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SEVENTH FRAMEWORK PROGRAMME

FIMCAR
V – Off-set Test Procedure: Review and Metric Development

FIMCAR
frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The off-set test is the most common test procedure in vehicle crash testing. These procedures are currently used in the European frontal directive (96/79/EC) and in consumer tests like Euro NCAP, IIHS, etc. In both compulsory and consumer testing cases, the ODB test consists of an impact into a honeycomb barrier (EEVC barrier) with a 40% overlap.

The current ODB procedures only assess the self-protection of the tested vehicle. There are no methodologies investigating the partner-protection (e.g. structural interaction or frontal force levels) using these test configurations.

Another off-set test procedure – the Progressive Deformable Barrier (PDB), a 50% off-set test – has been investigated for structural interaction and frontal force level assessment. The PDB is considered as the most promising off-set test procedure to assess partner-protection issues.

In the PDB test, the deformation of the honeycomb barrier can be measured after the test. The PDB honeycomb is stiffer than the EEVC barrier and becomes progressively stiffer with increased deformation. The barrier 3D deformation profile is used to analyse the structural interaction and force levels of the tested vehicle. The PDB assessment procedure shall use the barrier deformation as an input.

The specific objective of the deliverable is to define the fundamental concepts for developing assessment criteria and associated performance limits for the off-set test procedure.

In an initial phase, existing test procedures have been investigated and an initial assessment methodology has been developed. This includes the review from past compatibility research projects and review of current test protocols. The robustness of the assessment criteria is investigated and potential for misuse in vehicle design is identified.

Full scale tests and simulation studies were performed to investigate topics like robustness, repeatability and reproducibility of the test and the assessment criteria. Existing Euro NCAP tests performed in recent years were used to support this investigation.

Based on the results of the tests performed, different proposals for criteria and limits have been investigated. Although the PDB is a promising procedure to evaluate compatibility issues such load spreading, at this stage of the project the criterion was not possible to be fully developed.

For this reason the ODB is proposed as off-set test procedure, the ODB procedure will maintain the current self-protection requirements. However, PDB might still be an option for the future when validated compatibility metrics can be proposed. Therefore, the FIMCAR consortium agreed to further develop PDB criteria.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to describe the test procedures and assessments to evaluate self and partner-protection as defined in compatibility. The crash test and simulation results and analysis performed to develop the assessment criteria will be also included. The assessment will consist of performance criteria, metric and limits for evaluating the frontal compatibility using the off-set test procedure.

1.3 Structure of this Deliverable

In the beginning possible candidates for the FIMCAR off-set test procedure are described and evaluated following a pre selection of the FIMCAR off-set test procedure. Chapter 3 describes the development of the initial development of the Off-set assessment criteria development followed by a review of available test results in Chapter 4.

2 PROPOSAL FOR OFF-SET TEST PROCEDURE

2.1 Review of Existing Procedures

2.1.1 Off-set Deformable Barrier Procedure (ODB)

The ODB frontal crash test was developed from 1989-1995 [EEVC 2013], and it simulates the collision of the tested vehicle against another vehicle of similar mass. The main characteristic is the use of a deformable barrier, which was developed by the European Enhanced Vehicle Safety Committee (EEVC) [EEVC 2013]. The test consists of a frontal crash where the car impacts the barrier with an off-set of 40 percent, on the driver side. This is the current procedure used by the European regulation and directive where the test speed is 56 km/h. From 1996, Euro NCAP [Euro NCAP 2013] adopted this procedure to the European consumer information program, in the Euro NCAP test the speed is increased to 64 km/h.

The EEVC barrier is a calibrated kinetic energy absorber developed to be used for full scale crash testing in automotive passive safety and crashworthiness field. This barrier is based on the original work of EEVC Working Group 11. Based on aluminium honeycomb technology, this barrier is particularly used by car manufacturers and test laboratories worldwide for the assessment of motor vehicle passenger's protection in case of frontal off-set collision according to following standards:

- UN ECE R94, European Directive 96/79/CE, FMVSS 208, ARD 73/00
- Euro NCAP, IIHS, C-NCAP, ANCAP, J-NCAP etc…

In the off-set frontal crash test, the vehicle initially contacts the deformable aluminium barrier at the impact speed defined regarding protocols requirements. A Hybrid III (HIII) ATD is used to evaluate the self-protection of the vehicle is assessed through the dummy injury values. The HIII measures the likeliness of injuries in this type of crash.

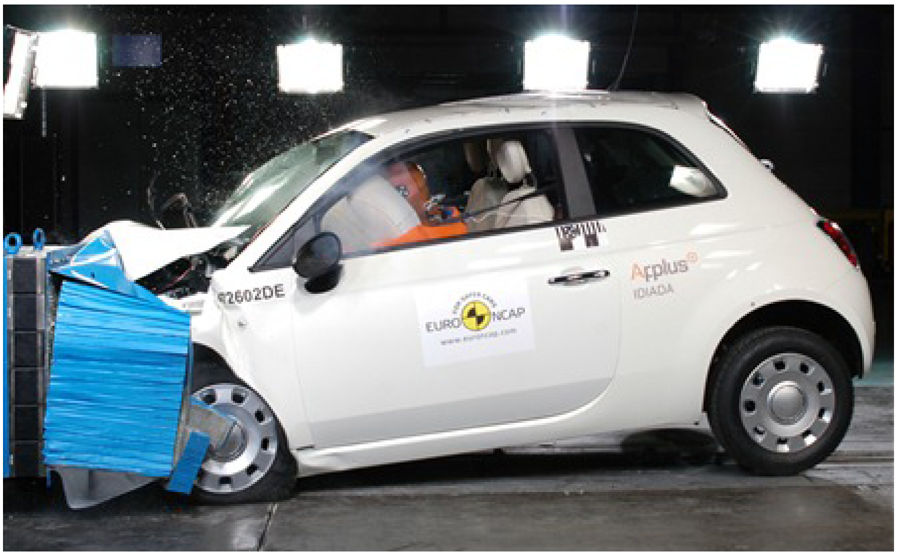


Figure 2.1: Euro NCAP ODB crash test.

2.1.2 Progressive Deformable Barrier Procedure (PDB)

The off-set test using the PDB is a 60 km/h and 50 percent overlap (on the driver side) test that simulates a frontal collision of the tested vehicle against an average modern car. The details of the test procedure are described in the [ECE 2007].

The PDB stiffness is in line with the current European vehicle fleet. When comparing the force deflection curve of 26 cars tested according to Euro NCAP protocol with the PDB certification corridor (note the corridor is shifted in order to account for the assumption that the first 500 mm of the crash in Euro NCAP are purely caused by the deformation of the barrier face) a good correlation can be demonstrated, see Figure 2.2

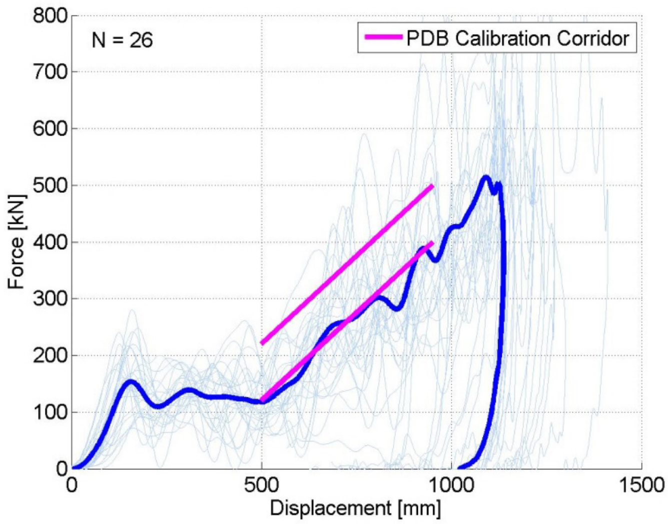


Figure 2.2 Average force-deflection curve of 26 cars tested within Euro NCAP from 2006 to 2009 together with the shifted PDB calibration corridor.

The PDB is significantly stiffer than the ODB [Delannoy 2005] and has been proposed by France in previous European research projects. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The PDB is a calibrated kinetic energy absorber developed to be used for full scale crash testing in automotive passive safety and crashworthiness field. This barrier is based on national research work in France. Based on aluminium honeycomb technology, this barrier has the ability to assess the tested vehicle aggressiveness.

Figure 2.3: PDB 60 km/h crash test.

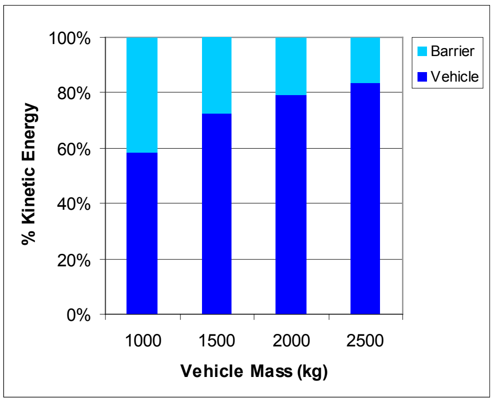
2.1.3 Narrow off-set procedure

The narrow off-set test is a frontal impact against a rigid obstacle with an overlap smaller than 30 percent, on the driver side. Recent research programs conducted by IIHS identified that a number of accidents are still source of severe injuries to the occupants. A narrow object (e.g. trees, lamp post) is one of these configurations. IIHS has been working for this research in order to determine what kind of additional tests should be added to its crashworthiness evaluation program. IIHS has been conducting a series of frontal pole impact tests to determine whether to add this test configuration to their US consumer information program. Now they added an off-set frontal impact at 64 km/h with 25 percent overlap against rigid barrier whose corner is pole shape [IIHS 2012] into their current program to address these injuries. This configuration leads to higher intrusions (compared to the larger overlap). A HIII dummy will be used in the driver side to measure the likeliness of injuries in this type of crash.

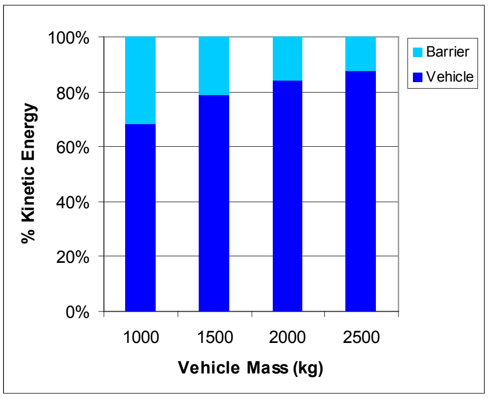
2.2 Proposed test configuration for assessing compatibility

Previous compatibility research projects identified frontal crash incompatibilities between vehicles, in principal due to the difference in front stiffness, bad structural interaction, insufficient compartment strength and mass difference. Today's self-protection requirement leads to design of large vehicles with a stiffer front end (compared to small vehicles) in order to compensate for their mass. The current frontal ODB test is more severe for heavy vehicles than lighter vehicles. Due to this self-protection trend, compatibility requirements are more and more difficult to achieve. However, the FIMCAR accident analysis showed that with new cars poor structural interaction, compartment strength (especially in accidents with HGV and objects) and high acceleration loading to the occupant seem to be more important [Thompson 2013 / Section II].

The test severity was defined in previous research projects using the EES (energy equivalent speed). Figure 2.4 shows the test severity trend in the ODB tests.



R94



Euro NCAP

Figure 2.4: Estimation of test severity, % of kinetic energy absorbed.

In Figure 2.4, the energy absorbed by the deformable barrier was estimated to be 50 kJ independent of vehicle mass and dimensions (see below). Furthermore kinetic energy after the impact was neglected.

The EES definition is currently used to estimate the test severity, EES formula is shown in Equation 2.1.

$$EES[m/s] = \sqrt{v[m/s]^2 - \frac{2 \times E_{ODB}[J]}{m[kg]}}$$

Equation 2.1: EES formula.

The energy absorbed by the barrier was obtained from a total of 17 Euro NCAP tests that were analysed in WP2, data from LCW was used to estimate the energy absorbed by the deformable element. From this study, 53.81 kJ represents the average of the energy absorbed by the barrier, which has been measured using load cell wall data of different family of vehicles. All cases assume that the deformation of the barrier occurs prior to the deformation of the vehicle. In the R94 test, the energy absorbed by the barrier can be also estimated in 50 kJ as it uses the same barrier and the barrier is bottomed out in the tests.

It is required to maintain current compartment strength, to improve front structural interaction and to limit vehicle front-end aggressiveness. In other words, it is necessary to assess the possibility to check and improve partner-protection while keeping the current level of self-protection.

The current ODB test was developed fifteen years ago and adapted to car designs (geometry and force deformation) from the 90's. Since then, introduction of regulation, ratings, insurance test and recently pedestrian tests have modified a lot of car front designs in terms of stiffness and geometry to achieve these requirements.

With the self-protection requirements for the ODB test, regulations and ratings, all cars offer equivalent behaviour against a fixed obstacle. These tests lead to stiffer front-end and higher compartment strength. Solutions have been optimised against the ODB test or the rigid wall but not in car-to-car configurations.

The proposed new procedure should not compromise or decrease the current self-protection level. That is why the proposed procedure checks compartment strength and structural interaction at the same time. The main objective is to assess compatibility issues identified in the accident research analysis (WP1) and decrease the injury risks in real world accidents.

Therefore, the vehicles need to improve partner-protection (structural interaction, front-end forces, etc.), and should maintain the current level of self-protection (compartment strength, dummy injury).

Figure 2.5 highlights heterogeneity in partner-protection caused by vehicles designed according today's regulation. Severity rate for self and partner-protection are calculated as noted in equation of Figure 2.5. Note that Figure 2.5 is an analysis of vehicle to vehicle frontal crashes.

$$SR(\text{protection}) = \frac{(\text{Fatalities} + \text{Severe\_injuries})_{int}}{(\text{Fatalities} + \text{Severe\_inj} + \text{Slight\_inj} + \text{Not\_inj})_{int}}$$

$$SR(\text{partner}) = \frac{(\text{Fatalities} + \text{Severe\_injuries})_{ext}}{(\text{Fatalities} + \text{Severe\_inj} + \text{Slight\_inj} + \text{Not\_inj})_{ext}}$$

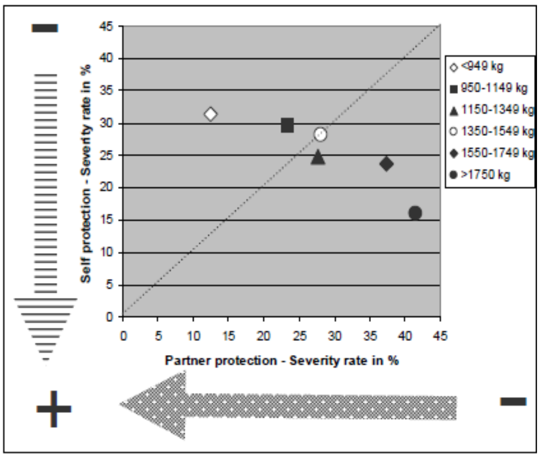


Figure 2.5: Severity rates in different vehicles [Chauvel 2011].

The line on the Figure 2.5 represents cases for which self-protection and partner-protection are identical. Vehicles ranging from 950 to 1549 kg are relatively close to this configuration. The heaviest vehicles (above 1550 kg) show high level of crashworthiness and weak performance regarding partner-protection, whereas vehicles under 950 kg present a smaller self-protection level associated with a small percentage of casualties in the opposite car [Chauvel 2011].

The off-set test configuration proposed to evaluate compatibility is the PDB procedure described in [ECE 2007, Delannoy 2007]. The 50 percent overlap and the 60 km/h speed ensure a high deceleration test pulse and a similar loading of the passenger compartment (compared to R94).

On the other hand, the 50 percent overlap and 150 mm ground clearance of PDB procedure ensure that the all relevant front parts of the vehicle are in direct contact with the barrier when tested in off-set conditions. An overview of test data collected in the previous research project VC-Compat is given in [Davies 2006]. Figure 2.6 shows a summary of the structural database results of VC-Compat.

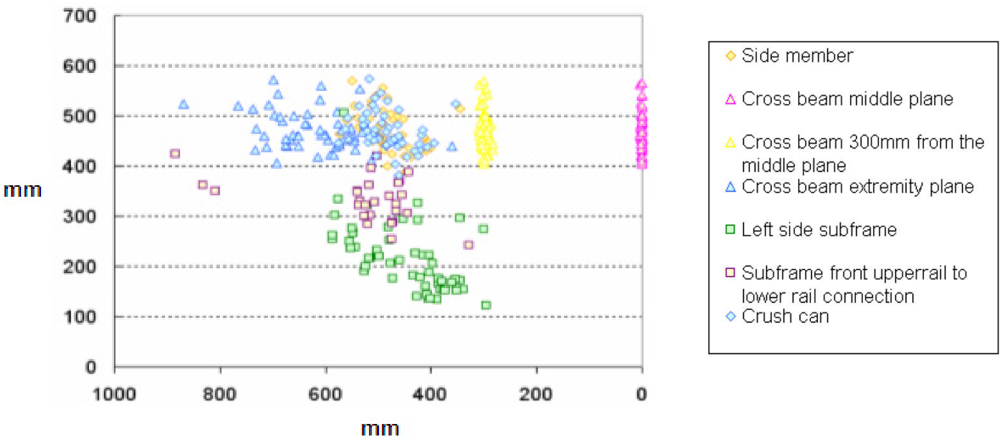


Figure 2.6: Vehicle structural database.

2.2.1 Justification of proposed barrier face (PDB)

The following list of issues of the current ODB barrier was provided by EEVC WG15 [ECE 2007]:

- Barrier instability for new generation of car, stiffness of barrier too low for modern vehicles.
- Test severity increases with car mass and constant test speed
- Self-protection level depends on the vehicle size and mass.
- Difficult to assess force levels with this barrier type and configuration with constant test speed (bottoming out of barrier causes undesired inertial loads for measurement of a car's frontal force).
- No assessment of structural interaction is possible because of load spreading in the barrier and subsequent barrier bottoming out.

The PDB stiffness increases with crush depth and also provides different force deflection characteristics in the upper and lower sections of the barrier (Figure 2.7). The PDB was designed to harmonise the test severity among vehicles of different masses. The PDB will encourage light vehicles to maintain the current passenger compartment stiffness without increasing the front-end force levels of heavy vehicles (Figure 3.3). This will lead to a better force matching between vehicles, one of the objectives towards compatibility.

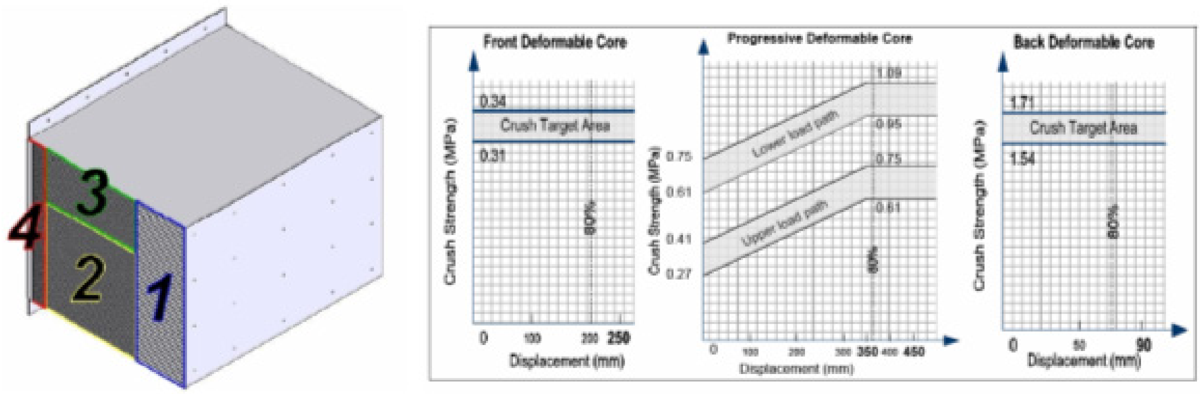


Figure 2.7: PDB characteristics [according to Delannoy 2005].

The PDB represents a significantly stiffer barrier compared to the ODB (current barrier) [Delannoy 2005]; Figure 2.8 shows a comparison between both barriers in terms of global force and energy.

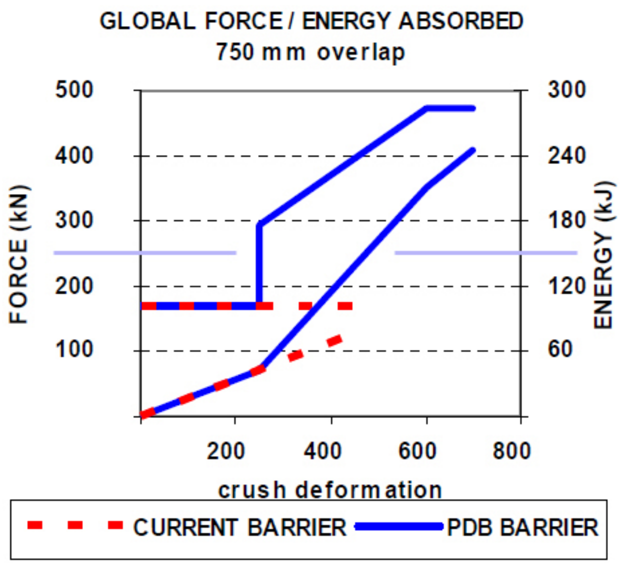


Figure 2.8: PDB vs. ODB [Delannoy 2005].

Furthermore, the dimensions and stiffness of the PDB make the bottoming-out phenomenon very unlikely. The barrier face is capable of generating sufficient differential deformation of the weak and stiff parts of the car's front structure to replicate what happens in most accidents. This will encourage future car designs to incorporate structures, which distribute the force on a large surface better for structural interaction and partner-protection.

The 60 km/h test speed with PDB will increase the test severity for light vehicles which will lead to an increase of the front structure stiffness. The severity for heavy vehicles is expected to be unchanged, so the frontal stiffness of heavy vehicles should not change. As conclusion, test severity for all vehicle mass range will be harmonised.

The PDB test procedure puts under control the energy absorbed by vehicle, the barrier is supposed to represent the opponent vehicle that should also be protected, it does not bottom-out and its deformations can be further analysed.

In the current off-set test procedures (ODB), the car impacts against a weak deformable obstacle (with barrier bottoming-out phenomenon even seen in tests with light stiff vehicles), so the barrier deformation cannot be analysed.

FIMCAR accident analysis results show a significant number of structural interaction issues, in which the load paths involved in the crash are not working in the same way as in a test performed in a laboratory. Although a car impact against a rigid wall might be simpler it does not represent the most common pulse observed in the real world accident (this effects for example crash structure behaviour and airbag firing time).

3 ASSESSMENT CRITERIA DEVELOPMENT AND VALIDATION

3.1 Analysing input of WP1 (accident data) and WP6 (assessment methods) about off-set procedure

3.1.1 General FIMCAR Strategy

Early activities in FIMCAR focused on the compatibility characteristics to be addressed and their priorities. It was important to divide the issues into as many topics as possible to ensure that the test candidates could address specific issues. The resulting overview of frontal impact and compatibility issues presented and discussed in FIMCAR is shown in Figure 2.8. From this organisational description, the issues for FIMCAR could be discussed within the group to establish a common understanding.

During FIMCAR Task 6.2, the candidate test procedures under development in WP2, 3 and 4 were monitored to identify if there was any risk that a compatibility characteristic would not be addressed in the final deliverables of FIMCAR. Through this preliminary evaluation process, the consortium came to a common agreement that FIMCAR should develop both a full width and an off-set test procedure to address all safety issues in frontal impact. This resolution was finalised in the General Assembly meeting in October 2010 and presented to the GRSP Informal Group on Frontal Impact.

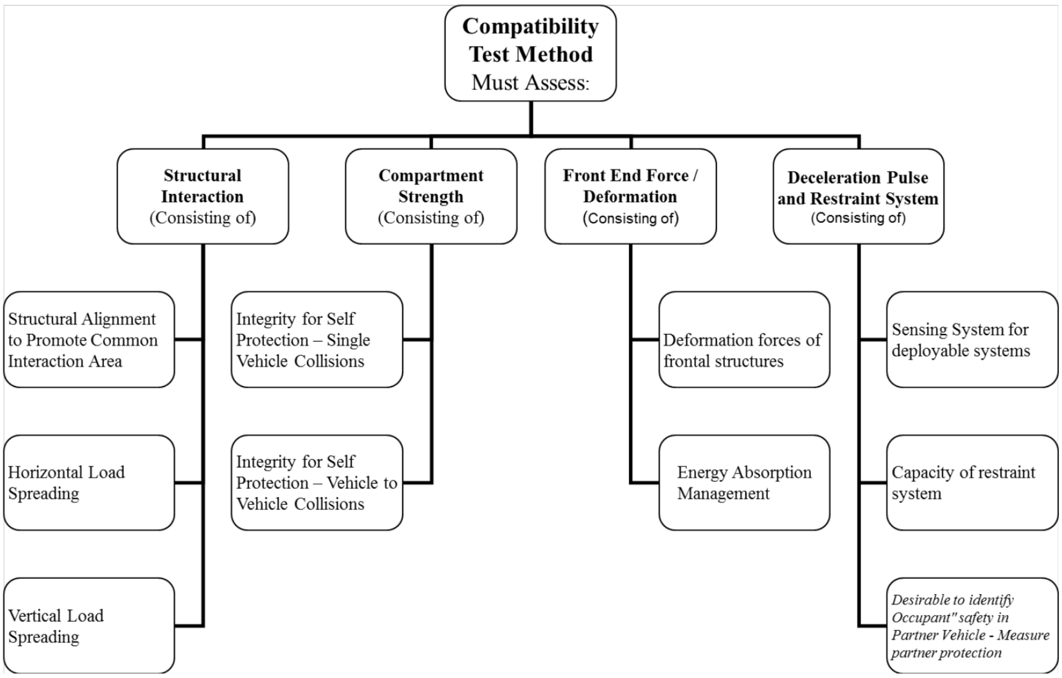


Figure 3.1: Compatibility characteristics [Thomson 2013 / Section XI].

Task 6.1 monitored the activities in WP1 as well as the external activities. An output of these activities is a final set of priorities for the frontal impact issues outlined in the previous figure. The FIMCAR consortium identified key issues that must be resolved within FIMCAR (Priority 1) and issues that should be addressed but are not critical to be finalised within FIMCAR. The results of this prioritisation process are shown in Figure 3.2.

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

Figure 3.2: Priorities rating of FIMCAR research issues [Thomson 2013 / Section XI].

The main features to note in the FIMCAR priorities are that the structural issues related to small vehicles have a lower priority. This is a result of the data from WP1 as well as some of the recent data from GRSP IG FI. Smaller vehicles are known to have higher injury risks in car-to-car impacts. Historically the issues were largely attributed to the weaker structures (compartment and frontal crashworthiness) in small vehicles compared to heavier vehicles, resulting in excessive deformation of small vehicles. Recent data now shows that the excessive deformation of small vehicle compartments (intrusion) is not overrepresented in accident data. The main issue with small vehicle safety appears to be high velocity changes for low mass vehicles and resulting acceleration related injuries to the occupants. The mass induced delta-v differences are not easily resolved in a fixed barrier regulation procedure.

3.1.2 Contribution of Off-set Test Procedure to Frontal Impact

There are 8 main priorities identified for frontal impact protection, see Figure 3.2. Not all these priorities are necessarily needed to be evaluated in an off-set procedure if it is combined with the full width test in a common frontal impact protection assessment. The main issues that are expected to be evaluated in an off-set procedure are the load spreading issues (Structural Interaction) and single vehicle collision compartment strength evaluation. In addition, the combination of a full width and off-set test provide a possibility to evaluate the restraint system for different pulses.

The off-set test has the potential to assist in evaluating structural alignment and deformation forces of frontal structures. As structural alignment is desirable in the initial crash stages, the full width test is the main candidate since it can continuously measure contact forces during the crash while the PDB only provides the final deformed shape of the barrier at the end of crash. The deformation forces of the front structures can be indirectly evaluated by the PDB barrier deformations. Although this is desirable for assessing force level matching between vehicles, the accident data in WP1 did not indicate that this issue was a high priority for current FIMCAR activities.

There were some critical structural interaction issues that were identified in the accident analysis in FIMCAR. The results in the FIMCAR Deliverable D1.1 [Thompson 2013] (see Section II) indicated that "over-ride/under-ride", small overlap, and fork effect were predominant in the cases with injuries and fatalities. These characteristics were observed in both vehicle-to-vehicle and vehicle-to-object collisions. These issues can be considered the main issues to be addressed in an off-set test procedure where the PDB provides the possibility to evaluate all these points.

The collisions with over-ride/under-ride are proposed to be resolved if vehicles have good structural alignment and vertical load spreading. It is therefore critical that an off-set test procedure can assess how well a vehicle distributes the loads from the proposed interaction zone, 406-508 mm, and the area above and below this area. Currently in FIMCAR the emphasis is to assess loads below the bumper and identify a need to assess loads above the bumper.

Both the small overlap and fork effect issues are related to the horizontal load spreading issue. Small overlap is related to how wide the vehicle can distribute crash loads in the outer extremity of the vehicle, essentially outboard of the main longitudinals. The fork effect is related to the front bumper cross beam strength, particularly between the main longitudinals.

Load spreading can be measured both with a full width load cell wall or an off-set test procedure. Previous [Davies 2006] and current research indicate that the best representation of car-to-car impacts is with a larger deformable barrier that introduces vertical and lateral shear within the vehicle's front structures. It is preferable if the barrier does not bottom out so that extreme deformations are introduced. A PDB approach can be an effective method for assessing load spreading.

3.1.3 Test Severity

The final test severity of the FIMCAR frontal impact assessment has not been finalised at the time of publication of this report. There are different strategies that can be considered. The most likely scenario for FIMCAR is that the full width test is used to assess the restraint system response and address the main injuries observed in the thorax. An off-set test would complement this evaluation by assessing the severe and fatal injury risks in frontal crashes. The current frontal impact regulation is based on the fatality risk in a 50% off-set, 50 km/h (for each vehicle), car-to-car impact. Further work with the accident statistics is needed to confirm these numbers but the current PDB test speed of 60 km/h appears to provide this severity level for most of the vehicles [Delannoy 2005]. Any increases in the desired protection level of an off-set test condition would require a review of the PDB test speed.

3.2 Review and Analysis of Test Data Available from Past Compatibility Research

Being the reference test procedure for crashworthiness in Europe, there is a huge amount of data for off-set test procedures. FIMCAR has been analysing the most relevant available data in some of these procedures such as Euro NCAP, PDB and R94 test data. Each pack of data has been used for a particular objective, e.g. test severity check (R94), assessment criteria development (PDB).

Below the list of data packs used in the off-set procedure:

- PDB tests at 60 km/h, total of 37 tests from previous research projects
- Euro NCAP test (total of 18) from FIMCAR partners testing for Euro NCAP
- ECE R94 tests from FIMCAR partners car makers (only used for reference)

3.3 Development of Assessment Procedure

The main objectives of the off-set test procedure are to address:

- Compartment strength
- Structural alignment
- Load spreading issues

- Restraint system issues (different test pulses).

The current ODB (ECE R94) test and the PDB (Progressive Deformable Barrier) procedure as proposed by France in previous projects were the main candidates. Previous research indicated that load cell measurements in off-set tests do not result in appropriate assessment of the load distribution (due to load spreading in the deformable barrier face load cell wall data is misleading) [Delannoy 2003].

Following that the first FIMCAR decision was taken to concentrate on the PDB procedure and to assess barrier face deformation, assessing the barrier face deformation is impossible with the current ODB barrier face because it is normally over crushed and the vehicle contacts the rigid barrier face.

3.3.1 ODB

The test severity in the current ODB test procedures, R94 and Euro NCAP, can be measured by the vehicle pulse and the dummy readings. Another methodology to measure the test severity is using the EES, Figure 2.4, which varies in function of the vehicle mass.

The Euro NCAP dataset available at FIMCAR has been used to establish the test severity for the ODB tests. This test severity has been estimated as explained in Section 2.2 of this report, the average of EES from a total of 17 Euro NCAP test has been estimated in 57 km/h, with values between 50.9 and 60.1 km/h.

A way to represent the EES against vehicle mass can be found in Figure 3.2, in this diagram the level of test severity for the R94 has been compared with the estimated EES for some PDB tests.

The assessment criteria for the ODB test procedures only consider self-protection issues. In case of R94, the parameters are focused on HIII dummy reading and risk of injury. Details are explained in [EEVC 2013]. Moreover, in the case of Euro NCAP configuration, the self-protection is evaluated not only by dummy parameters and risk of injury, but also by the passenger compartment assessment, details can be found in [Euro NCAP 2013]. It is worth to mention that in the Euro NCAP methodology, the passenger compartment parameters are evaluated following both subjective and objective criteria.

3.3.2 PDB

The test severity needs to be defined taking into account sufficient compartment strength requirements. A way to assess test severity is to use the vehicle deformation energy expressed by EES, as described in Equation 2.1. The proposed test procedure shall ensure a level of EES comparable to the today’s EES level (observed in ECE R94 test conditions), for that reason the PDB test speed is fixed at 60 km/h. The details of the test procedure are described in [Delannoy 2007].

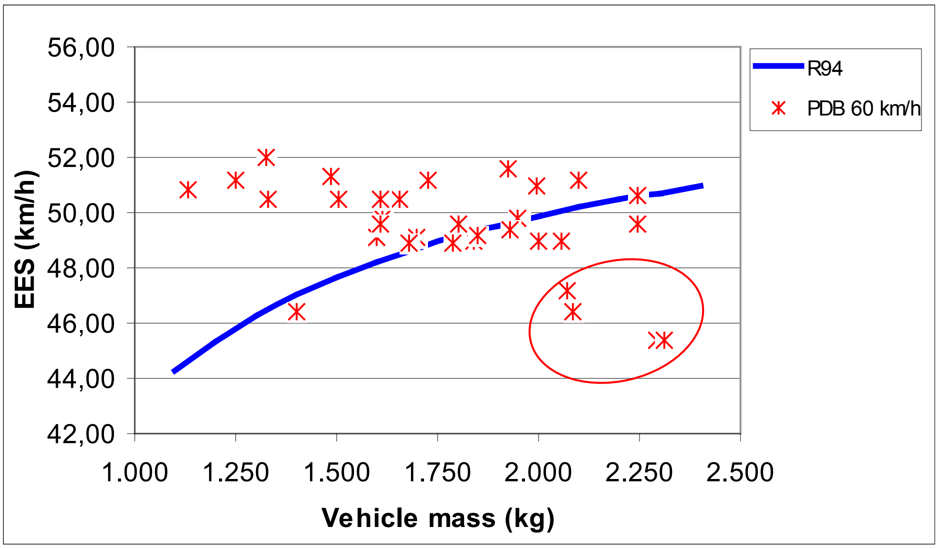


Figure 3.3: EES of PDB 60 km/h database.

The EES of the PDB tests has been calculated using Equation 2.1, where the energy absorbed by the barrier is a variable value and it is obtained from the deformation of the barrier [Delannoy 2007].

According to the database in few cases (red circle in Figure 3.3) the EES of the PDB60 test was reduced by about 5 to 10% compared to the EES of R94 test. The reduced EES is observed in vehicles with a mass between 2070 to 2310 kg, vehicles which are able to deform the barrier in a significant manner. The characteristics of these vehicles would allow them to reduce the front-end unit stiffness and as consequence deform less the barrier maintaining the current R94 level of vehicle deformation and passenger compartment loading. In other words, for future generation of vehicles the test procedure would provide the possibility to balance the barrier and vehicle deformations, which in some cases will mean reducing the stiffness of the front-end structure, giving the possibility to reduce the vehicle weight.

For most of the vehicle types, the PDB is not expected to reduce the passenger compartment stiffness. Reducing the passenger compartment stiffness would compromise the vehicle self-protection.

In the PDB test it is proposed to use a self-protection evaluation as it is used in current ODB test procedures. HIII dummies will be used in driver and front passenger position to evaluate the self-protection of the tested vehicle, equivalent methodologies for dummy evaluation as described in [EEVC 2013] and [Euro NCAP 2013]. In addition, it is proposed to use passenger compartment evaluations similar to the one described in the Euro NCAP protocol, the proposed methodology will include only objective evaluations of the passenger compartment such A-pillar and steering column displacements.

This 50 percent overlap off-set test will assess self-protection issues using dummy values and passenger compartment results and partner-protection issues using measurements from a PDB barrier after the test. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The 50 percent overlap and the barrier characteristics allow the PDB to identity the main structures involved in the frontal crash. Geometrical data from previous European research projects indicated that the main structures of the vehicles will interact with the PDB. Figure 3.4 shows the interaction areas for the front-end structures (PEAS and SEAS) in both, R94 and PDB barriers.

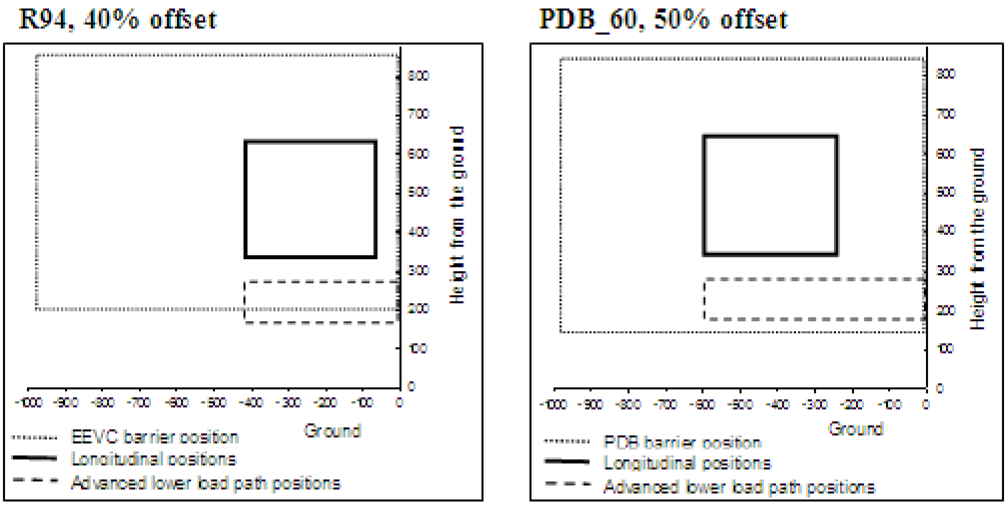


Figure 3.4: Barriers and structure location [Davies 2006].

The barrier stiffness 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 among vehicles of different masses by encouraging lighter vehicles to be stronger without increasing the force levels of large vehicles.

The key data used for compatibility in a PDB test is the post-crash deformations of the barrier. A 3D image, Figure 3.5, 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.

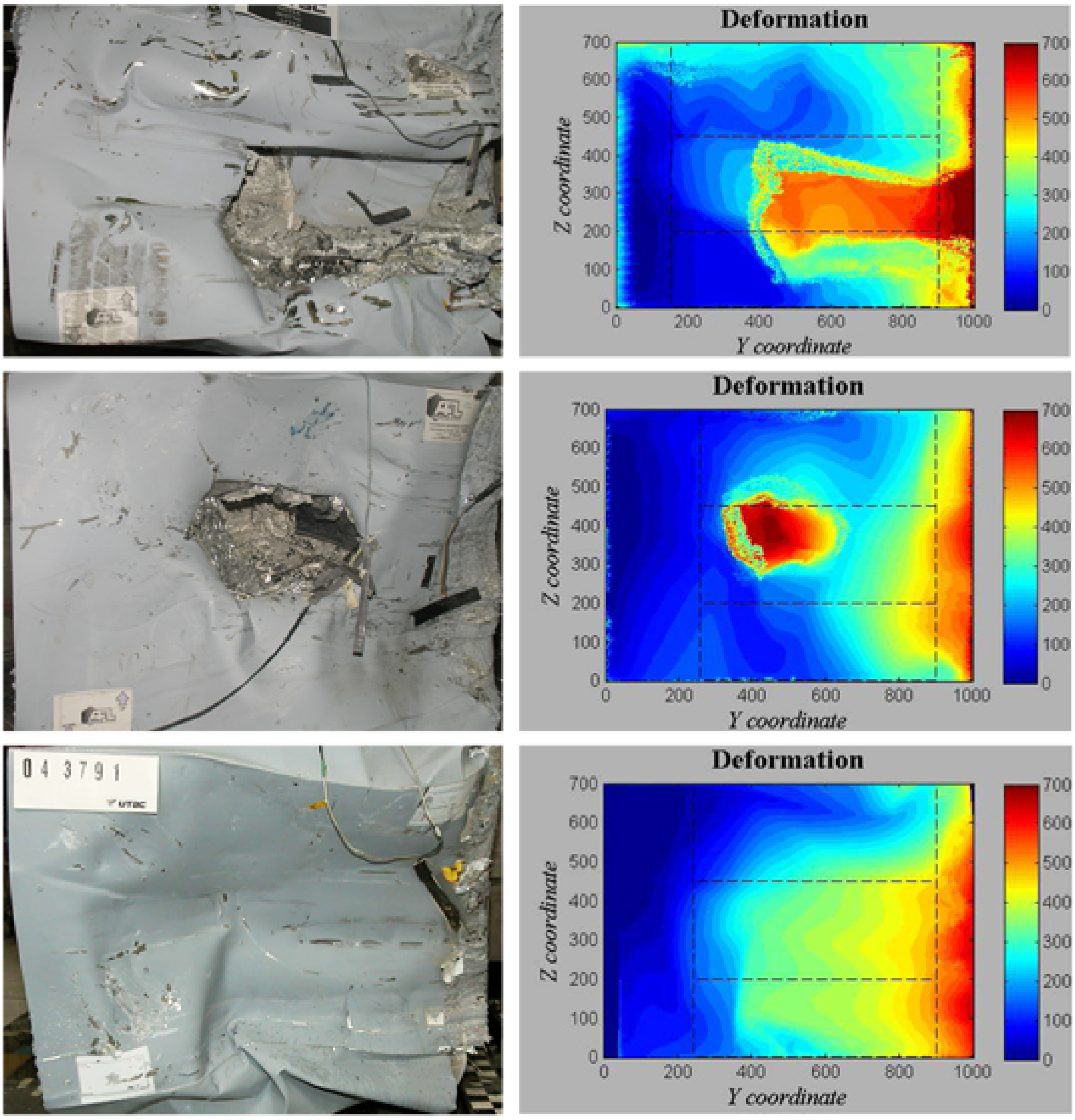


Figure 3.5: Example of PDB digitalisation.

The upper image of Figure 3.5 shows a barrier deformation of a stiff crossbeam but vertical load spreading could be improved, middle image shows poor load spreading, the longitudinal punched a hole into the barrier, lower image shows relatively good vertical and horizontal load spreading.

Metrics assessing the depth and distribution of the barrier deflections are under development in FIMCAR. Instrumented HIII dummies, as in current ODB test procedures, are used to assess the risk of injuries for the occupants.

The barrier will be divided in vertical zones, as shown in Figure 3.6, each area with a defined objective for evaluation. The precise location of the areas is still in discussion.

- **Upper Area** [e.g. from 820 to 600 mm to the ground]: For most of the vehicles this area is above the PEAS and SEAS structures. Significant longitudinal deformations in this area would induce a risk of under/overriding issues (i.e. risk for non-compatible situations in front-side collisions).

- **Middle Area** [e.g. from 600 to 350 mm to the ground]: Area including the CIZ (common interaction zone). For most of the vehicles this is the area where the PEAS are located. Deformations of the barrier will be required in this zone to promote the structural interaction between vehicles in case of frontal collision. On the other hand, the homogeneous deformations of the area will be promoted to encourage the improvement of different partner-protection issues like "fork-effect" or the "small overlap"
- **Lower Area** [e.g. from 350 to 180 mm to the ground]: For most of the vehicles this area is below the PEAS, in some cases the SEAS are located in this area. Deformations in the area will be promoted in order to promote compatibility issues. The homogeneous deformations of the zone will be as well promoted.

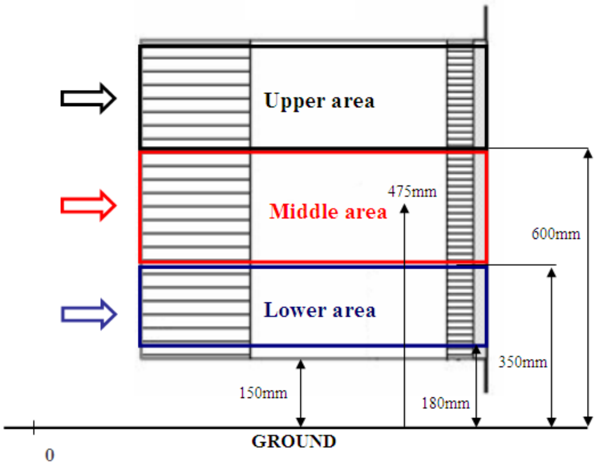


Figure 3.6: Areas of assessment.

The analysis within each zone does not consider the total width of the barrier; the extremities of the barrier are excluded. The zone width covers 150 mm from the barrier edge to a distance equal to the half of the vehicle width minus 100 mm, the horizontal limits are shown in Figure 3.7.

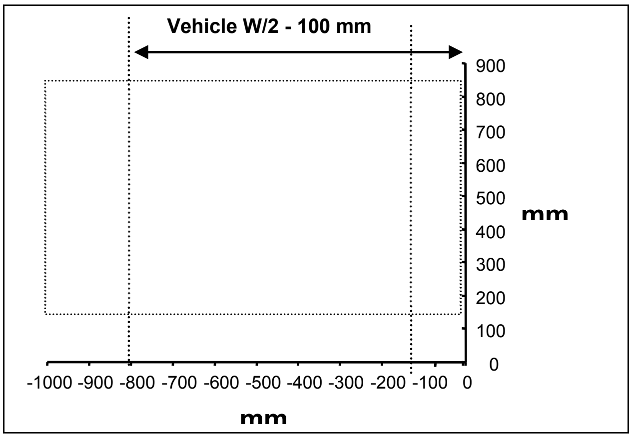


Figure 3.8: Lateral limits.

The zones defined ensure the evaluation of the front structure over a wide range, taking into account compatibility issues identified in FIMCAR WP1 such as fork-effect, small overlap or under riding but excludes the area of large deformation due to vehicle rotation and engine dump at the centre of the vehicle. The following two criteria are obtained from the barrier digitalisation. These parameters will be used to evaluate the partner-protection of the vehicle.

By dividing the barrier in zones, the assessment procedure will be developed focusing each zone to a particular compatibility issue and defining the appropriate criteria to assess this compatibility topic.

The off-set test assessment procedure was supported by a database of 37 PDB tests at 60 km/h. The barrier deformations of these tests were analysed and taken as a reference for further metric investigations. The database is the result of previous research projects, e.g. VC-Compat. In a first stage, the barriers were classified following a subjective approach, gathering the barriers that suggest a good performance in compatibility in a first group (G1), the barriers that suggested a bad compatibility performance in a separate group (G3) and finally the barriers between G1 and G3 were classified in G2, Figure 3.9. Vehicle data (e.g. mass, model, etc.) was not taken into account for the subjective classification, only barrier deformation was considered.

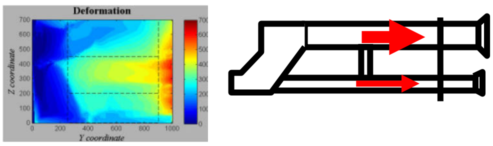
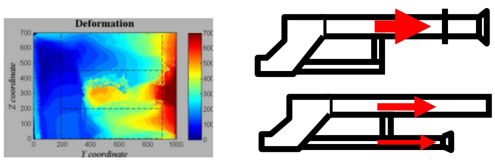
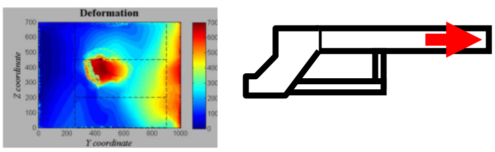
Group 1		⇨ PEAS including stiff cross-member, SEAS that contribute to the deformation of the barrier. Good connections between PEAS and SEAS which suggests a proper engagement with the partner vehicle. ⇨ Barrier that suggests good performance in compatibility.
Group 2		⇨ PEAS including stiff cross-member, no significant contribution of the SEAS in the deformation of the barrier. Marginal connections between PEAS and SEAS. ⇨ PEAS with weak cross-member, partial contribution of the SEAS to the deformation of the barrier. Marginal connection between PEAS and SEAS.
Group 3		⇨ PEAS with weak cross-member, no significant contribution of the SEAS to the deformation of the barrier. Marginal connections between PEAS and SEAS. ⇨ Barrier that suggests poor performance in compatibility.

Figure 3.9: Subjective classification by groups

In a second stage, the barriers in each group (G1, G2 and G3) were classified from best to worst performance also using subjective criteria, see Figure 3.10.

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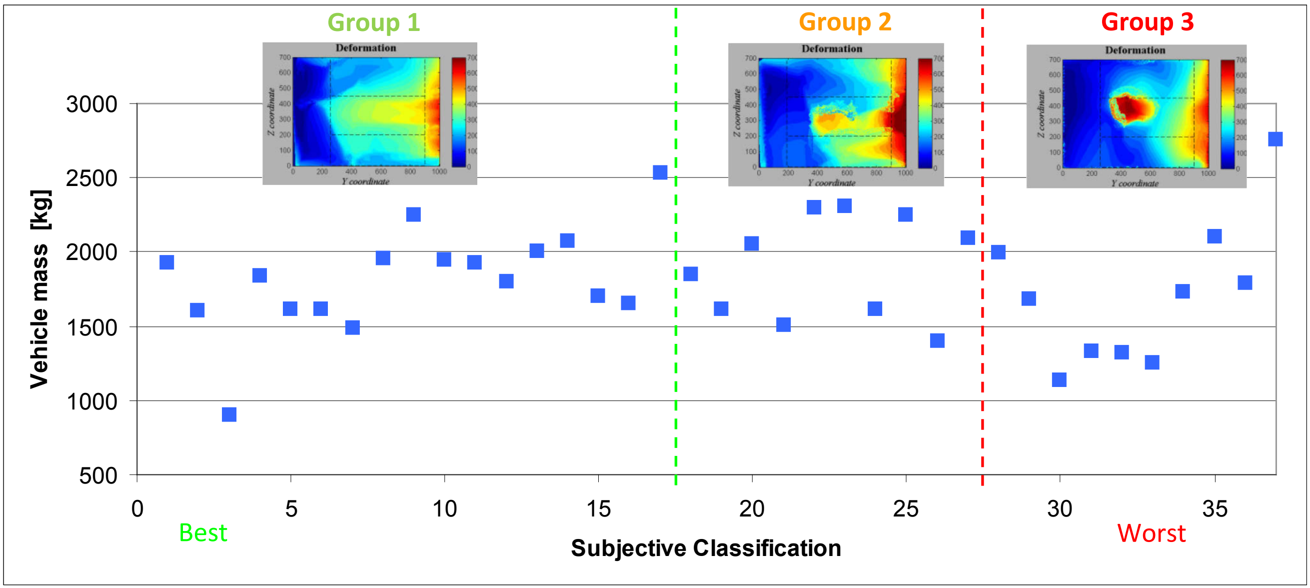


Figure 3.10: Subjective classification from best to worst.

The subjective classification described above was agreed among WP2 partners and used as guidance for an initial stage of the development of the metric, a good correlation between the subjective classification and the initial proposals for metric (objective method) gave a good starting point for the development of the metric.

3.4 Development of Assessment Criteria and Metric

In order to assess compatibility using the PDB 3D image, two different criteria were developed. The criteria are assessing the barrier deformation in all three axes, the **detection of load paths,** which focus on the assessment of the deformation in the longitudinal axis, while the **load spreading** criteria assess the characteristics of the deformations in the horizontal and vertical axes, see Figure 3.11.

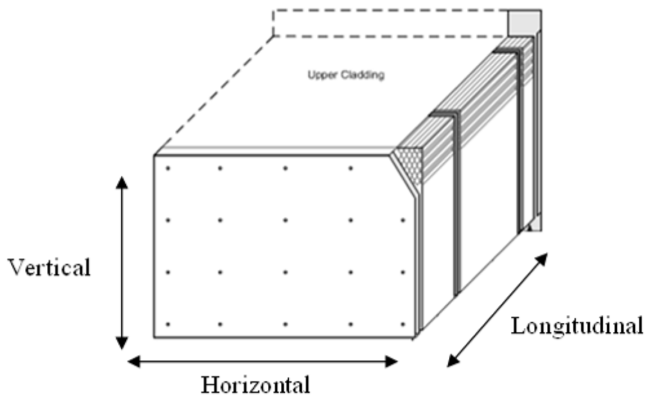


Figure 3.11: PDB barrier axis.

3.4.1 Draft Metric

The objective of the metric is to discriminate good and bad performance in compatibility.

In an initial phase of the development of the metric, a single score (*S*) approach was developed. The score being the result of a formula which combines the longitudinal deformation and load spreading criteria for the lower, middle and upper areas, S_i, where *i=U, M* and *L*.

As shown in Equation 3.1, the result will take into account the load paths detection criteria, *d*, and the load spreading criteria, *H*, for the Upper, Middle and Lower area of the barrier.

$$S = f(S_U, S_M, S_L) \qquad S_i = f(d_i, H_i)$$

Equation 3.1: Scoring formula.

The score, including "weighting factors" for the different sub-scores, can be developed following the priorities to evaluate the frontal compatibility.

Several metrics were investigated in WP2. Figure 3.12 shows an example of correlation between subjective (as explained in Section 3.3.2 of this report) and objective classification using the TV criteria (see Chapter 3.4.4) for assessing the load spreading. A reasonable good correlation can be observed. However, some discrepancies were found, those are mainly due to the effect of sharp edges and boundaries of assessment areas on the TV criteria.

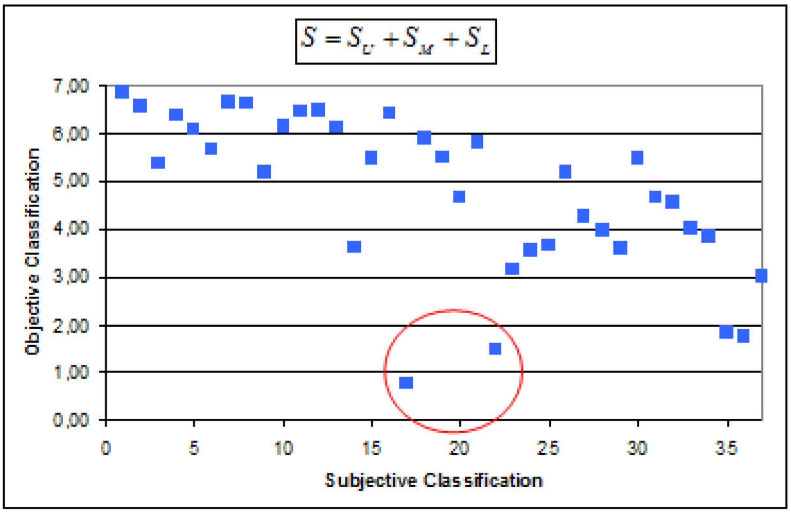
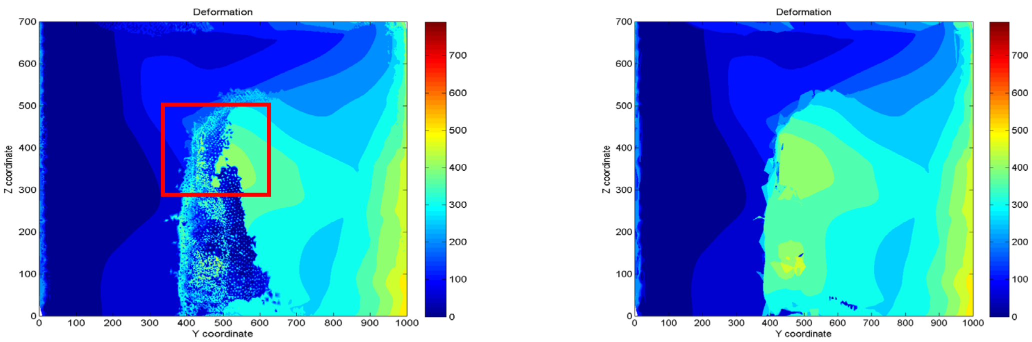


Figure 3.12: Subjective vs. objective classification.

As shown in Figure 3.13 the TV criterion is very sensitive to sharp edges. The left picture of Figure 3.13 shows the image and TV value before post-processing of the image. After post-processing, right picture, the TV value is about 50% lower (note: the lower the TV value is the better is the rating).



TV for middle area 3871 | TV for middle area 1430

Figure 3.13: Post-processing PDB scan.

So it is recommended to post-process the PDB scan in order to remove measurement/scanning issues before analysing any assessment criteria.

3.4.2 Strategy for Metric Development

In second phase and following the priorities established from the FIMCAR consortium the metric was re-issued, the metric was focusing on the main objectives defined by the group. These priorities are summarised in the following key issues:

- Relevant crash loads to be in the common interaction zone (406 to 508 mm). Loads should be distributed horizontally across the common interaction zone
- Vertical load distribution will be assessed inside and below the interaction zone.

3.4.2.1 Relevant Crash Loads to be in the Common Interaction Zone (406 to 508 mm). Loads Should be Distributed Horizontally Across the Common Interaction Zone

In the PDB assessment procedure this requirement should be reflected in the criteria assessing the deformations of the barrier at the middle area.

According to that point, the longitudinal deformation will be used to assess if the PEAS are able to deform the barrier in a sufficient manner, but not limiting its maximum deformation.

In other words, a limit for minimum deformation could be established, while no limits of maximum deformations will be further investigated.

The longitudinal deformation criteria should provide an estimation of the amount of load in the area and the load spreading criteria its horizontal load distribution. This analysis will give an estimation of potential risk for compatibility issues like “small overlap” or “fork effect”.

3.4.2.2 Vertical Load Distribution will be Assessed Inside and Below the Interaction Zone

The criteria obtained at the lower area should answer this requirement. The longitudinal deformations will provide an idea about the loads in the area below the interaction zone. The metric should promote the presence of lower load paths (SEAS), in particular for vehicles involving a crash test with a large kinetic energy.

In the case that SEAS will be detected, then the load spreading criterion at the lower area will also contribute in the metric.

Finally, the upper area will contribute also to the metric. Vehicles without load paths in the common interaction zone, but with excessive high PEAS, which are above the zone will be penalised.

In these cases, the longitudinal deformation criteria in the area above the common interaction zone will give an estimation of potential risk of “overriding” issues.

The proposed metric will be based on a PASS/FAIL approach.

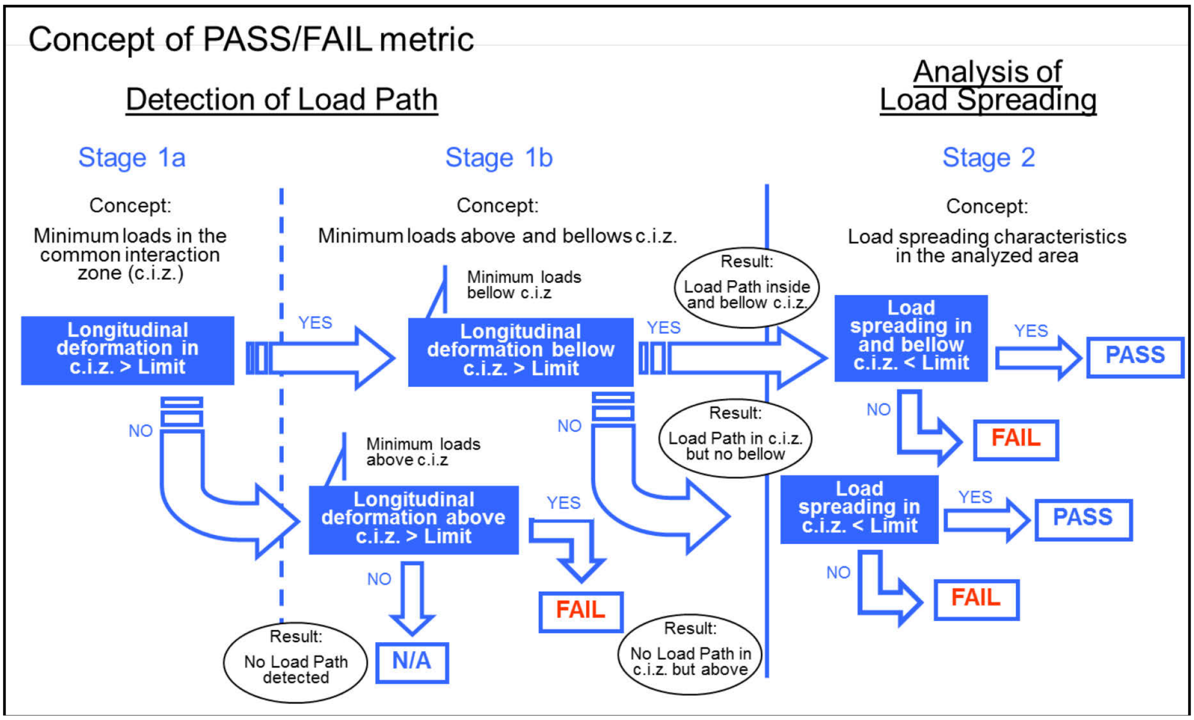


Figure 3.14: Proposal for metric.

Figure 3.14 shows the logics and concepts that are addressed by the proposed metric, the metric is believed to analyse, in a first stage, the presence of a load path and, in a second stage, the characteristics of that load path in terms of spreading the load through the barrier.

Scoring concepts like capping criteria were also investigated in the metric in order to address some relevant issues detected in compatibility. Exceeding a capping limit could indicate an unacceptable high risk of a specific issue in compatibility (i.e. over/under-ride) which will result as fail.

3.4.3 Load Path Detection (Longitudinal Deformation)

The aim of the criteria is to identify front-end structures, which are able to deform the barrier in a significant manner. The load path will be evaluated by the barrier deformation. The 3D measurements of the barrier will allow the identification of the vehicle load paths.

The load path detection will be assessed by the Longitudinal Deformation of the barrier. The Longitudinal deformation *(d)* criterion has been developed using statistics characteristics of the deformation at a defined zone, taking coefficients of the barrier longitudinal deformations.

The parameter and limits can also be used to limit the front-end stiffness controlling the maximum deformation of the barrier. Figure 3.15 shows an example of limits for detecting load paths. In this proposal also the stiffness of the vehicle will be evaluated, limiting the maximal longitudinal deformation.

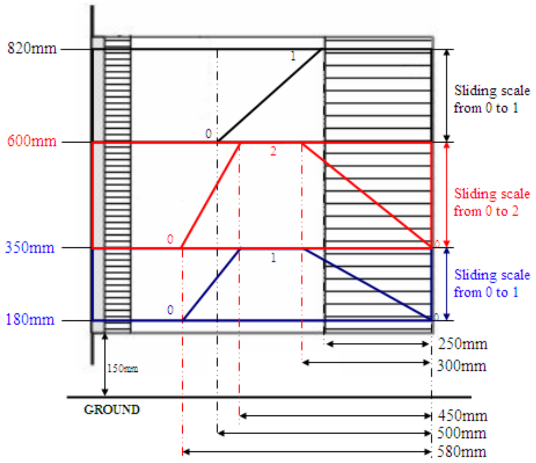


Figure 3.15: Load path detection, longitudinal deformation.

Different criteria for assessing the load path detection have been investigated.

3.4.3.1 Quantiles of Barrier Longitudinal Deformation

The **Quantiles** are points taken at regular intervals from the cumulative distribution function (CDF) of a random variable. Dividing ordered data into q equal-sized data subsets (e.g. q equal to 100 quantiles). The q numbers are the data values marking the boundaries between consecutive subsets. The presence of a load path in the defined area is assessed using q-th's% of deformation.

A minimum value for different q-th's% of longitudinal barrier deformation will be required for identifying a load path, in other words, a load path will be detected if certain q-th's% values are above certain limits.

The limits for this parameter will be established taken the PDB 60 km/h tests database as reference. Figure 3.16 shows some examples of vehicles with (red traces) and without (blue traces) SEAS able to deform the lower area of the barrier.

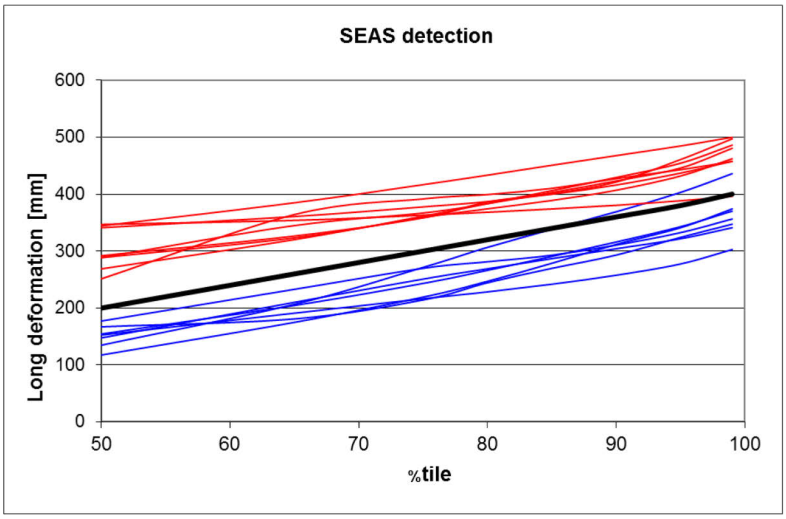


Figure 3.16: q-th% for assessing SEAS.

3.4.3.2 Mean of Longitudinal Deformation

The **Mean** is the sum of the values of a data set divided by the number of values. A minimum mean value of longitudinal deformation of the barrier will be required for identifying a load path, in other words, a load path will be detected if the mean values will be above certain limit.

The presence of a load path in the defined area is assessed using the mean of deformation of the analysed area.

The limits for this parameter will be established taken the PDB 60 km/h tests database as reference.

3.4.4 Load Spreading

The aim of this criterion is to assess the load spreading characteristics of a specific load path. This criterion is identified as a key issue for FIMCAR consortium. Therefore, its development is particularly important for the project. Several ideas have been developed for this criterion, following the more relevant ones are summarised.

The limits for these parameters will be established taken the PDB 60 km/h tests database as reference.

3.4.4.1 Total Variation (TV)

A possible criterion for assessing the load spreading is the image Total Variation. The Total Variation *(TV)* is defined as an estimation of the total amount of variation of an image, mathematically defined as the average length of contour lines (isolines) of the image. In a first stage the map (image) is filtered by an additional low-pass filter. Then, the map is normalised, so all images have the same dimension, in other words only vertical and horizontal deformations are taken into account. The gradient of the length is given the magnitude of change of slope. *TV* is proportional to the sum of lengths of the gradient of the map at all points.TV provides an estimation of the overall homogeneity of the barrier print at the investigated area. Equation 3.2 summarises the formulas used to evaluate the TV criteria.

$$(y,z) \rightarrow x = l(y,z) \qquad \sum_{x,y} l(y,z)^2 = 1 \qquad H = \int \left|\nabla l(y,z)\right| dydz$$

Equation 3.2: Mathematical formulas for TV.

The aim of the TV criterion is to assess horizontal and vertical load spreading.

As already described in Paragraph 3.4.1 the TV value is very sensitive to sharp edges especially at boundaries of assessment zones.

3.4.4.2 Smooth Deformation Index (SDI)

In a similar way as the TV, the SDI is an estimation of homogeneity for a pre-defined assessment area. The criterion also uses the concept of calculating the sum of isolines, but not for the complete area of the barrier. The analysis is concentrated in an area with more than x percent of maximum deformation ($A_{deformed}$).

The process of calculating the criterion is summarised in Figure 3.17.

Step 1:

- Calculate size of deformed area with more than x percent (e.g. 20% ... 50%) of maximum deformation → $A_{deformed}$ (x%)

Step 2:

- Calculate sum of length of equidistant isolines (e.g. 10 mm) within $A_{deformed}$ → iso_{sumL}

Step 3:

- Calculate x percentile (e.g. 99%tile) of deformation → $def_{x\%tile}$

Step 4:

- Calculate "normalised" sum of length of equidistant isolines: $norm\_iso_{sumL} = iso_{sumL}/def_{x\%tile}$ to compensate for the vehicle weight

Step 5:

- **Calculate smooth deformation index:**
  $SDI = A_{deformed}$ (x%) / $norm\_iso_{sumL}$

Figure 3.17: Smooth deformation index (SDI) in 5 steps.

Large deformed areas and/or short length of isolines contribute to provide a high value for this criterion, which is an indicator of good level of load spreading. Complex calculation of isolines is conducted with MATLAB scripts.

As in case of TV, the SDI assesses horizontal and vertical load spreading simultaneously which can be either an advantage or a disadvantage. For the smooth deformation index analysis the assessment areas of Figure 3.6 are combined in order to reduce boundary effects.

The smooth deformation index is analysed

- for different percentages of maximum deformation (20% ... 90%, in 10% increments),
- for different percentiles of deformation (50% and 99%) and
- for different areas of investigations
  - lower and middle area combined:

    y_{min}=150 mm, y_{max}=vehicle width/2 - 100 mm; z_{min}=180 mm, z_{max}=600 mm above ground
  - lower, middle and upper area combined:

    y_{min}=150 mm, y_{max}=vehicle width/2 - 100 mm; z_{min}=180 mm, z_{max}=820 mm above ground

Since both percentiles of deformation (50% and 99%) shown mass dependent results and quite bad correlation with subjective ranking further analyses are conducted with an updated formula.

- without x percentile of deformation (step 3 and 4 of Figure 3.17 were deleted) and
- with more weight on the deformed area ($A_{deformed}$ squared).

In this approach small stiff structures are penalised by a small deformed area. Heavy vehicles having more and longer isolines can naturally compensate with a larger deformed area (e.g. with an additional load path).

Although the updated SDI shows promising results further research is needed and following open issues need to be addressed:

The sum of length of isolines is very sensitive (in accordance to the TV value) if sharp edges are located close to the boundaries of the assessment zone. This boundary issue might be solved by an assessment zone that depends on vehicle height (e.g. from 180 mm to bonnet leading edge).

In order to reduce over- /underride risk an additional requirement for the upper area might be needed to limit the deformation in the upper area.

The key advantage of SDI is that there is an indirect detection of load paths included in the formula via $A_{deformed}$ and that no stepwise approach for different assessment areas needs to be taken into account.

3.4.4.3 Area of Significant Deformations

The Area of significant deformations criterion is defined as the ratio between a measured area of deformation, A_{def}, and an ideal area of deformation, A_{ideal}, (A_{def}/A_{ideal}).

A_{def} is the area where the deformation is above a certain q% (e.g. 40%), as shown in Figure 3.18. The ideal area, A_{ideal}, is a demarcated area of deformation that takes into account the width of the vehicle (Y limits). For the vertical limits (Z limits) of A_{ideal} some investigations have been done, taking these three options of limits:

- Middle area of PDB: (400 to 600mm from ground)
- LCW Rows 3 and 4: (330 to 580mm from ground)
- Common interaction zone as defined in Part 581: (406 to 508mm from ground)

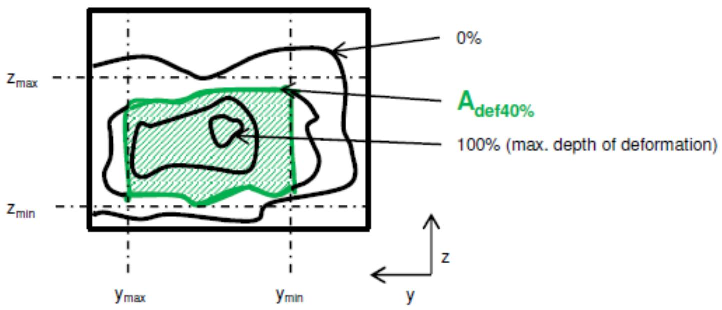


Figure 3.18: Estimation of Adef.

Values of A_{def}/A_{ideal} close to 1 will indicate a good behaviour in terms of load spreading. In case of non-homogeneous result the criteria will be close to 0.

This criterion is taking into account vertical and horizontal load spreading.

3.4.4.4 Horizontal Load Spreading

In that case the criterion is focused in horizontal load spreading. The area of investigation is divided horizontally in a total of **N** equal sub-zones. The vertical limits of overall area will be fixed (e.g. 330 to 580 mm from ground). The horizontal limits and in consequence the final size of the sub-zones will differ in function of the width of the vehicle.

Dividing the area of analysis in sub-zones allows investigating the horizontal load spreading over the total area of investigation. The further analysis of the sub-zones will be done in terms of differences of longitudinal deformations and relative distance between them.

Different parameters can be calculated from these **N** sub-zones.

- D is the average of longitudinal deformation of the complete area

- $D_{i\,(i=1\ to\ N)}$ is the average of longitudinal deformation for the i sub-zone
- $q\%_{i\,(i=1\ to\ N)}$ is the q% of longitudinal deformation for the i sub-zone

Several criteria were developed and investigated using the above mentioned parameters, some examples are:

- D/D_i gives an estimation of the horizontal variation of the i sub-zone compare to the total average
- $e_i=D-D_i$ is the deviation of a sub-zone from the overall average of deformation
- $ddy_i=q\%_i / Q\%_i$ is defined as the derivation of small q% divided by larger Q%

Combining these criteria will provide an estimation of the horizontal load spreading. Figure 3.19 shows an example for this kind of analysis, for N=6. In this example some deviation for the outer part of barrier can be observed, e_1=195. Apart of that issue, the PEAS show a quite constant loading to the barrier, only D_2 is slightly above the average of area deformation.

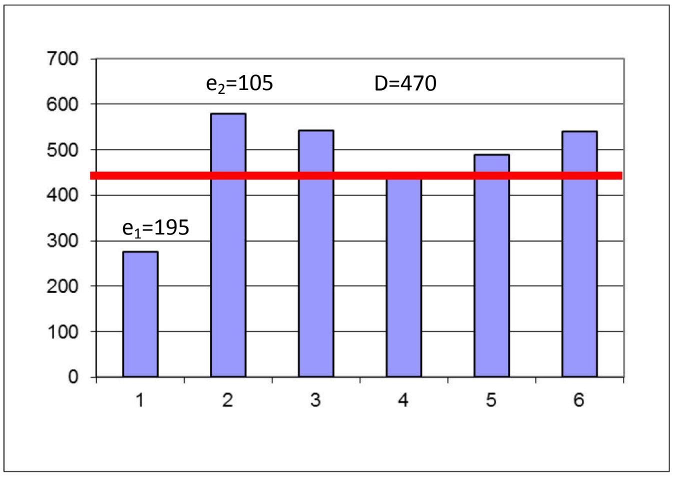


Figure 3.19: Load Spreading analysis, Di vs i.

3.5 Investigate Robustness of the Assessment Criteria and Potential for Misuse in Vehicle Design

An important requirement for the implementation of a new test procedure is the robustness of the developed metric and assessment criteria.

Corresponding investigations need to be done for the robustness of the different assessment criteria (e.g. barrier deformation, dummy injury values) via simulations and full vehicle tests.

Since the assessment criteria are mainly based on barrier deformations a key enabler for a robust assessment is the digitised deformation plot. Therefore the input for the assessment criteria has to be independent of the measurement method and the laboratory. Barrier faces will be measured by different laboratories in Task 2.2 to confirm repeatability and reproducibility of deformation plots.

Furthermore the robustness of the test procedure also depends on other test parameters (e.g. test speed, overlap, etc.). Test parameters within the specification of the test protocol must not have a significant influence on the assessment criteria. On the other hand, vehicle design parameters that have an impact on compatibility (e.g. different stiffness of crossbeam and subframe, etc.) shall have a significant influence on the assessment criteria.

In order to identify these vehicle design parameters and to determine the maximum allowed scatter for test parameters a simulation-based sensitivity analysis will be conducted using the “Parametric Car Models (PCM)” which were developed by TUB and presented in Section IV. The simulation matrix is described in more detail in section 4.1.1. Worst case scenarios of these simulations can be used to identify potential for misuse in vehicle design (e.g. strong subframe in conjunction with weak crossbeam, strong PEAS positioned in the upper area).

Additional simulations with “Generic Car Models (GCM)” which were developed by CRF and presented in Section IV were also conducted. Further details and results can be found in Chapter 4.1.2.

Overall repeatability and reproducibility of the PDB test procedure will be finally confirmed by full vehicle tests in Task 2.2.

MATLAB scripts to calculate the PDB criteria and investigate the robustness of the assessment criteria were developed in WP2. They were also used to double-check the results of the PDB crash analysis software [FIMCAR 2013].

3.6 Conclusions

Combining the load path detection and analysing the load spreading characteristics of the detected load path seems to be most adequate method to assess partner-protection issues using the off-set test procedure. The 3D measurements of the PDB will support this methodology.

The fundamentals of the assessment method using the PDB 60 km/h off-set test were defined. Different criteria and metrics were investigated for assessing compatibility issues.

The TV and TV upgrade criteria, in combination with the longitudinal deformation criterion, have shown a good correlation with a subjective assessment. However, the complexity of the TV methodologies and some issues like the important punishment that are caused by sharp edges of barrier deformation makes the TV criteria a non-suitable methodology to be further proposed.

Another promising criterion for assessing the load spreading, the area of significant deformations, was also analysed. However, the criterion was also discarded due to the bad correlation showed with the subjective classification.

For its simplicity and some promising correlation results, the horizontal load spreading seems the best option for evaluating the load spreading of a detected PEAS and SEAS. However, it was not possible to deliver a robust compatibility metrics for the PDB in time to be considered within the FIMCAR project. Nevertheless the FIMCAR consortium agreed to further develop the load spreading criteria based on the concepts of the horizontal load spreading criteria.

The final assessment methodology will be defined following the priorities that will be identified in FIMCAR, the basics have been established as shown in Equation 3.2. The PDB metrics including limits needs to be further developed and validated using the upcoming tests that will be performed in FIMCAR project.

During the testing and simulation activities of the project, the test severity has been also investigated. The conclusions in regards to this issue can be found in Section 4.1.1 of this report.

4 TESTING AND ANALYSIS OF TEST PROCEDURE

4.1 Simulations Performed for the Criteria Development

As already described in section 3.5 simulations were requested

- To investigate the robustness of the metric and assessment criteria and
- To identify potential for misuse in vehicle design.

WP5 performed some simulations with “Generic Car Models” (GCM) developed by CRF and conducted a sensitivity analysis with “Parametric Car Models” (PCM) developed by TUB that are included in this report.

More details regarding vehicle models and modelling techniques can be obtained in Section IV.

4.1.1 Simulations with Generic Car Models (GCM)

GCM models with and without sub-frame load path were used to simulate PDB tests at 60 km/h and with 50% offset according to PDB test protocol [ECE 2007].

- GCM1_A: Supermini without sub-frame load path
- GCM1_B: Supermini with sub-frame load path
- GCM2_A: Small Family Car with sub-frame load path
- GCM2_B: Small Family Car without sub-frame load path
- GCM3_A: Large/Executive Car with sub-frame load path

Figure 4.1 shows the GCM1A and GCM1B barrier deformation results. For the simulation runs with GCM an internal CRF PDB model was used.

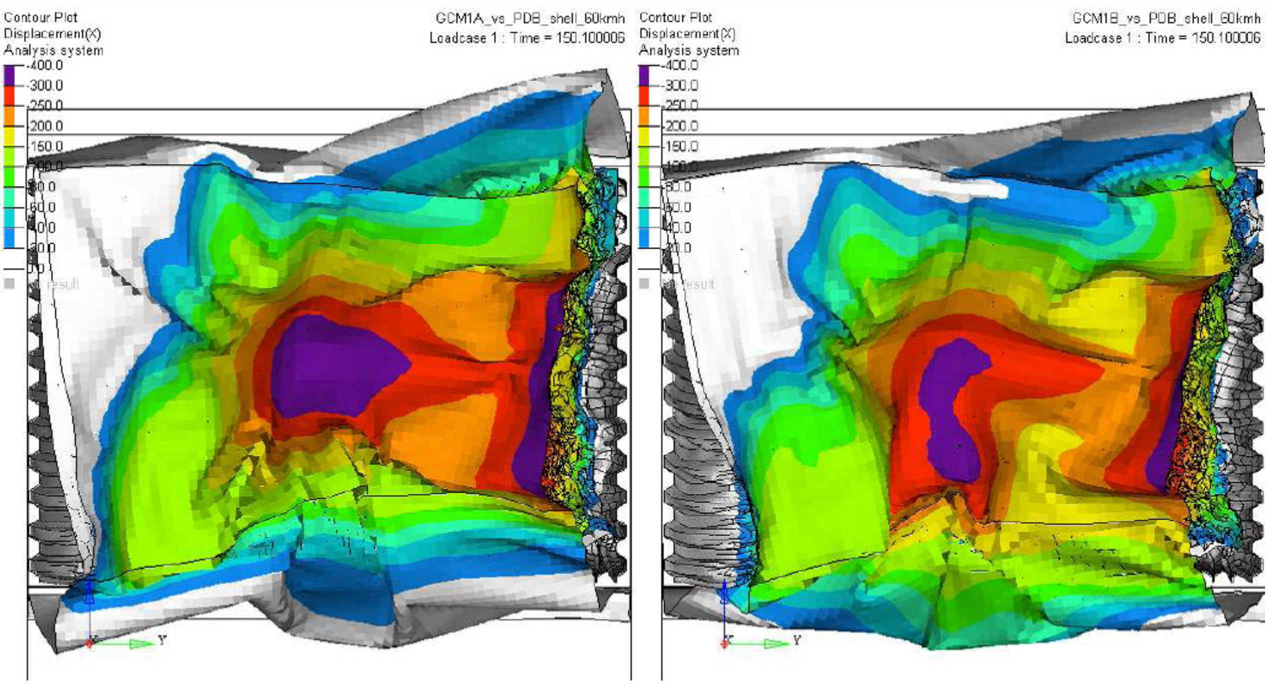


Figure 4.1: GCM1A and GCM1B barrier deformation.

As shown in Figure 4.1, the subframe of GCM1B deforms more the barrier at the lower area than GCM1A that does not have a subframe. This is numerically reflected by the lower longitudinal deformation for GCM1A (243 mm) compared to GCM1B (310 mm).

Table 1 shows the summary results that were analysed with BDA soft (v12.2010) [FIMCAR 2013], in the summary results, the longitudinal deformation is represented by the 99% of deformation and the load spreading (H) by TV criterion.

Table 1: GCM – PDB results.

Model	Simulation results			Results from BDA software [FIMCAR 2013]				
	Barrier Energy [kJ]	EES [km/h]	Force [kN]	Barrier Volume [l]	U Area 99% long. def. [mm]	M Area 99%long. def. [mm]	L Area 99%long. def. [mm]	M Area TV [-]
GCM1_A	62.9	42	343	135	281	346	243	1656
GCM1_B	63.6	42	357	133	236	314	310	1732
GCM2_A	82.3	40	391	166	664	365	336	1202
GCM2_B	82.4	41	381	152	595	359	309	1430
GCM3_A	129.1	36	444	249	717	507	444	1546

The numerical simulation work is a good methodology to assess the PDB test severity. In this kind of study, the PDB deformation can be analysed using the numerical methodology, which reduces the number of errors always existing in the actual testing.

As reported from the PDB test database, the test severity for the PDB has been identified as an issue in WP2. The GCM analysis supported this investigation. The variety of vehicles represented by these models in terms of vehicle sizes and front-end structures gave the possibility to conduct an analysis focused on the test severity for this family of vehicles.

The models were tested following the PDB 60 km/h and the ODB 56 km/h (test reference) configurations. Vehicles from different sizes and front-end structures were simulated in equal test conditions. Output parameters like maximal intrusions, EES and accelerations can be used to estimate the test severity for the different models.

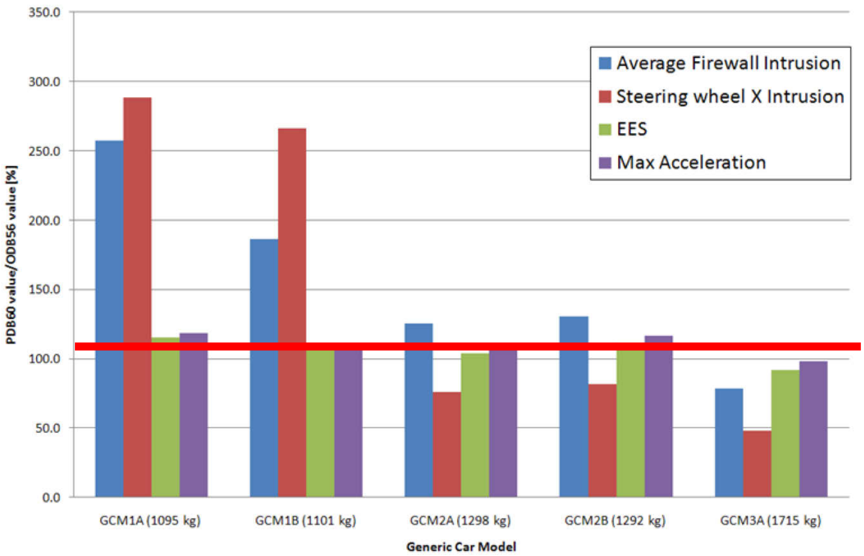


Figure 4.2: GCM – ODB vs. PDB results.

Figure 4.2 shows the test severity results for the 5 GCM vehicles comparing PDB60 against ODB56. The intrusion results were obtained from the maximal dynamic value. These values are considered to be slightly higher than the static ones, typically reported in physical testing.

The EES and the Max Acceleration seem to be the more appropriate criteria to assess the level of test severity. As it can be shown in Table 1, for the super-minis and small family cars the test severity is supposed to be higher for the PDB60. The opposite is observed in the case of the GCM3A (large executive vehicle), the EES in the PDB60 is about 10% below the ODB56.

This result is confirming the estimations from the PDB60 database, Figure 3.3, where for certain kind of vehicles the PDB represents a slightly more severe test that the ODB56 while in some large and stiff vehicle the opposite is observed.

4.1.2 Simulations with Parametric Car Models (PCM)

The requested simulations with PCM will be also conducted according to the test-setup of PDB test protocol [ECE 2007] with a PDB barrier offset of 50% and a vehicle velocity of 60 km/h.

In total 3 different types of cars (executive car, large family car and supermini) were modelled as PCMs. Based on the parametric design of the basis model the 3 models were generated with typical structural concepts. Therefore, the supermini model was designed without a sub-frame. Due to the fact that the engine of the large family car is very close to the cross-beam it was decided to use the executive car for the sensitivity analysis.

Figure 4.3 shows the PCM - Executive car FE-model, for the simulation runs the FIMCAR PDB model developed by GME was used:

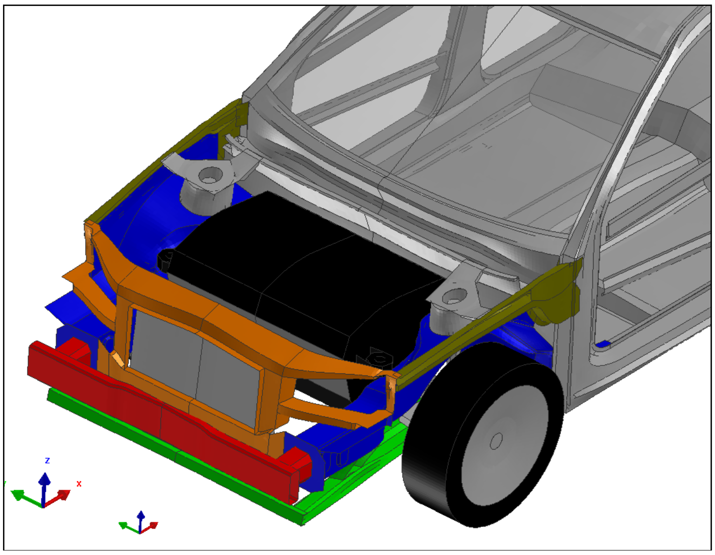


Figure 4.3: PCM – Executive car.

The requested sensitivity analysis will investigate the influence of different parameters on the PDB assessment criteria and developed metrics. These parameters are geometric parameters, describing the position and the stiffness of several structures, and crash severity parameters like vehicle mass and closing speed.

Table 2 shows a summary of the number of simulation to run.

Table 2: Simulation matrix for PCM.

Parameter of study	Number of runs	Priority
Vehicle mass	5	3
Test speed	5	3
Cross-beam stiffness	5	1
Cross-beam height	5	2
Cross-beam length (Y-direction)	5	2
Sub-frame length (X-direction)	5	2
Sub-frame stiffness	5	1
Sub-frame height	5	2
Sub-frame length (Y-direction)	5	2

In addition some worst case runs without crossbeam resp. collapsed crossbeam in order to produce holes in the barrier are planned.

Due to budget limitation simulation runs were prioritised as follows:

- 1st priority: stiffness of cross beam and sub frame
- 2nd priority: geometrical variations (width and position of structures)
- 3rd priority: vehicle mass and initial velocity

First simulation results indicated PDB barrier model (Version 1.0) quality issues that had to be further investigated to improve the validation of the barrier model. It will be validated against the barrier certification tests (trolley tests with rigid impactors) comparing force-displacement curves and scanned barrier deformations. Furthermore especially rupture of the cladding plate will be taken into account.

For this reason no conclusions regarding the sensitivity analysis can be drawn in this report.

4.2 Tests Performed for the Criteria Development

At the date of December 2011, a total of 3 tests were performed in WP2. Table 3 shows the up-to-date test matrix and the main objective of each test. WP2 plans to continue with the testing phase until the end of the project. The main objective of the coming tests will be the final development of the assessment procedure and prove the repeatability and reproducibility of the assessment.

Table 3: Test matrix.

Vehicle to test	Laboratory	Test Date	Test configuration	Objective	Partner-protection
Supermini 2	FIAT	Jun 2011	PDB60 [3]	Test severity validation (self-protection) and comparison with other test modes (FWRB and MPDB)	Good performance expected
City Car 1	UTAC	Sep 2011	PDB60 [3]	Comparison with FIAT 500 in terms of the vehicle performance	Good performance expected
Supermini 1	PSA	Nov 2011	PDB60 [3]	Test severity validation (self-protection) and validation of the compatibility assessment	Marginal performance expected
Supermini 2	BASt	Jan 2012	PDB60 [3]	Repeatability issues	Good performance expected

The tests performed relate to Task 2.2. Table above shows a total of 4 tests performed within WP2 following the PDB60 test procedure as defined in the EEVC proposal for amendment, details can be found at [ECE 2007]. The test consists on a 50% off-set against a Progressive Deformable Barrier (PDB) at a target speed of 60 km/h. In the test, 2 ATD HIII 50%ile Males were seated at the driver and front passenger positions, the dummies are used to estimate the level of injuries caused by the crash test.

4.2.1 Supermini 2 Test

Supermini 2 was selected with the objective of evaluate the PDB60 test severity and confirm the good performance of the vehicle in terms of partner-protection.

In order to evaluate the test severity different test pulses for Supermini 2 were compared (all tests from FIMCAR database). Figure 4.4 gives an estimate test severity level normalised to the USNCAP maximal acceleration peak.

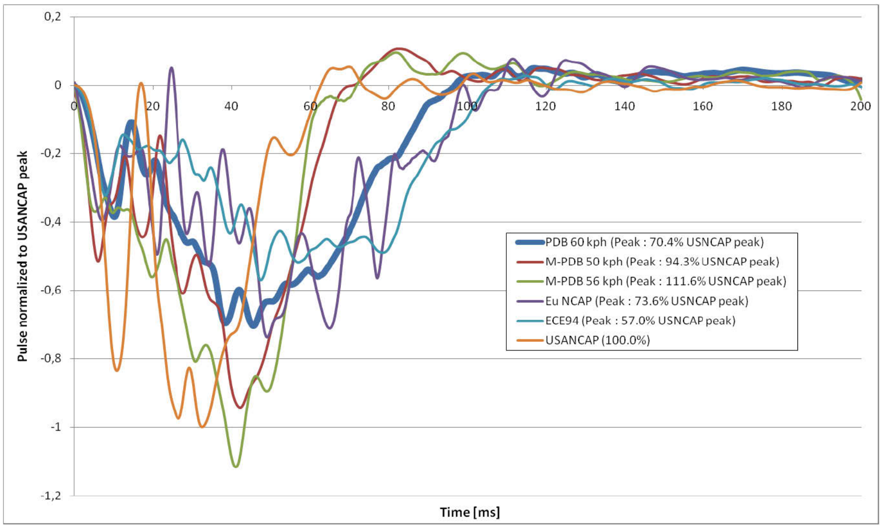


Figure 4.4: Supermini 2 B-pillar pulses.

Figure 4.4 shows Supermini 2 pulse at the driver's side for different kind of tests. As shown in the graph the PDB60 curve, dark-blue, is very close to the Euro NCAP one.

It is well known that the Euro NCAP (ODB64) test is more severe than the UNECE R94 test (ODB56). Then, for this particular case and taking the acceleration response as reference, we can conclude that the PDB60 represents a more severe test than the ODB56, light-blue trace in the graph. In terms of vehicle intrusions Supermini 2 achieved a very low A-pillar displacement, 1 mm for both cases, PDB60 and ODB56.

Regarding partner-protection issues, Supermini 2 loaded the middle and lower area of the barrier as shown in Figure 4.5. The load spreading for the middle area was particularly good.

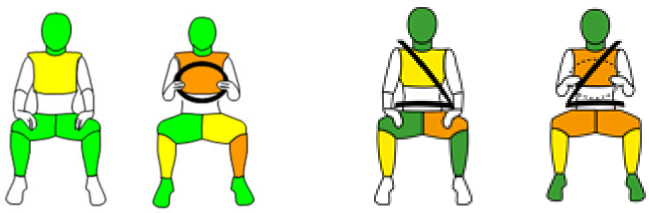
PDB60 MPDB50

Figure 4.5: PDB deformation Supermini 2.

Barrier deformation for the PDB60 and the MPDB50 test show similar pattern. This shows the general repeatability and robustness of the barrier deformation even under completely different crash conditions. However, there is a rupture in the front plate of the PDB60 test while it could not be observed in the MPDB test.

4.2.2 City Car 1 Test

In this case the test severity between PDB60 and ODB64 was also comparable, dummy readings have been compared, Figure 4.6.



PDB60 Euro NCAP [Euro NCAP 2013]

Figure 4.6: City car 1 dummy results.

In both test configurations driver and passenger dummy were loaded in a similar manner. Head injuries were below the Euro NCAP higher performance [Euro NCAP 2013], 5% risk of injury ≥AIS3. Driver and passenger's chest were loaded likewise in both tests. The driver's chest had a higher injury risk compare to the passenger. The injuries at the lower extremities were also comparable, driver legs recording higher values than passenger for both test configurations.

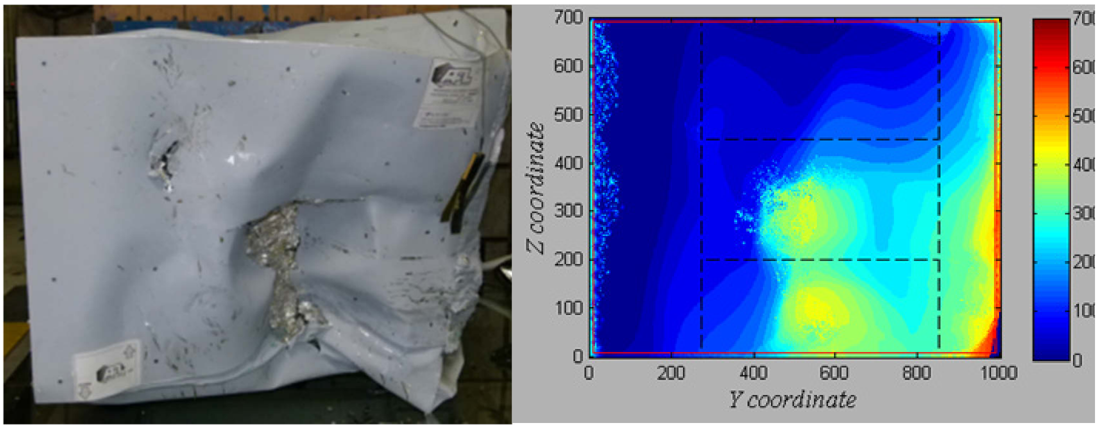


Figure 4.7: PDB barrier deformation of City car 1.

The PEAS and SEAS of City car 1 loaded the middle and lower area of the barrier respectively, Figure 4.7. The load spreading for the middle area was marginal.

4.2.3 Supermini 1 Test

The Supermini 1 crash pulse achieved a maximum peak of about 40 g. Figure 4.8 shows the B-pillar acceleration against vehicle displacement.

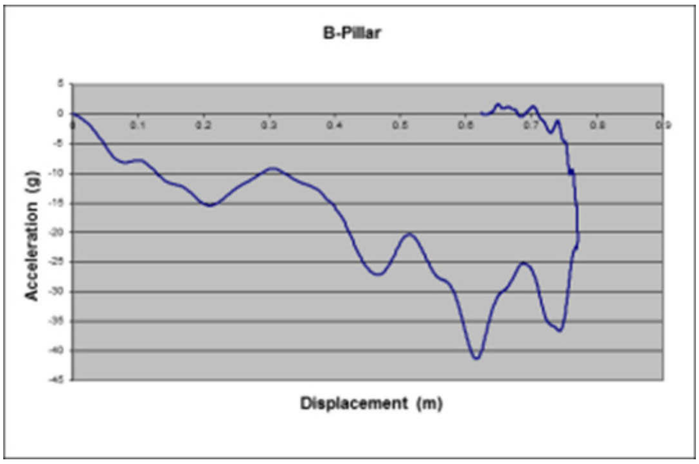


Figure 4.8: Supermini 1 PDB60 crash pulse.

Figure 4.9 shows the dummy results for PDB60 and Euro NCAP tests. The overall results in both tests are equivalent. It is remarkable that there are higher chest injury risks for both occupants in the PDB test compared to the Euro NCAP.

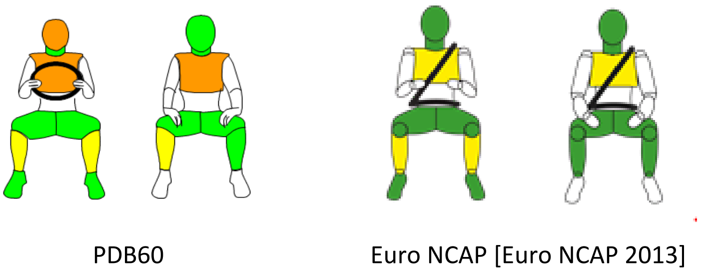


Figure 4.9: Supermini 1 dummy results.

In terms of vehicle intrusions Supermini 1 achieved a low A-pillar displacement, 23 mm in the Euro NCAP test and 17 mm in the PDB60.

The PEAS of Supermini 1 loaded the middle and lower area of the barrier respectively, the load spreading for the middle area was marginal, Figure 4.10. The lower part of the barrier was not deformed. Therefore no SEAS have to be detected for this car.

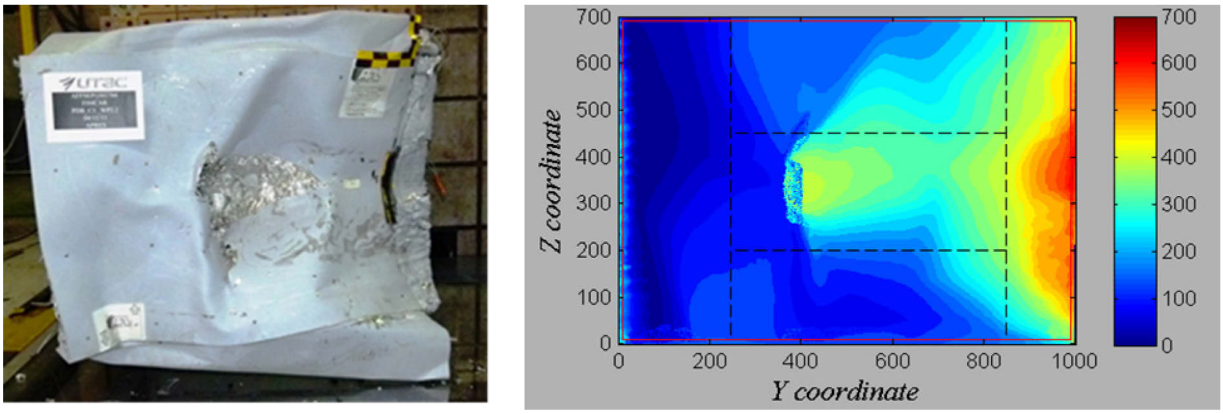


Figure 4.10: Supermini 1 PDB barrier deformation.

4.3 Conclusions

Simulation and testing work conducted in WP2 show that PDB test severity is comparable with the severity for the ODB test procedures (R94 / Euro NCAP). In particular, the PDB seems to be a slightly more severe test procedure for most of the small and light vehicles, while for some large car the severity is slightly below the current ODB56 approach. For example, the three vehicles tested in WP2 following the PDB tests seems to be at the similar level of ODB64 and therefore above the ODB56. But as simulation results show for the GCM3 model (large executive car), the PDB test appear to be less severe than the ODB56. This result correlates with the trend for PDB database.

WP2 plans to conduct more testing activities with large vehicles in order to try to validate the result obtained by simulation work and the database.

The PDB results obtained in this testing series will be further used for developing the partner-protection criteria proposed in WP2.

5 DISCUSSION AND CONCLUSIONS

The current ODB procedures assess the self-protection of the tested vehicle. There are no methodologies investigating the partner-protection (e.g. structural interaction or frontal force levels).

According to the accident analysis performed in FIMCAR, reported in Deliverable D1.1 and Section II, self-protection topics like passenger compartment intrusions and high acceleration are still an issue on the road. The present ODB test procedure addresses these self-protection issues and therefore the procedure is still valid to maintain today's self-protection level.

The test results obtained in the project with the PDB highlighted that the severity of this test procedure was comparable to the current ODB tests for most of the analysed cars. Therefore, the PDB test seems to be an acceptable method to evaluate self-protection issues except for very heavy vehicles.

Self-protection issues could be also assessed by PDB test procedure, the tools and methodology to assess self-protection can be adopted from the current ECE R94 test.

In order to address some partner-protection issues, also reported in FIMCAR's accident analysis, WP2 has identified the PDB test procedure as the most promising methodology. The fundamentals for assessing partner-protection issues with the PDB approach have been defined.

The PDB methodology consists of assessing the barrier deformation. The PDB will be vertically divided in zones as shown in Figure 5.1. The 350 to 580 mm from ground area is harmonised with the FW methodology, this area includes the CIZ.

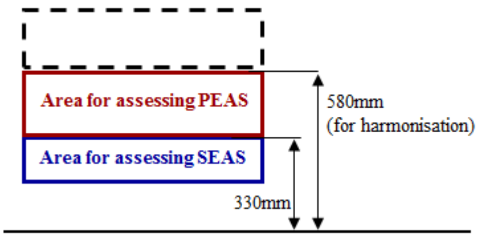


Figure 5.1: PDB areas of assessment.

The structural interaction was defined as the main issue for improving the partner-protection of a vehicle. The vertical location of the load paths, assessed by the barrier deformation caused by the longitudinal, provides an estimation how the tested vehicle will interact with an opponent car.

First priority was established on detecting the vehicles load paths in the CIZ and below that zone.

The contribution of the SEAS was defined as an added value to contribute in partner-protection issues. 50 to 65% of longitudinal deformation, or mean deformation, were identified as the most promising parameters to detect the load paths, Figure 5.2 shows the result of the PDB60 database for SEAS detection.

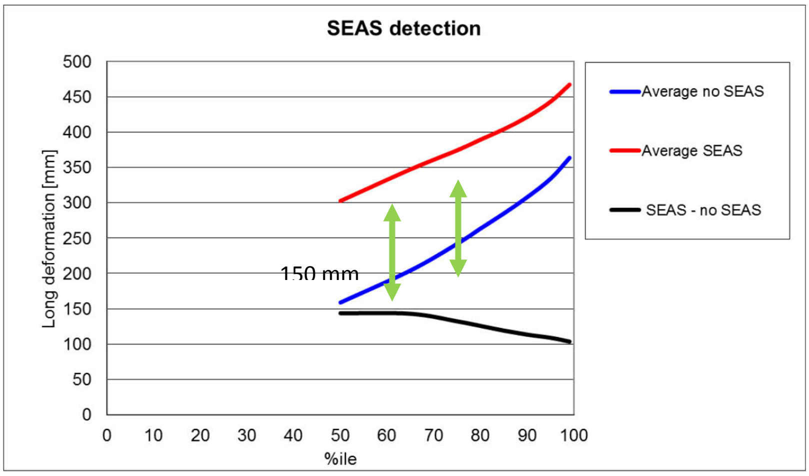


Figure 5.2: Load path detection.

The load spreading in the CIZ was also identified as a main issue to be addressed by the PDB procedure. Several proposals for assessing the characteristics of the load spreading were investigated in WP2. The load spreading criterion will focus on assessing the horizontal load distributions in the area where the CIZ is located. This criterion will be addressing compatibility issues like the small overlap and the fork effect.

Although the subjective assessment of PDB barrier scans is promising to rate the load spreading it was not possible to develop a PDB metrics that is robust enough to propose the PDB as part of the FIMCAR frontal impact assessment approach. The ODB56 will be kept in order to maintain current self-protection requirements. However, PDB might still be an option for the future when a validated compatibility metrics can be proposed.

It should be noted that work to develop compatibility metrics for the PDB test will continue within the project because the FIMCAR members believe that the PDB test has potential for compatibility assessment in the longer term.

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7 GLOSSARY

ATD:	Anthropomorphic Test Device
BDA:	Barrier Deformation Analyser
CIZ:	Common interaction zone (as described in Part581 zone)
EES:	Energy Equivalent Speed
EEVC:	European Enhanced Vehicle Safety Committee
Euro NCAP:	European New Car Assessment Programme
FW:	Full Width Frontal Impact
GCM:	Generic Car Models
HIII:	Hybrid III test dummy
IIHS:	US Insurance Institute
LCW:	Load Cell Wall
NHTSA:	US National Highway Traffic Safety Administration
ODB:	Off-set Deformable Barrier Test (current ECE R94/Euro NCAP)
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PCM:	Parametric car models
PDB:	Progressive Deformable Barrier
PEAS:	Primary Energy Absorbing Structures
SEAS:	Secondary Energy Absorbing Structures
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility