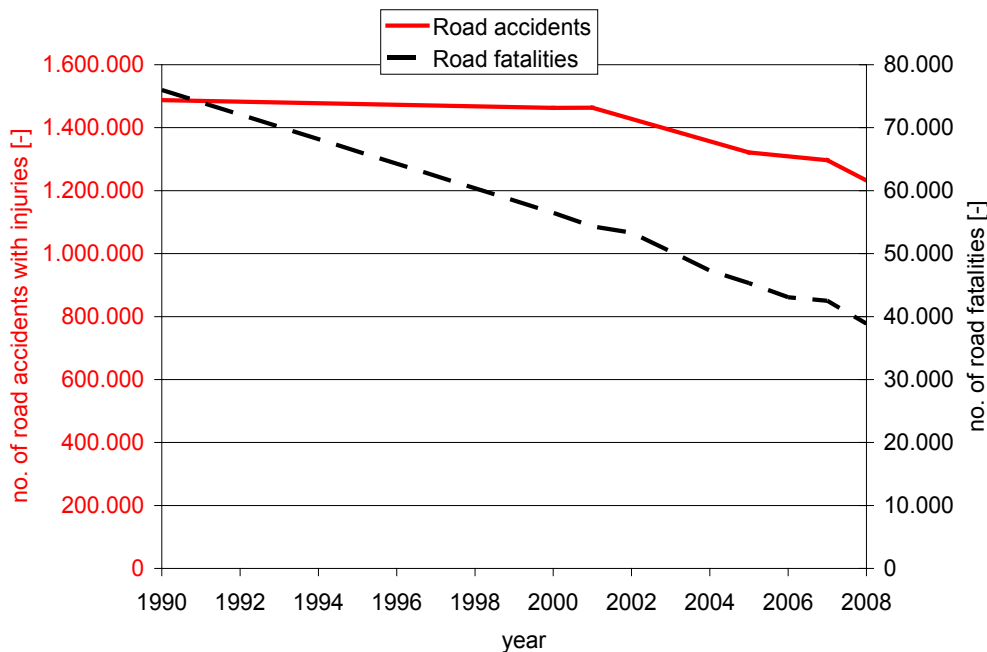


Figure 1.1: Development of road accidents causing injuries and road fatalities in EU27 [Nicodème 2010].

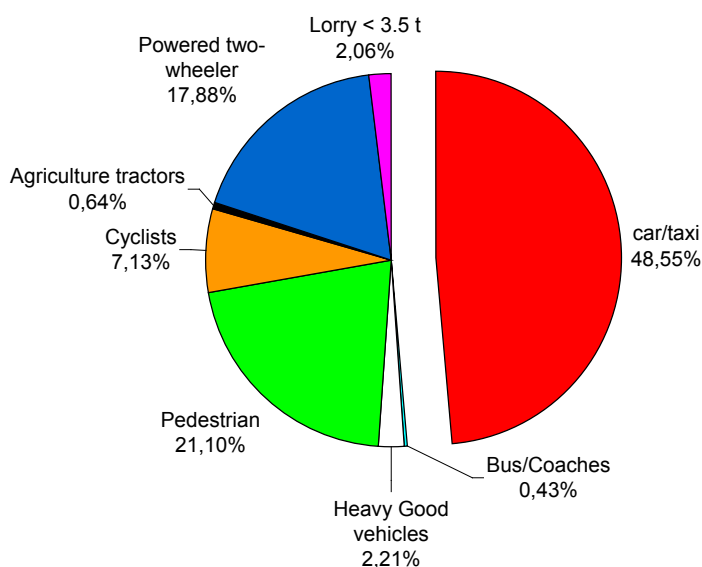


Figure 1.2: Distribution of road fatalities amongst road user categories 2008 in EU27 [Nicodème 2010].

The passive safety capabilities of cars are mainly assessed by crash tests. Currently different frontal test procedures are used in the different regions of the world. The most important test procedures are:

- Off-set test (40% of vehicle width) against a deformable element as currently used for homologation of cars in Europe (ECE R 94), the consumer information test program Euro NCAP, the US insurance company IIHS and others
- Full width test against rigid wall as currently used for homologation of cars in the US (FMVSS 208), the consumer information program US NCAP, homologation of cars in Japan and others

After the introduction of these tests, in particular the offset test, the safety performance of cars has improved in terms of test results. However it appears that cars rated good or excellent in the test programmes do not always perform well in car-to-car accidents. This behaviour was attributed as incompatibility between cars. It is this characteristic that was deemed important to assess and initiated different research activities.

Crash compatibility sometimes is a compromise between self and partner protection and it is important to not sacrifice one for the sake of the other. Compatibility will be used in the following document as a concept that is a combination of both self and partner protection. To break down the problem into specific issues, individual compatibility characteristics are identified that address only one aspect of frontal impacts i.e. self or partner protection. The goal of the project was then to identify the suite of tests that address all the important compatibility characteristics.

Compatibility is a global problem and research activities have taken place predominantly in the US, Japan and Europe. In all these areas, the activities are distributed between industry and government funded research activities. Different test methods have been investigated in the various regions but the global consensus in the IHRA compatibility working group [O'Reilly 2003] is that both an off-set and a full-width test are needed to fully assess

compatibility and frontal protection performance. Each region has unique compatibility issues related to their respective traffic fleets, but similar strategies and approaches can be observed. A number of test alternatives are available for further development. An overview of the activities previous to FIMCAR is provided below.

European compatibility research has been undertaken at various research centres but the most significant activities have been coordinated by or reported to the EEVC WG15 (European Enhanced Vehicle Safety Committee Working Group 15 (Frontal Impact Compatibility)). This working group finished a mandate to investigate the test procedures needed to assess crash compatibility [Faerber 2007]. The working group results confirm that improving compatibility will have positive cost benefit results for Europe. Test methods to detect and assess compatibility were investigated with a focus on developing structural interaction assessments. The difficulty in defining an objective test approach for structural interaction was encountered by the working group. A list of open questions was developed, identifying the next steps needed to finalise compatibility test approaches.

One recent activity to note is the development of a moving deformable barrier test using a deformable element. This test method has been put forward by many researchers in Europe, USA and Japan as a long term solution to compatibility and has been reported previously [Summers 2002; Seyer 2003; Versmissen 2006].

Compatibility issues in the US are dominated by LTV/SUV (Light Truck Vehicles / Sport Utility Vehicles) impacts with smaller passenger cars. The most noteworthy development has been the industry voluntary commitment (coordinated through the Alliance of Automobile Manufacturers) [Auto Alliance 2003] to provide geometric overlapping of structures in frontal impacts, particularly in LTV to passenger car impacts. The commitment was initiated in 2003 and required 100% compliance for vehicle geometric designs by 2009. Parallel to the geometric requirement for structures, research into the parameters controlling compatibility has been investigated, including physical test requirements. One of the test methods under investigation is the high resolution load cell barrier that measures the force distribution over the vehicle front during a full width barrier test. This test approach is also under investigation by NHTSA and metrics such as the Average Height of Force (AHOF), Initial Stiffness (Ks), and Work Stiffness (Kw) have been derived from this type of test data and correlated to real world crashes [Summers 2005]. The US stakeholders have focussed their research efforts on the Full Width Rigid Barrier (FWRB) because it is the foundation of its frontal impact regulation. Most full width tests and analyses in the US have been for rigid barrier face.

Further work in frontal compatibility testing has been proposed in the Auto Alliance expert working group. The implementation of a moving deformable barrier for frontal crash testing had been investigated since the 1990's and has now been reviewed as method to control the frontal force levels in vehicles as well as addressing structural interaction. Further developments of this MDB have not been reported since 2008 although applications of an MDB for small overlap conditions has been under recent development [Saunders 2012].

The Japanese vehicle fleet, similar to Europe, is not characterised by a large LTV/SUV population that is found in the US. However, a particular difference in the Japanese and European vehicle fleet is the presence of so called mini cars in Japan that are designed to offer maximum internal space for a limited vehicle length. These cars normally have their

bumper directly in front of the engine and do not incorporate any kind of crush can in the design because repair tests i.e. the RCAR (Research Council for Automobile Repair) bumper test, are not applicable. Legislative and consumer tests in Japan are based on the Full Width Rigid Barrier test and the recent adoption of the UNECE R94 offset test. The Japan Automobile Research Institute (JARI) as well as Honda has presented recent investigations of the use of load cell wall data as a method to assess compatibility. Alternative test approaches (with or without deformable honeycomb barriers) have been assessed and compared to car-to-car tests.

The Japanese automobile industry has investigated different testing or evaluation approaches. Toyota has researched the moving deformable barrier test for frontal impacts, partly in conjunction with the US industry research activities, and has developed a specific deformable element more complex than the EEVC or PDB barrier element. Analysis of load cell wall data from a full width test has also been proposed [Yonezawa 2011]

Previous research work on compatibility (e.g., EUCAR Compatibility project [Zobel 2001], EEVC WG 15 [Faerber 2007], VC-COMPAT [Edwards 2007] and other international and national research projects and working groups) has shown the main issues for improving compatibility are:

- Structural interaction
- Global force level matching
- Compartment strength and stability

The two most challenging compatibility issues were *structural interaction* and *global force matching*. Structural interaction describes how the contact forces are distributed across collision partners and the stability of the deforming structures. Good structural interaction is not commonly found in modern vehicles due the differences in vehicle sizes and crashworthiness designs. Poor structural interaction leads to phenomena such as over/underride or fork effect which in turn lead to undesirable deformation and intrusion of the occupant compartment. Frontal force level matching is desirable to ensure that crash energy is appropriately shared between collision partners. Current international consumer and regulation test methods cause frontal crush forces to be mass dependent and require heavier vehicles to be stiffer than lighter vehicles. Earlier studies found this disparity in vehicle force levels caused heavier vehicles to over-crush lighter vehicles and produce undesired occupant compartment deformations. The two compatibility characteristics described above require a *strong and stable occupant compartment* to support energy absorption in frontal structures.

One explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility. An improved and more detailed description of compatibility characteristics is a key point to base any research project that addresses compatibility. For example, structural interaction can likely be divided into different sub areas dealing with geometric placements of structures or the way structures are internally distributing loads in the car. Until a terminology is commonly agreed on, there will be difficulty to design and evaluate a test approach with a general description like structural interaction.

The FIMCAR project worked with two main research activities. One was to develop an evaluation strategy for selecting some combination of suitable test configurations and the second was the technical development activities of specific test candidates. The first activity required terminology, priorities and selection criteria. The second involved crash testing, computer simulation and data processing to develop test procedures as well as assessment criteria and performance limits.

The FIMCAR project was designed to investigate the possibility of combining different configurations to assess compatibility. These tests are the Full Width Rigid Barrier (FWRB), Full Width Deformable Barrier (FWDB), Offset Deformable Barrier (ODB), Progressive Deformable Barrier (PDB) and a Mobile Deformable Barrier (MDB). To achieve this objective the following sub-objectives needed to be addressed:

- to analyse the accident situation of recent cars in order to check whether or not the frontal impact issues reported in previous projects are still relevant in ECE R94 compliant cars
- to identify critical injury mechanisms in frontal impacts
- to define frontal impact issues that should be addressed by the FIMCAR assessment approach
- to develop a rating approach for the individual assessment procedures and the proposed assessment approach
- to further develop off-set, full-width and MDB procedures including their crashworthiness metrics
- to assess different measures to achieve increased compatibility including numerical simulation and vehicle-to-vehicle and vehicle-to-barrier testing
- to develop assessment approaches for vehicle-to-vehicle (M1 vehicle with a total permissible mass less than 3.5 t) frontal compatibility – off-set, full overlap and MDB tests, taking into account overall safety in accident environment
- to propose an assessment approach for vehicle-to-vehicle compatibility aiming at regulation process
- to develop generic and parametric fleet models suitable for the assessment of compatibility (e.g. by improvements of existing generic car models developed within the APROSYS project)
- to analyse the future benefit of using Virtual Testing for the assessment of frontal impact performance
- to harmonise guidelines and regulations within Europe as well as globally with the USA, Japan and other countries
- to conduct a benefit analysis for compatible cars promoted by new compatibility test methods environment
- to develop a methodology for predicting future fleet characteristics

2 MAIN RESULTS

2.1 Accident Analysis

The specific objectives of the accident analysis work were:

- Determine if previously identified compatibility issues are still relevant in current vehicle fleet
 - Structural interaction
 - Frontal force matching
 - Compartment strength in particular for light cars
- Determine nature of injuries and injury mechanisms
 - Body regions injured
 - Injury mechanism
 - Contact with intrusion
 - Contact
 - Deceleration / restraint induced

The main data sources for this accident analysis study were the CCIS and Stats 19 databases from Great Britain and the GIDAS database from Germany. The different sampling and reporting schemes for the detailed databases (CCIS & GIDAS) sometimes do not allow for direct comparisons of the results. However the databases are complementary – CCIS captures more severe collisions highlighting structure and injury issues while GIDAS provides detailed data for a broader range of crash severities. The following results represent the critical points for further development of test procedures in FIMCAR

Compatibility issues

- Poor structural interaction has been observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.
 - In CCIS, structural interaction problems were identified in 40% of fatal and 36% of MAIS 2+ injured cases. However, it is only in cases where there was intrusion present (25% of fatal and 12% of MAIS 2+ cases) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. This is because in cases with intrusion improved structural interaction will increase the energy absorption capability of the car's front-end and thus reduce the intrusion. This, in turn, will help decrease the casualty's injuries caused by contact with intrusion. In cases without intrusion improved structural interaction will change the shape of the compartment deceleration pulse which may or may not help decrease the casualty's injuries depending on the response of the restraint system.

It should be noted that in 23% of the CCIS fatal cases the accident severity was so high that it was not possible to determine whether or not a compatibility issue had occurred.

- Frontal force and/or compartment strength mismatch issues between cars in the current fleet appear¹ to be less of an issue than poor structural interaction.

¹ Note: structural interaction problems could be masking frontal force mismatch problems

- In CCIS, for all accidents, force and/or compartment strength mismatch problems were identified for 8% of fatal and 2% MAIS 2+ survived occupants. However, it should be noted that force and/or compartment strength mismatch problems can only be objectively identified for accidents in which there is compartment intrusion into the vehicle.
- In CCIS, for car-to-car impacts force and/or compartment strength mismatch problems identified for 9% of fatal and 3% MAIS 2+ survived occupants
- Compartment strength of vehicles is still an issue in the current vehicle fleet.
 - Occupants with injuries caused by contact with intrusion CCIS 25%, GIDAS 12% of MAIS 2+ injured occupants
 - When an occupant sustains an injury caused by 'contact with intrusion' in the majority of cases it is the most severe injury, often a leg or thorax injury but sometimes a head or arm injury.
- In a matched pair analysis of car-to-car impacts a relationship was found between mass ratio² and driver injury severity, namely the higher the mass ratio the higher the driver injury severity. However, no such relationship was found between mass ratio and intrusion. The implications of this are that intrusion (and hence compartment strength) is not the major contributory factor to more severe injuries in the lighter car in a car-to-car impact. However, it should be noted that the data sample used for this analysis was relatively small and hence confidence in this result is limited. In addition the result may have been confounded by the age of the vehicle (newer vehicles generally have better compartment integrity) and the age of the occupant.
- Compartment strength is a particular problem in collisions with HGVs and objects, with these collisions having a high proportion of fatal and MAIS 2+ injuries
 - In CCIS, 31% of car-HGV cases resulted in intrusion in the car, compared to 25% for car-to-car cases
 - In GIDAS, 20% of car-HGV cases had MAIS 2+ injury severity for the car occupant, compared with 7% for car-to-car cases

Injury patterns

- AIS 2+ injuries to the thorax are the most prevalent. AIS 2+ injuries are also frequently sustained by the head, legs and arms.
 - Over 80% of fatally injured occupants and 35% of MAIS 2+ survived occupants sustained AIS 2+ thorax injuries in CCIS
- AIS 2+ injuries related to the restraint system (i.e. those caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injury by contact with other car interior structures) are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not.
 - Over 40% MAIS 2+ occupants sustained AIS 2+ injury attributed to restraint loading in both CCIS and GIDAS datasets.
- Analysis of injury mechanisms in CCIS found that 45% of MAIS 2+ injured occupants had an AIS 2+ injury related to the 'restraint system', 40% had an AIS 2+ injury caused by 'contact with no intrusion' and 25% had an AIS 2+ injury caused by 'contact with

² mass ratio above 1 means that the partner vehicle is heavier

intrusion' In the majority of cases these injuries were the most serious injuries that the occupant had.

- When the most severe injury was related to the 'restraint system' the injury was mainly to the thorax (62%) with some to the arms (21%) (clavicle fractures).
- When the most severe injury was related to the 'contact no intrusion' the injury was mainly to the legs (42%) with some to the arms (30%) (clavicle fractures) and thorax (12%).
- When the most severe injury was related to the 'contact with intrusion' the injury was mainly to the legs (46%) and thorax (30%).
- For accidents for which there is intrusion, for MAIS 2+ injured occupants AIS 2+ injuries to the legs are the most prevalent
 - Where intrusion was present about 70% MAIS 2+ occupants sustained AIS 2+ leg injuries in CCIS
 - Note: about 40% sustained AIS 2+ thorax injuries
- AIS 2+ injuries resulting from contact with the intrusion occur in a large proportion of cases where compartment intrusion is present
 - 65% of MAIS 2+ occupants in cars with intrusion sustained AIS 2+ injury attributed to contact with intrusion (CCIS)
- High proportion of fatal and MAIS 2+ injuries in cases with high overlap (>75%)
 - In GIDAS, 41% of MAIS 2+ survived were in high overlap cases
 - In CCIS, 40% of MAIS 2+ survived and 31% of fatal occupants were in crashes with high overlap
- GIDAS analysis showed that the proportion of MAIS 2+ injuries due to acceleration loading (i.e. injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures) increased for higher overlap cases, whilst proportion of MAIS 2+ injuries due to contact with intrusion increased for lower overlap cases
 - In GIDAS 25% of MAIS 2+ survived were in low overlap cases indicating possible issues with low overlap and/or narrow object impacts. However, much lower percentages were seen in car-to-car impacts and CCIS data.
- Greater proportion of fatal and MAIS 2+ injuries for elderly occupants compared with other age groups
 - In CCIS dataset, occupants over 60 years old represent 18% of injured occupants, however account for 52% of fatalities and 25% of MAIS 2+ survived occupants
- In GIDAS, serious injuries (AIS 2+) due to acceleration loading (restraints) could be identified to occur more often for women than men and are linked with slightly higher proportions for front passengers than drivers.

2.2 Test Selection Approach

One explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility. An improved and more detailed description of compatibility characteristics is a key point to base any research project that addresses compatibility. For example, structural interaction can likely be divided into different sub areas dealing with geometrical placements of structures or the way structures

are internally distributing loads in the car. Until a terminology is commonly agreed on, there will be difficulty to design and evaluate a test approach with a general description like structural interaction.

From a review of previous research and additional accident analysis, FIMCAR members have established and defined a list of issues that describe the challenges in vehicle crashworthiness. The consortium agreed that:

- Compatibility consists of self and partner protection.
- Improved compatibility will decrease the 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.

It is important to separate the physical test process from the assessment of the test results for a test configuration. The assessment of compatibility comes when a combination of test configurations and assessment procedures are used to evaluate vehicle performance. The following definitions were developed within FIMCAR to address technical test developments:

- The *test procedure* specifies the test protocol which includes the barrier face, test speed, overlap etc. That means that the test procedure is also a description of how the test is executed.
- The *assessment procedure* includes the test procedure and the definition of the compatibility metrics. The signal processing requirements and performance criteria are identified.
- The *assessment approach* is then the final combination of the assessment procedures that should evaluate the total safety performance of a vehicle for partner and self protection issues.

In order to address compatibility, a detailed list of compatibility characteristics were identified and prioritised by the consortium.

A frontal impact and compatibility description and prioritisation approach was started early in the FIMCAR project. The issues were divided into 4 main groups: Structural Interaction, Compartment Strength, Frontend Force / Deformation, Deceleration Pulse and Restraint System Assessment. These groupings were further broken down into sub groups to focus the test candidate development. The items listed in Figure 2.1 could be identified in previous research activities. Some of the subtopics could be identified as self protection or partner protection issues and the main idea was to provide a comprehensive description of all frontal impact issues. In brief:

- Structural Interaction describes how the structures of a vehicle deform at the local level when interacting with a collision partner. To achieve good structural interaction there must be some type of *structural alignment* which requires that there are corresponding structures in each collision partner that are geometrically and structurally capable of interacting with the opponents main crash structures. It is preferable that this alignment occurs as early as possible in the crash to maximise the energy absorption and ride down characteristics for the occupant. As it is not possible to achieve good structural alignment for all possible collision types and

collision partners, it is desirable to have good *horizontal and vertical load spreading* so that a robust and stable deformation of all structures can be facilitated.

- Compartment Strength is important to ensure the passenger compartment is free of intrusions and that the frontal energy absorbing structures have a stable reaction base. All vehicles must exhibit good compartment *integrity in single vehicle collisions* such as crashes into objects and HGV. Smaller vehicles have extra risks when colliding with heavier vehicles and one can identify the need for some vehicles to have higher requirements for compartment *integrity for self protection in vehicle-to-vehicle collisions*.
- Front End Force/Deformation Characteristics have two complementary functions depending on the vehicle mass. There is a clear relationship between vehicle deformation forces and vehicle size and there is an interest to control the *deformation forces in frontal structures* when different vehicles collide. Although difficult to guarantee, it is important to not create situations where one vehicle is too stiff and over-crushes a partner vehicle and exploits the energy absorption of the partner vehicle before its own energy absorption processes begins. Similarly it is not desirable to create a vehicle that does not deform in, for example, a single vehicle impact. Insufficient *energy absorption management* will produce vehicles that do not suitably protect an occupant. One can view deformation forces in frontal structures as a means to ensure partner protection and energy absorption management as a self protection issue.
- Deceleration Pulse and Restraint System issues are important parts of a vehicle safety assessment. It is desirable to evaluate the *sensing system for deployable systems* to different crash pulses and deformation patterns to avoid single point optimisation of safety performance. There should also be sufficient *capacity of restraint system* so that an occupant is protected for a high severity impact that could be foreseen. An additional point that is interesting to investigate (but may be difficult to implement as a regulation) is the *evaluation of occupant safety in a partner vehicle*.

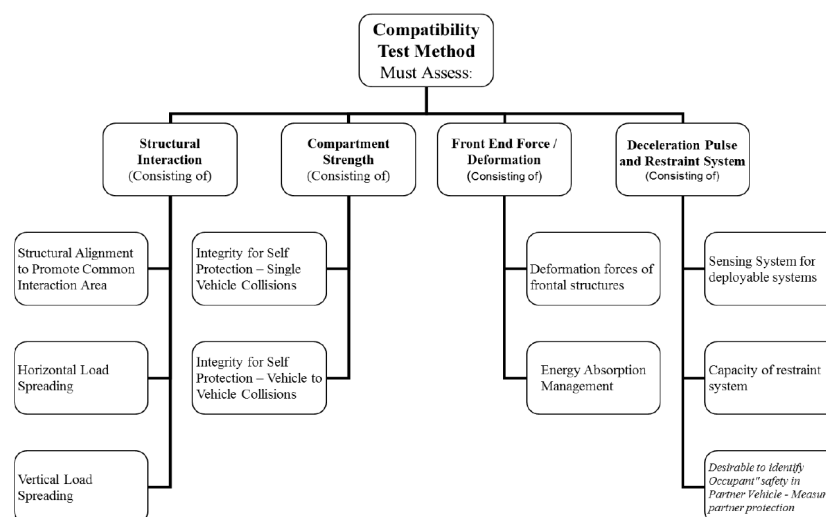


Figure 2.1: Compatibility characteristics.

The main sources for establishing the priorities and selection criteria were the FIMCAR accident analysis analysing frontal impact accidents of UN-ECE Regulation 94 compliant cars

(FIMCAR Deliverable D1.1 [Thompson 2013]) and the experts present in the FIMCAR meetings.

The high proportion of MAIS 2+ injuries in accidents with large overlap reinforced the need for a test condition that requires a vehicle safety system (comprising the frontal structural and occupant restraint system) is able to withstand a high deceleration, large overlap condition that is not addressed by the current UN-ECE Regulation 94 requirements. Based on the information in Figure 2.1 and FIMCAR Deliverable D1.1 [Thompson 2013], an updated list of critical compatibility requirements could be developed. In addition, the top level issues described in Figure 2.1 could be reviewed and prioritised in the format shown in Table 1.

Table 1: Main compatibility topics and associated priorities.

| | Assessment requirements | | | | | | | |
|-----------------------|-------------------------|---|---|------------------------------|--|--|-------------------------------|-------------------------|
| | Structural Interaction | | Front End Force / Deformation (Consisting of) | | Compartment integrity | | Restraint system | |
| | Alignment | Load Spreading (Load paths / connections) | Deformation forces of frontal structures | Energy Absorption Management | Sufficient for single vehicle accident | Enhanced for light vehicles in vehicle to vehicle accident | (Assess over range of pulses) | Test Restraint Capacity |
| Priorities For FIMCAR | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 |

Priority 1 items are those that the consortium identified as important for FIMCAR to resolve within the project while Priority 2 items were important but deemed not critical to resolve during the project duration. The most interesting points to note were that the *Deformation forces of frontal structures* and *enhanced compartment strength for light vehicles in vehicle-vehicle issues* were not a high priority for FIMCAR. This is due to the result from the FIMCAR Deliverable D1.1 [Thompson 2013] where smaller cars were not found to have a higher risk of intrusion than heavier vehicles. Although this was a conclusion in earlier studies [Faerber 2007], evolution of vehicle safety is resulting in stronger vehicle compartments. As lighter vehicles were not found to have a higher risk of compartment intrusions, even for heavier crash partners, frontal force differences between vehicles were not as critical as perceived earlier. This is a conclusion from a limited dataset and it should be noted that there is still a higher injury risk for small vehicle occupants in car-to-car crashes. Further work is needed to make definitive conclusions but the injury risk for small vehicles seems to now be more related to the higher delta-v a small car experiences rather than its structural capacity.

Table 2: Evaluation criteria and associated priorities.

| Priority 1 | Priority 2 |
|---|---|
| 1 A common interaction zone defined as 406-508 mm (based on US Part 581 zone) | 5 Vertical load spreading above 508 mm |
| 2 Initial Loading of barrier is evaluated above and below 457 mm | 7 Horizontal load spreading beyond longitudinal members |
| 3 Vertical Load spreading evaluated in Part 581 zone | 10 Address mass dependent injury risk |
| 4 Vertical Load spreading evaluated between 180 and 406 mm | 12 Two different pulses for restraint system triggering |
| 6 Horizontal load spreading between longitudinal members | 13 Two different pulses for restraint system capacity |
| 8 Current compartment strength requirements maintained | |
| 9 Appropriate severity levels for occupant protection | |
| 11 Field Relevant pulses in the tests | |
| 14 Monitor crash pulses from all test configurations | |
| 15 Acceptable Repeatability/Reproducibility performance | |
| 16 Appropriate pass/fail thresholds | |
| 17 No step effects in metrics | |
| 18a) Good cars as rated good | |
| 18b) Poor cars as rated poor | |
| 19 Detection of vehicle architecture | |

Project discussions of the accident analysis and compatibility requirements and priorities led to a ranking of priority 1 and priority 2 issues that were evaluated in the project, presented in Table 1.

| | Item 1 | Item 2 | Item 3 | Item 4 | Item 6 | Item 8 | Item 9 | Item 11 | Item 14 | Item 15 | Item 16 | Item 17 | 18 a) | 18 b) | Item 19 |
|------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|-------|-------|---------|
| PDB | | | | | | | | | | | | | | | |
| ODB | | | | | | | | | | | | | | | |
| MPDB | | | | | | | | | | | | | | | |
| FWDB | | | | | | | | | | | | | | | |
| FWRB | | | | | | | | | | | | | | | |

Figure 2.2: Potential of test procedures.

The issues in Table 2 became the basis for evaluating the different full-width and offset test procedures and to see which combination of test and assessment procedures can provide a complete assessment approach for frontal impact and compatibility. The different load cases created in the full-width and offset test configurations facilitates the evaluation of different compatibility characteristics. The potential for each test method is illustrated in Figure 2.2. The benefits and limitations of the different test procedures are apparent and, more importantly, the inability of a single test procedure to fulfil all 15 priority 1 requirements. The main weakness of the offset tests is the ability to assess structural alignment in the beginning of a crash (Item 2) while the full width tests do not suitably assess compartment strength (Item 8).

2.3 Car-to-Car Test Results

The assessment of compatibility in frontal impacts has to address the importance of different vehicle structures. A critical component in the assessment is to identify, quantitatively, what constitutes good performing structures. In particular, the concepts of structural alignment and structural interaction needed to be investigated. Structural alignment is incorporated in candidate compatibility assessments to achieve geometric alignment of identifiable crashworthiness structures. Structural interaction is also a global assessment of how structures interact with a collision partner. The performance of lower vehicle structures in a crash has been identified as important as they may not be evaluated in a structural alignment assessment, but can contribute to structural interaction and thereby improve collision outcome. There has been, however, no clear definition of the characteristics for lower load paths that improve vehicle safety and how these structures manifest themselves in proposed test procedures.

FIMCAR has developed a vehicle crash test program that investigates the performance of vehicle structures using three different test series. The first test series used Super-mini vehicles with different front end architectures. These tests with and without, geometric alignment allowed the effectiveness of a lower load path to be compared to a case without a lower load path. A second set of tests investigated the importance of lower load paths for SUV type vehicles where the main front structures may not align with the main structures in a collision partner, but a lower load path may offset the consequences of this initial misalignment. A final test series investigated how the lower load paths in higher SUV type vehicles influence safety in side impact conditions and thus identify potential side effects of a new assessment procedure.

Results of the test program show that the presence of a lower load path contributes to a more robust performance of the vehicle. The rearward offset of a lower load path could be reviewed and used to quantify when a lower structure design can contribute to structural interaction in both frontal and side impact configurations.

2.4 Simulation Models

In order to reduce testing efforts numerical simulation is a reliable tool for the assessment and optimisation of car design. However, compatibility is an issue exceeding the borders of the vehicle fleet of one manufacturer. Due to confidentiality of the FE models and different software codes at different OEMs it is impossible to crash car models of different manufacturers with each other. To overcome these important limitations, two different approaches for common target vehicles within the FIMCAR project were developed. The Generic Car Models (GCM) are detailed numerical models which represent average cars within different vehicle categories (super-mini, small family car, executive car). Although they are models of cars which will never actually be built, i.e. virtual prototypes, they are of a comparable standard to the models that OEMs build of their cars. The Parametric Car Models (PCM) are also representing average cars of each category but are modelled in a simplified and parametric way. This latter approach allows reduced computational efforts and fast modification of the models.

The GCM models were developed from the three models originally generated by CRF within the past EC project APROSYS, in which the concept of a generic car model was adopted for

the first time. These models were successfully used in the research conducted by several partners of that Consortium. For FIMCAR use, these original models were modified and improved with special focus on the front structure design. The overall number of vehicle models was increased with the addition of model variants. For super-mini and small family categories, two models were generated in each class in order to describe the two main architectural/structural car variants that can usually be found on the road, i.e. with and without a third load path in the frontal frame (structural elements below the main rails). The availability of both structural solutions in the GCMs is important for the study of compatibility issues.

Five different models were generated within FIMCAR (2 super-minis, 2 small family cars and one executive). Three different FE codes (LS Dyna, PAM-Crash and RADIOSS) were used to address the software codes used by the consortium. The models can be used to evaluate the behaviour of the crash structure (e.g., crash pulse, deformation characteristics and intrusions). However, no restraint systems are included in the models thus no assessment of dummy readings is possible. For the assessment of the occupant loading conditions the evaluation of the crash pulse and compartment intrusions is necessary.

The model development work consisted mainly of an engineering activity operated on the vehicle models in order to obtain realistic crash behaviour in frontal crashes (full width and offset rigid barriers). Once this realistic behaviour had been obtained from the models in one code environment (LS-Dyna), then the models were translated in the other environments (Radioss and Pam-Crash). The correlation of results between code versions were verified and improved to the levels judged appropriate for the studies to be conducted within the project.

GCMs behave in a realistic manner; this realistic behaviour is the target that guided all their development work and that represents their validation. As the full width rigid barrier test is one of the two crash configurations used for the development of GCMs, comparison with publicly available US NCAP crash test data was used. Figure 2.3 shows the front design of the GCMs.

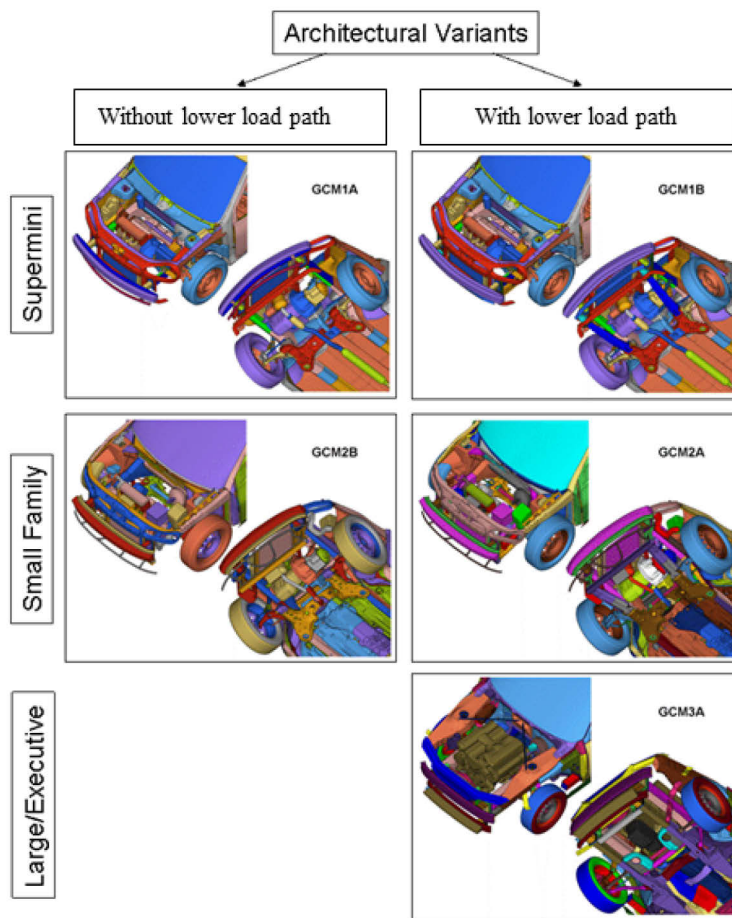


Figure 2.3: Architectural variants of GCMs.

All together three different PCMs were generated (super-mini, large family car and executive) in three different FE codes (LS Dyna, PAM-Crash and RADIOSS). The models can be used to evaluate the behaviour of the crash structure (e.g., crash pulse, deformation characteristics and intrusions). However, no restraint systems are included in the models thus no assessment of dummy readings is possible. For the assessment of the occupant loading conditions the evaluation of the crash pulse is necessary.

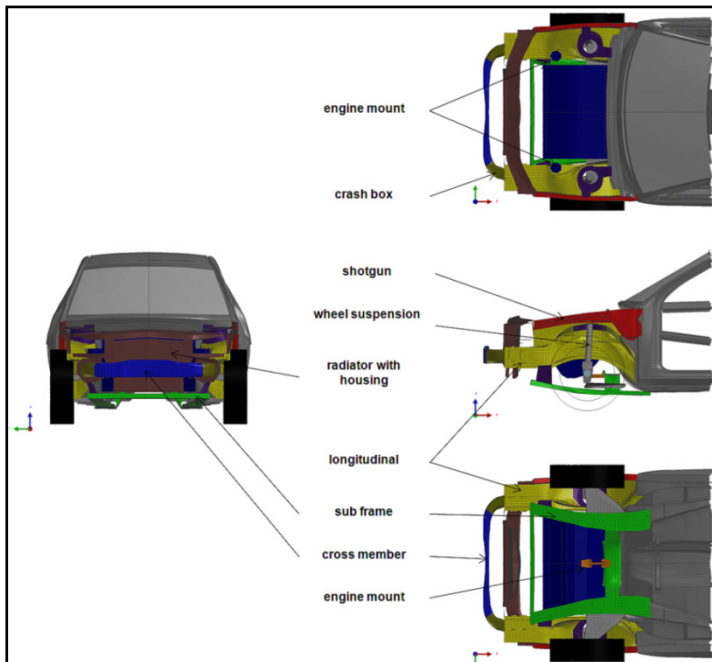


Figure 2.4: Front end structures of the PCMs.

The models were validated using US NCAP crash test data. In addition external dimensions, masses etc. from different cars of the three classes were collected and averaged. Figure 2.4 shows the front design of the PCMs.

2.5 Analysis and Development of Off-set Assessment Procedure

The main candidates for the off-set assessment procedure were the ODB test procedure as currently used for UNECE Regulation 94 and the PDB test procedure as proposed by France for future UNECE regulation.

The current off-set test approaches, most common in vehicle testing, are used in the European frontal directive (96/79/EC) and in consumer tests like Euro NCAP. These consist of an impact into a honeycomb barrier (EEVC barrier) with a 40% overlap. There are no current activities investigating the use of this test configuration for measuring structural interaction, but frontal force levels have been measured using a load cell wall mounted behind the deformable element and was investigated previously [Edwards 2007]. Another off-set test procedure – the Progressive Deformable Barrier (PDB) – has been investigated for structural interaction and frontal force level assessment. This 50% off-set test condition measures the deformation of the honeycomb barrier after the test. The PDB honeycomb is stiffer than the EEVC barrier and becomes progressively stiffer with increased deformation. The barrier deformation is used to analyse the structural interaction and force levels of the tested vehicle.

The main objectives of the off-set test procedure are to address structural alignment, load spreading issues, compartment integrity and the restraint system issues (different test pulses).

Initial discussions in the FIMCAR project suggested that the existing ODB in UNECE Regulation 94 was not capable of evaluating the compatibility (partner protection) of a vehicle. The PDB became the preferred offset test procedure for further development as it

was anticipated that a metric for assessing the load spreading capabilities of a vehicle could be developed during the project. There have also been significant discussions on the ability of the PDB to provide a sufficiently severe test condition for all vehicle masses.

The PDB test is a 50% overlap off-set test which uses deformation measurements from a progressive deformable barrier to assess car's compatibility in terms of partner and self protection. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The 50% overlap and the barrier characteristics allow the PDB to identify the main structures involved in the frontal crash. Geometrical data from previous European research projects (VC-Compat) [Edwards 2007] and IMPROVER [van der Zweep 2006] shown that the main structures of the vehicles will interact with the PDB.

The barrier stiffness of the PDB increases with depth and has upper and lower load levels to represent an actual car structure. The progressive stiffness of the barrier has been designed so that the Equivalent Energy Speed (EES) for the vehicle should be independent of the vehicle's mass. The use of a PDB barrier should thus harmonise the test severity amongst vehicles of different masses by encouraging lighter vehicles to be stronger without increasing the force levels of large vehicles.

The key data used in a PDB test is the post-crash deformations of the barrier. A 3-D image of the barrier is recorded in the computer and the depth and distribution of the deformations are used to assess the vehicle's compatibility characteristics. Although the subjective analysis of the deformed PDB barrier face suggests a good possibility to judge the load spreading capabilities of the tested car (see Figure 2.5) it turned out that it is difficult to mathematically describe a metrics that objectively rates the car.

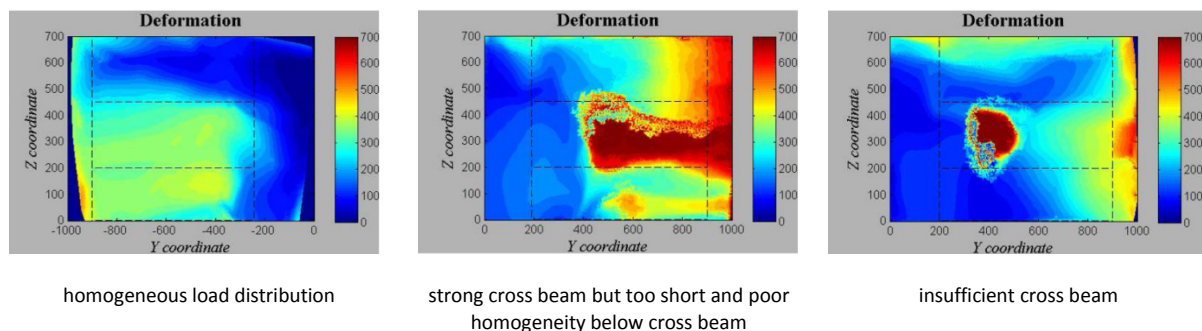


Figure 2.5: Subjective assessment of PDB barrier deformations.

At the time of the evaluation of the different test candidates, there were clear issues with the metrics being developed for the PDB and, at the time of evaluation, no robust metrics were available for the group. The test criteria proposed for assessing load spreading were based on complicated mathematical concepts and involved quantifying iso-curves for barrier deformations. There were discontinuities when the iso-curves crossed the assessment boundaries and this introduced step effects that were not consistent when applied to different vehicles. An additional issue regarding the test severity for heavier vehicles arose for the PDB and, at the time of evaluation, the comparison of test severity for identical vehicles for PDB and ODB tests could not be presented.

It needs to be noted that at the end of the FIMCAR project a draft (M)PDB metric was presented that analyses the lateral deformation gradients (slopes) of the barrier deformation.

2.6 Analysis and Development of Full-width Assessment Procedure

The main aim of the full-width test procedure is to control a vehicle's structural alignment and to provide a severe deceleration pulse for the assessment of the restraint system.

Two types of full width test were investigated the Full Width Rigid Barrier (FWRB) test and the Full Width Deformable Barrier (FWDB) test. For both tests, the use of Load Cell Wall (LCW) data to control the structural interaction characteristics of a vehicle by controlling the measured force distribution was investigated.

The FWRB test is conducted in many countries (USA, Canada, Japan, etc.) for both regulation and consumer testing programs. Test speeds range from 50 to 56 km/h.

The FWDB test has a 300 mm deformable element. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure. Although essentially the same test configuration as the FWRB, the additional honeycomb is included to attenuate the initial contact with the barrier and introduce more shear forces within the vehicle structure. Past research shows that the deformable element reduces the influence of small, stiff structures such as protruding bolts, and the drive-train loads on the barrier.

For both the FWRB and FWDB tests metrics to assess a vehicle's ability to apply loads in a common interaction zone were developed. The main aim of these metrics is to enforce vertical structural alignment because this is a first basic step to increase the compatibility of car crash outcomes. After a common interaction zone is defined, issues such as horizontal distribution or frontal force can be addressed.

The concept on which this development is based incorporates aspects of the US voluntary commitment for the improvement of the geometric frontal impact compatibility of Light Trucks and Vans (LTVs) [Barbat 2005]; and the current investigations by Japan [Yonezawa 2009]. The concept was decided following the review of metrics developed previously, e.g. AHOF, homogeneity criterion. The aim of the US voluntary commitment is to ensure that LTVs have structure in alignment with a common interaction zone from 16 to 20 inches (406 – 508 mm), further named as "Part 581 zone") measured vertically from the ground to enable better interaction with cars. Current investigations by Japan are researching the feasibility of metrics which assess the forces measured in rows 3 and 4 of the load cell wall.

The full width rigid and full width deformable barrier both provide a hard pulse for the occupant and use similar test instrumentation. The main difference is the time window available for assessing vehicle structures. A rigid barrier may only allow a short assessment duration before the engine contacts the load cell wall and begins to mask the structural forces with high contact loads. The deformable barrier face attenuates the engine contact and allows for a longer evaluation period before the engine contact.

The influence of the barrier face on the measurement capabilities of the load cell wall was important in the decision to choose a FWRB or a FWDB. The FWRB is able to directly measure the structural loads from the vehicle as there is no honeycomb filtering the forces.

However the FWRB could not assess loads in Rows 1&2 that come after the analysis window for structural alignment, sometimes as short as 6 ms. There have been suggestions to modify the FWRB with an override barrier (ORB) when assessing higher vehicle structures such as SUVs [Patel 2009], but FIMCAR data suggests that it may be possible to assess the SEAS that are beneficial for car-to-car collisions by the FWDB while the ORB as present seems not to be able to distinguish sufficiently between beneficial and poor SEAS.

It is expected that the FWDB test results are more representative of real world accident performance w.r.t. to restraint system triggering and stability of energy absorbing structures. Figure 2.6 shows the deformation pattern of the same car in different test configurations. There are similarities in the deformations in the car-to-car and FWDB test where the crash box is not used due bending of the main structures. The deformation pattern of the FWRB test, however, is evenly distributed vertically and laterally and the energy absorption structures like the crash box are well exploited. This shows that cars with good deformation behaviour in FWRB test do not necessarily deform in a stable manner in car-to-car impacts. It is thus difficult to predict car-to-car crash performance from FWRB test results.



Figure 2.6: Comparison of front structure deformation pattern in different frontal impact tests.

The technical advantage for assessing structural alignment and for testing the cars in a more representative way was for the FWDB while the FWRB offers easier global harmonisation and potentially less test variability due to a deformable face, see Table 3.

Table 3: Advantages of different full-width tests.

| FWDB | FWRB |
|---|--|
| <ul style="list-style-type: none"> • More representative of real world accident especially in initial stage of impact. • More representative for initial deceleration of vehicle and loading of main rails which is important for sensing of crash for restraint system triggering. • Engine dump loading attenuated, making assessment of vehicle structures that are relevant to crash that are loaded later in the impact, i.e. an assessment can be made of the vehicle's main rails as opposed to its crush cans. • Results in more realistic deformation pattern of the front structure following to shear forces which are not applicable in FWRB • Can detect SEAS structures, so no need for supplementary test, e.g. ORB. • Possibly can assess horizontal structures (bumper beams). | <ul style="list-style-type: none"> • Effectively already de-facto worldwide standard test so hence would be easier to introduce from harmonisation point of view. • LCW measures vehicle forces directly, i.e. not filtered by deformable element. • No problems with stability of deformable face or possibility of load spreading by deformable face. • More test data available for development of metric |

2.7 Analysis and Development of Moving Deformable Barrier Assessment Procedure

One of the test modes investigated during the FIMCAR project to improve frontal impact and compatibility is a so-called Moving Deformable Barrier test (MDB test). This is a frontal test with a moving test vehicle and moving trolley equipped with a deformable element. In various initiatives in Europe and the US this type of test is seen as a next step in the future evaluation of vehicle safety with a good possibility for harmonization. Based on the experience of various projects prior to the FIMCAR project, a test protocol has been drafted in the FIMCAR project. Two main parameters: test speed and trolley mass, key factor to define the severity of the MDB test have been defined during the FIMCAR program.

Using the draft protocol a number of MDB tests have been carried out, the main objectives of the test were:

- assessment of feasibility of the test set up and protocol
- definition of the test severity; trolley mass and impact speed
- assessing of repeatability and reproducibility
- development and validation of compatibility metric / horizontal load spreading

The results of 15 MPDB test have been used for the FIMCAR investigations. In general terms, the tests according the draft protocol were feasible in various laboratories using different test trollies. Special attention is needed for the wheel alignment of trolley and test vehicles to avoid incorrect offsets.

For the explored vehicle mass range, kerb weight from 1000 kg to 2200 kg, a fixed trolley mass of 1500 kg and a test speed of 50 km/h (for vehicle and trolley) results in an acceptable

test severity. For vehicles outside this range, for example light electrical vehicles and heavy SUV's, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out to date. These series of tests both showed good results, giving an indication for good R&R; however more tests are needed to make this statement statistically relevant.

Various investigations have been made for compatibility metrics to assess the load spreading of the tested vehicles. It was not possible to define metrics based on load cell wall recordings or trolley accelerations. The metric for horizontal load spreading based on the deformation of the PDB barrier, as defined for the stationary offset test of FIMCAR, is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of the overall vehicle width and a vertical area between 305 and 555 mm (row 3 and row 4 of the Full width load cell) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicles with an even (homogeneous) deformation pattern or a barrier with localised holes.

The FIMCAR project proves that the MPDB test is a good candidate for future frontal compatibility test and assessment activities. More tests and studies are needed to define the test severity for light and heavy vehicles and to confirm the R&R results.

International discussions are needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in the shorter term, as it has advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

2.8 Definition of FIMCAR Frontal Impact Assessment Approach

The list of criteria and their prioritization provided a basis for an objective comparison of the test procedures. The technical development of each test and assessment procedure was documented and its capability to assess each of the requirements was reported. The methods for assessing each requirement varied and were essentially confirmation (yes/no), engineering documentation (data presentation) or assessment with reference vehicles with known properties. The latter case was critical as no single vehicle could be identified as fulfilling all compatibility requirements, but vehicles could be identified that fulfilled one or more compatibility requirements. Lists of physical or numerical vehicle models were developed to document performance in terms of bumper cross beam stiffness, presence of lower load paths, and global performance. Experience in the VC-Compat project suggested that vehicles exhibit a combination of different compatibility characteristics, but specific issues could be isolated in car-to-car tests.

Data from each of the test development work packages in FIMCAR were summarised in a table format based on the items but only the Priority 1 issues were addressed in the evaluation. As expected, there was no single test method that could satisfy all the issues and a combination of test procedures was necessary. As a result, the selection of an assessment approach could be separated into two independent evaluations – one for the full width and one for the offset test configurations.

A key point to note in the following presentation of results is that the initial prioritisation activities and evaluation activities occurred in the first 2 years of the project, before the full assessment metrics for any test procedure were finalised. The goal was to focus the final validation and documentation activities on the most viable test and assessment procedures.

After the initial evaluation of the test procedures, the consortium selected the full width deformable barrier test as the most promising candidate. There were different metrics available that had exhibited promising results. The outstanding issues that needed to be resolved were the selection and validation of the final assessment metric, criteria for occupant injury, and the test speed. Once this was established, integration with the offset test was required.

After selection of the Full Width Deformable Barrier in the FIMCAR assessment approach, further work was needed to finalise the structural alignment metric, confirm a test speed, report the repeatability and reproducibility results and identify the occupant injury criteria. Due to the fact that none of the final FIMCAR test procedures had a capability to assess horizontal load spreading; some further research of the FWDB test was conducted to develop this capability.

FIMCAR Deliverable D3.2 [Adolph 2013] documents the final verification of the metric for evaluating the structural alignment of vehicles. The main results and recommendations of the FWDB investigations in the later stages were:

- FWDB test speed of 50 km/h. This meets the desired test severity of a 50 km/h delta-v identified from accident analysis and also produces a high crash pulse. The test speed was verified by combining the risk to be involved in an accident within a specific delta-v range and the injury risk for that delta-v. The result indicates that the test delta-v should be between 47 and 57 km/h. Taking into account the rebound velocity and to avoid too aggressive test requirements, the test speed was fixed at 50 km/h.
- Structural Alignment: The metric to assess structural alignment currently proposes that a vehicle must exert minimum loads in Rows 3&4 and can use loads in Row 2 to help meet this requirement under certain conditions. The minimum load requirement promotes structural alignment and the credit of loads from Row 2 encourages vertical load spreading. The metric can be defined as:
 - Up to time of 40 msec:
 - $F_4 + F_3 \geq [\text{MIN}(200, 0.4F_{T40}) \text{ kN}]$
 - $F_4 \geq [\text{MIN}(100, 0.2F_{T40}) \text{ kN}]$
 - $F_3 \geq [\text{MIN}((100-LR), (0.2F_{T40}-LR))]$
 - where:
 - F_{T40} = Maximum of total LCW force up to time of 40 msec
 - Limit Reduction (LR) = $[F_2-70] \text{ kN}$ and $0 \text{ kN} \leq LR \leq 50^* \text{ kN}$
 - * Note values to be confirmed taking into account the new test velocity
- Horizontal Load Spreading: The FWDB test approach is unable to assess the horizontal load spreading in a repeatable manner because of issues such as bottoming out of the barrier face

The FWDB metric was validated using the geometric data for the main structural members and the load cell wall data. There was a good correlation between the physical structures and the metric, see Figure 2.7. Further validation using car-to-car test results in FIMCAR

confirmed the metric suitability. The main car-to-car test approach in FIMCAR was to repeat test configurations to with different structural alignments. Only one vehicle, the Super Mini (SM) 1 was tested in corresponding FWDB configurations.

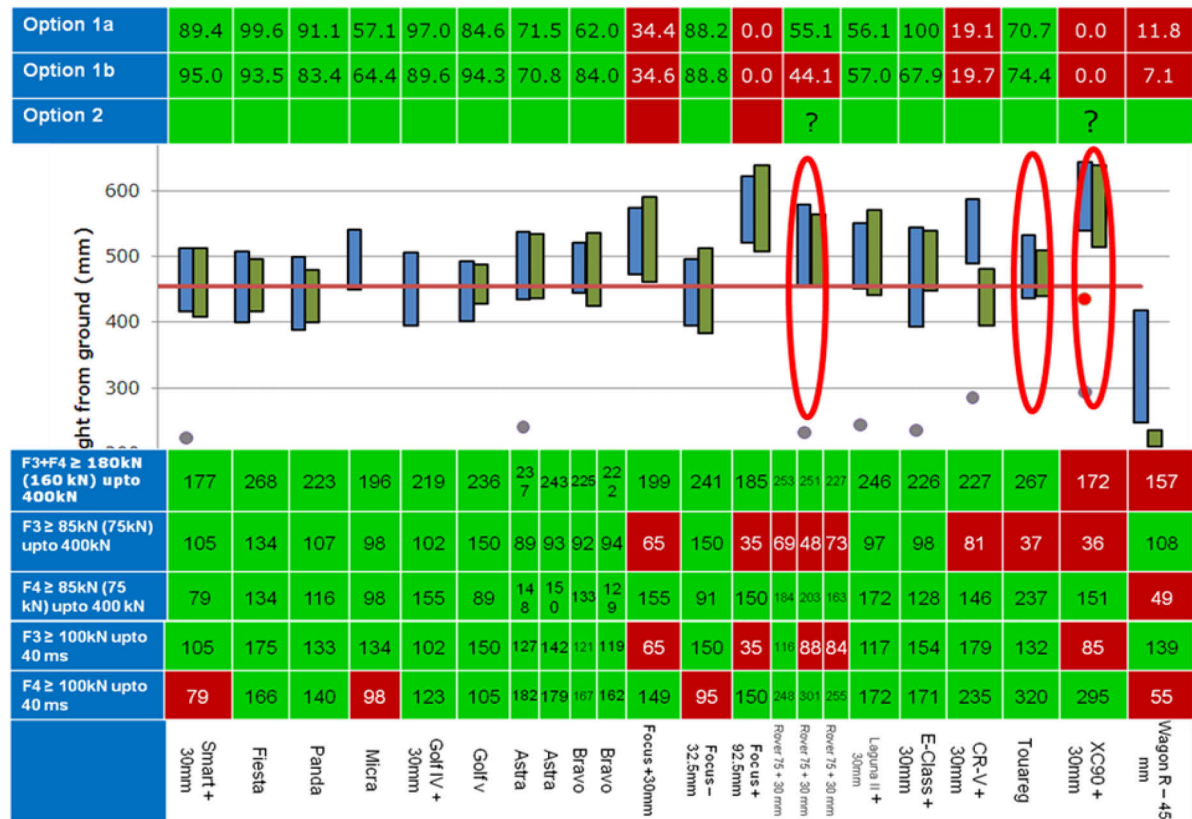


Figure 2.7: Validation of the FWDB metric.

The first result to note is that the vehicles that pass the FWDB metric with both a good distribution between Rows 3 and 4 (fulfilling structural alignment) and also qualifying for a Limit Reduction (LR) had good car-to-car test results regardless of test conditions. SM1 exhibited poor compatibility with a total misalignment of 76 mm while SM2 had good compatibility with a higher (100 mm) misalignment.

The SUV car-to-car tests demonstrated that structural alignment was preferred over the case when PEAS were misaligned but SEAS were still able to provide vertical load spreading. The FWDB were able to detect the vertical load spreading of SUV 2 even with SEAS that were positioned approximately 200 mm behind the bumper cross beam.

The ODB test is proposed as is currently specified in UN-ECE Regulation 94. The current test speed is 56 km/h and no load cell or barrier assessments are proposed. Currently an additional requirement on vehicle intrusions is proposed to ensure all vehicles have a stable occupant compartment. A maximum deformation of 50 mm to the A-pillar is the proposed threshold for this requirement. It is important to note that this requirement will not likely change any of the cars produced for the European market today as Euro NCAP requirements are much more demanding. However, the FIMCAR consortium was reluctant to rely on Euro NCAP assessment for future car safety and proposes the additional requirement to ensure that cars that may not be designed to give good scores in Euro NCAP and may not be tested by Euro NCAP meet a minimum compartment strength requirement. First discussions in

international working groups indicated a general acceptance of an additional requirement on the cabin intrusion but the use of A-pillar displacement was considered as being design restrictive by car manufacturers. Therefore a better definition of the requirement seems to be needed.

Two tests for frontal impact requirements are proposed by FIMCAR and each test configuration must be totally fulfilled, independent of the results of the separate tests.

The repeatability and reproducibility of the existing ODB test criteria were not reviewed as they are well known and accepted. The FWDB was investigated through a combination of component and full scale tests. Component tests were conducted at TRL, BAST and UTAC and reported in FIMCAR Deliverable 3.2 [Adolph 2013]. The component tests showed that the variation of load cell readings was consistent between the tests and below 10%. The component tests also showed no crosstalk or load spreading issues that were critical for the metric.

Full scale tests with a FWDB were reviewed from previous projects (VC-COMPAT, APROSYS) and FIMCAR. The earlier projects had limited test data to review - 2 tests with the same vehicle at different test labs. FIMCAR required 3 tests at 2 labs with the same vehicle. The results from the earlier projects showed good repeatability and reproducibility although some were only for two vehicles. The FIMCAR test results did not show good repeatability and reproducibility consistently. The total loads measured in the three tests were within expected test variation, but the 2 tests at the same research institute had slightly different results which resulted in different evaluation outcomes while one of the two tests was sufficiently reproducible to the third test. The chosen test vehicle had demonstrated instability in car-to-car impacts (FIMCAR Deliverable D6.1 [Sandqvist 2013]). The load cell wall at where the tests were repeated did not meet the instrumentation requirements identified by FIMCAR. Because of these issues further validation is required to confirm whether or not the LCW with deformable barrier has good enough repeatability and reproducibility for the regulatory application. However, FIMCAR has concluded that the FWDB repeatability and reproducibility is acceptable, i.e. in line with other crash tests, for cars with a stable front structure in this test mode. For further analysis of R&R the use of a car with a stable front structure and sum forces above 500 kN is recommended. Furthermore the LCW requirements as developed by FIMCAR should be met for the LCWs used.

2.9 Load Cell Wall Certification and Calibration

As load cell wall readings are used for the FWDB metrics it was felt necessary to define a Load Cell Wall (LCW) certification procedure. The procedure consists of the LCW definition and certification requirements in terms of wall flatness. In addition a specification and calibration requirements for the transducers was defined.

Possible approaches for the certification of assembled walls were discussed between partners and Kistler (an LCW manufacturer and external expert). It was decided to only have requirements on wall flatness included in the certification. Other options like full scale trolley tests with well-defined loading surfaces are expensive and include inaccuracies like orthogonality to the wall. Certification requirements for the wall flatness were based on measurements of three existing walls and an analysis of a trolley test done by BAST.

In addition to the wall certification a load cell specification and calibration section was included in the procedure. It is based on existing procedures for load cells used in crash test dummies. A series of load cells was tested to check and refine requirements set for non-linearity and hysteresis.

Static calibration is currently done for all LCW's in Europe using specifications as set by the LCW manufacturers. However, for usage in test protocols load cell specifications and performance limits are needed. Also a calibration procedure is required that includes information on items like hysteresis and non-linearity. In discussions with partners it was decided to generate a Load Cell Specification and Calibration document based on the following documents:

- SAE J2570: Performance Specifications for Anthropomorphic Test Device Transducers
- ISO 6487: Measurement techniques in impact tests - Instrumentation
- SAE J211: Instrumentation for Impact Test, Rev. 07/2007
- DIN EN ISO 376

Using the references mentioned above specifications and a calibration protocol were defined for the load cells. Parameter values were set based on needs for the FIMCAR metrics and manufacturers specifications of existing walls.

The wall flatness is mainly (or even only) an issue in case a barrier with deformable element is used in front of the LCW. The deformable barrier is backed by a plate of about 2 mm thickness which spreads the loads between neighbouring cells if the load cells are not aligned. Although non-alignment of cell faces can (at least partially) be compensated by adjusting the protective layers it was decided to collect flatness data from a number of existing walls and based on this define requirements for this parameter.

The resulting values for the wall flatness assessment for different load cell walls were used to define a LCW certification procedure (Transducers shall be positioned such that centre point locations and corners of adjacent cells are aligned to have a depth variation of 1 mm or less.). Other requirements like cell size (125x125 mm), ground clearance (80 mm), cell numbering are based on state of the art use procedures of load cell walls.

2.10 Benefit Analysis

Although the number of road accident casualties in Europe is falling the problem still remains substantial. In 2011 there were still over 30,000 road accident fatalities [European Commission 2012]. Approximately half of these were car occupants and about 60 percent of these occurred in frontal impacts. The next stage to improve a car's safety performance in frontal impacts is to improve its compatibility for car-to-car impacts and for collisions against objects and HGVs. Compatibility consists of improving both a car's self and partner protection in a manner such that there is good interaction with the collision partner and the impact energy is absorbed in the car's frontal structures in a controlled way which results in a reduction of injuries. Over the last ten years much research has been performed which has

found that there are four main factors related to a car's compatibility [Edwards 2003; Edwards 2007]. These are structural interaction potential, frontal force matching, compartment strength and the compartment deceleration pulse and related restraint system performance.

The objective of the FIMCAR project was to develop an assessment approach suitable for regulatory application to control a car's frontal impact and compatibility crash performance and perform an associated cost benefit analysis for its implementation.

The cost benefit analysis performed to estimate the effect of the following potential changes to the frontal impact regulation:

- Option 1 – No change and allow current measures to propagate throughout the vehicle fleet.
- Option 2 – Add a full width (FW) test to the current offset Deformable Barrier (ODB) test.
- Option 3 – Add a full width test (FW) and replace the current ODB test with a Progressive Deformable Barrier (PDB) test.

The following conclusions were made:

- For the benefit analysis it was assumed that the introduction of a full-width test with appropriate compatibility and dummy metrics has the potential to address the frontal impact issues under/override related to structural alignment and restraint related acceleration type injuries. Limited potential of the full width test was expected for addressing fork effect issues. It was also assumed that the replacement of the ODB by the PDB/MPDB test procedure with an appropriate homogeneity metric had the potential to address the frontal impact issues under/override related to vertical load spreading, fork effect and low overlap as well as frontal force matching/compartment strength.
- The benefits of three potential changes to the frontal impact regulation were calculated for GB and Germany and scaled to give an indicative estimate for Europe.
 - For Option 1 'No change', a small benefit of about 2.0% or less of all car occupant Killed and Seriously Injured (KSI) casualties was estimated;
 - For Option 2 'Add FW test: Benefit of 5% to 12% of all car occupant KSI casualties was estimated. It was shown that this benefit consisted of:
 - Structural alignment (under/override related to structural alignment): 0.3% - 0.8%. However, it should be noted that the benefit related to structural alignment was likely under-estimated.
 - Restraint system:(restraint related deceleration related injuries): 5% - 11%
 - For Option 3 'Add FW test and replace ODB test with PDB test' 9% - 14% of all car occupant KSI casualties.
 - Note: Benefit percentages for Options 2 and 3 do not include the benefit of Option 1 'No change'.
- Break-even costs for options 2 and 3 were calculated. Comparison of these costs with costs estimated by previous projects indicated that the monetary value of the benefits of implementing Option 2 should be greater than the costs to modify the cars for restraint system changes. However, further work is needed to determine precisely what changes would be needed to deliver the injury reduction assumed for the benefit analysis and precisely what test configuration (in particular dummies) and performance limits would be needed to enforce these changes.

The following points should be noted:

- The benefit was calculated assuming the implementation of complete assessment procedures. However, appropriate dummy assessment values and dummy selection have not been addressed by FIMCAR and appropriate PDB/MPDB metrics are not yet established.
- Possible further potential benefits from the definition of a common interaction zone related to truck underrun protection and roadside guard rails were not considered in the study.

2.11 Influence of FIMCAR Assessment Approach on other Impact Types

The objective of this part was to describe the expected influence of the candidate test procedures developed in FIMCAR for frontal impact on other impact types. The other impact types of primary interest are side impact, collisions with road restraint systems (e.g. guardrails) and heavy goods vehicle impacts. These collision types were chosen as they involve structures that can be adapted to improve safety. Collisions with vulnerable road users (VRU) were not explicitly investigated in FIMCAR. It is expected that the vehicle structures of interest in FIMCAR can be designed into a VRU friendly shell.

Information used for this analysis came from simulations and car-to-car crash tests conducted in FIMCAR or review of previous research. The three test configurations (full width, offset, and moving deformable barriers) were the input to the FIMCAR selection process. There are 3 different types of offset tests and 2 different full width tests. During the project test procedures could be divided into 3 groups that provide different influences or outcomes on vehicle designs:

1. The ODB barrier provides a method to assess part of the vehicles energy absorption capabilities and compartment test in one test
2. The FWRB and FWDB have similar capabilities to control structural alignment, further assess energy absorption capabilities, and promote the improvements in the occupant restraint system for high deceleration impacts.
3. The PDB and MPDB can be used to promote better load spreading in the vehicle structures, in addition to assessing energy absorption and occupant compartment strength in an offset configuration.

The review of how all candidates would affect vehicle performance in other impacts (beside front-to-front vehicle or frontal impacts with fixed obstacles) is reported in this section to support the benefit analysis reported in FIMCAR. The grouping presented above is used to discuss all 5 test candidates using similarities between certain tests and thereby simplify the discussion.

The common theme is the potential to structurally align vehicle components with the opposing structures. In some cases, like truck RUPs (Rear Underrun Protection), requirements of the collision partner are not ideal for passenger vehicle designs. Introduction of performance requirements that harmonise geometric alignment will support future harmonisation of crashworthiness designs, independent of passenger cars. International harmonisation of concepts like the common interaction zone will improve future vehicle and infrastructure safety performance.

Stiffness issues with current vehicle designs are not expected to be affected negatively by the FIMCAR approach. The combination of a FWDB and ODB will create a balanced frontal

stiffness that cannot be expected to be softer than vehicle side structures, nor stiffer than HGV frames. Current compartment strength needs to be maintained and the frontal stiffness can be tuned to appropriate levels through the combined full width and offset test requirements.

The current test candidates and final assessment procedure selected by FIMCAR do not have any obvious negative implications for side impacts, HGV impacts, nor impacts with road equipment. The worst case scenario is that the introduction of a FW metric with minimum load requirements in Rows 3&4 can lead to sub-optimization and worsened horizontal load spreading. This risk is small and the selection of a FWDB will likely mitigate this side effect. The deformable barrier dampens the peak loads and introduces a need to have larger contact surfaces to generate sufficient loads in the assessment area.

The current assessment approach in FIMCAR may introduce limited improvements for the investigated collisions, but it is expected that the harmonization of interaction areas of HGV and road side equipment will allow to a convergence to compatible structural designs in the road and traffic network.

2.12 Potential of Simulation Tools Towards the Evaluation of Compatibility

For the assessment of vehicle safety in frontal collisions compatibility (which consist of self and partner protection) between opponents is crucial. The use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

A review of the use of Virtual Testing (VT) in today's European vehicle and product type approval, and the on-going work for future implementation of VT in vehicle type approval and rating is the basis for the estimation of the potential of simulation tools. Combined with the experience from the use of simulation tools in the FIMCAR project, a 4-step roadmap for implementation of VT tools in the compatibility development is proposed.

Step 1

2013 - 2020: further evolution of GCMs concept (Generic Car Models) and consequent availability of first agreed/recognised reference VT model family for regulatory and/or rating application, with associated definition of verification and validation procedures. Convergence towards PGCMs concept (Parametric Generic Car Models) for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models are then capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020 - 2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly i.e. through indicators like OLC (Occupant Load Criterion) or other similar criteria as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted for type approval model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025 - 2030: first full vehicle-crash regulations (type approval and even self-certification) for car-to-car compatibility based on full VT (structural behaviour and dummy biomechanical response based on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030 - 2040: VT maturity reached, with type approval based on full system simulations (structural and biomechanical behaviour included, with human body models (HBM) as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the protocol).

3 POTENTIAL IMPACT

The main objective of the FIMCAR project was to develop a proposal for an assessment approach for future frontal impact regulation for UNECE. During the development the FIMCAR partners discussed the interim findings with external experts, e.g., during two workshops, in meetings of the currently active Informal Group of Frontal Impact of GRSP that has the mandate to propose a new UNECE frontal impact regulation, Euro NCAP amongst others. This communication guided partially the FIMCAR decisions and helped to make external groups aware of the project's activities.

The activities and results in FIMCAR were discussed in both UNECE and Euro NCAP working groups and have resulted in significant discussions external to the project. FIMCAR has been instrumental in raising the discussions on compatibility in external, international working groups and will result in changes in both Euro NCAP and Regulation 94 in the near term (2014-2017)

The GRSP Informal Group on Frontal Impact already considered the FIMCAR results as valuable input for their own decisions, which in the end might be different to the FIMCAR decisions, as the scope to be considered might be different. The latest discussions indicate that a full width test is an accepted requirement for R94 testing. FIMCAR has contributed to the motivation and test speed for a Full Width test. The barrier face and evaluation criteria are still under discussion.

The Euro NCAP technical working group on frontal impact has identified the full width rigid barrier as a new test requirement for the consumer test program. The inclusion of a 5%ile female dummy decision may also be a result of both FIMCAR and parallel project Thorax. It is important to note the Euro NCAP has had different decisions on the barrier face and underlines the need for larger European projects to deliver qualified data for review. The appropriateness of the decisions taken by external parties can later be evaluated with the FIMCAR data.

According to the conducted benefit analysis approx. 5 – 12 % of the European killed or seriously injured people would benefit from the implementation of the FIMCAR results.

3.1 Additional Benefits of the FIMCAR Project

While vehicle safety was the main goal of the project, the results of the project provide important information for future vehicle designs that may have other consequences in terms of environmental impact and new economic benefits. The results of interest are the structural architecture of the vehicles and applications of virtual testing.

Many research projects had proposed that multiple load path vehicles were advantageous for compatibility. FIMCAR was the first to really document the type of structures most beneficial using objective data. The use of lower load paths that are not too far rear of the bumper should lead manufacturers to modify their designs for more robust and efficient forward structures. A direct benefit could be anticipated by the reduction of material needed to design a single load path vehicle in terms of both its longitudinal structure and anchorage in the passenger compartment. Cantilever type structures (i.e., Single load path) tend to be less optimised for mass than a multiple support structure. Moves to this design approach in Europe can lead to both more safety/unit mass as well spur increased European

industrial activities in alternative material and production technologies. Informal discussions with industrial partners indicate some activities are already starting in this area.

FIMCAR had considerable model development activities related to GCM and PCM vehicle models. The application of these models was beneficial for the project and highlights how the design process for vehicles requires less time and materials. While physical testing is still needed and encouraged, there are identified applications for simulations in the homologation process that can start reducing the financial burden on industry. A particular problem is the increased level of documentation for safety performance that has historically been based on experimental data. The subsequent integration of virtual testing into the type approval process will provide for better real world safety without exponentially increasing the testing burden on the manufacturer. Virtual testing of worst case vehicle variants in the future is one way to reduce costs for testing while providing guaranteed safety with complementary test and simulation data.

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