DEVELOPMENT OF A STRUCTURAL INTERACTION ASSESSMENT CRITERIA USING PROGRESSIVE DEFORMABLE BARRIER DATA

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Paper Number 13-0421

ABSTRACT

Structural interaction has been one of the critical issues for improved frontal impact protection. An evaluation procedure for structural interaction has been difficult to develop using objective test data procedures. While previous research with the PDB barrier has been promising based on subjective evaluations, an objective assessment criteria has been elusive. Part of the EU project FIMCAR focused on the development of an assessment procedure to assess important frontal impact characteristics like load spreading.

Test and simulation data from vehicle impacts with the PDB or MPDB were collected for different vehicle models, spanning a range of vehicle masses and vehicle classes. Available car-to-car crash tests were also collected for reference. The main information analyzed w.r.t. the assessment of load spreading was the deformation pattern of the PDB barrier after a test. These deformation plots were reviewed and subjectively assessed by experts. The subjective assessments were used to develop key characteristics that should be detected by a numerical assessment of the 3D data. These subjective assessments were then compared to different objective (numerical) assessments for the barriers to ensure correlation of the results and then validated with available car-car data. Assessment of the influence of assessment area and scanning resolution were also performed.

The deformation profiles could be grouped into three main groups where the horizontal and vertical load spreading distinguished vehicles with good or poor performance. The main focus was the development of an assessment of the horizontal load spreading between the longitudinals. A metric based on the slope or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate. A horizontal assessment area based on 60% of the overall vehicle width and a vertical area between 330 and 580mm from ground was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern or a vehicle with localized structures.

The candidate for an (M)PDB metric that assesses horizontal load spreading provides an objective method to assess structural interaction. The assessment has been validated for the vehicles that can be clearly grouped into a good or poor performance category. There are a number of vehicles that are in a borderline area that require further evaluation. The cases where vehicle-to-vehicle crash data is available have validated the performance of those vehicles. Further validation using field data and car-to-car test or simulation results can finalize the metric development.

The paper addresses a central issue for frontal impact performance. While structural alignment and occupant compartment stability issues can be addressed by adding the FWDB test procedure as proposed by the FIMCAR project to the current ODB procedure, there is no test procedure available that reliably assesses horizontal load spreading. The proposed DDY metric for the PDB test procedure allows the front structure for

vehicles to be assessed and be updated to also assess vertical load spreading.

INTRODUCTION

Crash compatibility, defined as the level of self and partner protection, between the two vehicles involved in a collision is a key factor in the assessment of vehicle safety performance in frontal impacts. Compatibility has been considered a crucial concept for frontal impact safety for many years, but no final assessment approach has been defined. There are several test procedures that have been classically considered for the assessment of crash compatibility. Two tests approaches come from previous research activities (EEVC WG15 and FP5 VC-COMPAT), and both are composed of an offset and a full-width test procedure. However, in both cases there was no final decision in the assessment methodology. A third test procedure, based on a moving deformable barrier, has been investigated in the latest research activities regarding compatibility.

The FIMCAR (Frontal Impact and Compatibility Assessment Research) research project was co-founded by the European Commission within the 7th Framework Programme to address the compatibility issue and aim to provide answer to questions identified in previous research projects. Previous research projects identified some frontal crash incompatibilities between vehicles, due to the differences in front stiffness, bad structural interaction, insufficient compartment strength and mass differences. One of the goals of FIMCAR was to develop and proposed a compatibility assessment methodology that would be accepted by the majority of the involved industry and research organizations. For that purpose, different off-set, full-width and mobile deformable barrier (MDB) procedures were analyzed during the project and their capabilities for the assessment of frontal compatibility were investigated.

In this paper, the activities performed within the FIMCAR project using the Progressive Deformable Barrier, PDB, and the Mobile Progressive Deformable Barrier MPDB to develop and propose a structural interaction assessment criteria are described.

Off-set existing procedures

Three off-set procedures are currently used in regulations, research and consumer testing activities:

- Off-set Deformable Barrier Procedure (ODB)
- Progressive Deformable Barrier Procedure (PDB)
- Small Overlap Procedure

The ODB frontal crash test was developed by the Enhanced European Vehicle-Safety Committee (EEVC) between 1989 and 1995 and simulates the collision of the tested vehicle against another vehicle of similar mass [1]. The test consists in a frontal crash where the car impacts a kinetic energy absorber (a deformable barrier also developed by the EEVC and based on aluminum honeycomb technology) with an off-set of 40% on the driver side. This crash test is currently used in the European regulation and Directive at a speed of 56 km/h. The European Consumer Testing Program Euro NCAP adopted this same procedure in 1996 increasing the test speed to 64km/h [2]. A Hybrid III Anthropomorphic Test Device (ATD) is used to evaluate the self-protection of the vehicle measuring parameters such as forces, deflections or accelerations that are related with the probability of sustaining an injury of a determined severity during the crash. This EEVC barrier is used by car manufacturers and crash test laboratories all over the world for off-set frontal passenger vehicle's protection assessment according with the following standards:

- Regulatory : UN ECE R94, European Directive 96/79/CE, FMVSS 208, ARD 73/00
- Consumer testing: Euro NCAP, IIHS, USNCAP, C-NCAP, A-NCAP, J-NCAP, etc…

However, there are no current activities that investigate the use of this procedure for measuring structural interaction, although for some studies a wall of load cells was mounted behind the deformable barrier to measure the force levels during the frontal impact [3].

The PDB procedure is performed at 60km/h and 50% overlap on the driver side and simulates a frontal collision of the tested vehicle against other vehicle. The stiffness of the PDB is significantly higher than the ODB and is in line with the current vehicle fleet in Europe. The barrier was proposed in previous research projects by France, is also

based on aluminum honeycomb technology and is only used for research activities.

Figure 1. (PDB 60 km/h crash test).

The small overlap procedure consists in a frontal impact against a rigid obstacle with 25% overlap on the driver side, leading to higher intrusions than the larger overlaps. In 2012 the Insurance Institute for Highway Safety introduced the small overlap tests in its assessment of frontal impact protection, after some research programs highlighted that narrow objects are still one of the sources of severe injuries [4]. The test is performed at 64km/h and the assessment of self-protection is performed trough the measurements of a Hybrid III dummy seated in the driver position.

Limitations of ODB procedure assessing compatibility and advantages of PDB

The requirements currently set for self-protection lead to the design of large vehicles with a stiffer front end (compared to small vehicles) in order to compensate for their mass because the ODB test is more severe for heavy vehicles than the lighter ones. These tests also lead to higher compartment strength, since the solutions have been optimized against ODB or rigid wall but not car-to-car configurations. The current ODB procedure was developed being adapted to the geometry and force deformation of vehicles from the 1990's, but both the geometry and stiffness have changed a lot in the current vehicle's front design. This makes compatibility requirements more and more difficult to achieve, but the fact is that improving partner-protection while keeping the current levels of self-protection is needed for future vehicles.

The EEVC WG15 provided some issues of the ODB barrier such as barrier instability for the new generation of cars due to the low stiffness of the barrier, test severity has increased with the increased of car mass and keeping constant speed, self-protection is depending on vehicle size and mass, it is difficult to assess force levels with constant speed (bottoming out of barriers causes undesired inertial loads) and the assessment of structural interaction is not possible because of load spreading and subsequent barrier bottoming out.

To overcome these issues, the new PDB was developed to harmonize the test severity among vehicles of different masses, encouraging the light vehicles to improve the passenger compartment stiffness without increasing the force levels of the heavy vehicle's front end, and leading to a better force matching between vehicles. Its stiffness increases with the crush depth and provides different characteristic in the vertical axis. The dimensions and the stiffness make the bottoming-out very unlikely in the PDB and the barrier face is capable of generating sufficient differential deformation of both the weak and stiff parts of the car's front structure to replicate what happens in most accidents. The PDB barrier represents the opponent vehicle and the fact that it does not bottom-out allows the analysis of the opponent vehicle deformations. The assessment of load spreading is impossible with the ODB while the PDB is designed to assess the load spreading based on barrier face deformation.

The design of this barrier has the intention of encouraging future car designs to incorporate structures that distribute the force on a large surface better for structural interaction and partner-protection. The 60 km/h test speed of the PDB procedure 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 be modified. In conclusion, test severity for all vehicle mass range will be harmonized. This speed will also ensure that the level of EES is comparable to current levels (ECE R94).

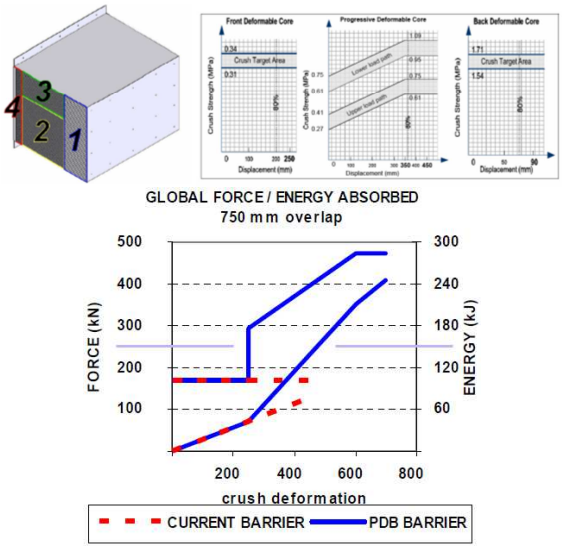

Figure 2. PDB characteristics (top) and comparison of ODB and PDB in terms of global force and energy

FIMCAR APPROACH

Based on previous work and the accident analysis performed during the FIMCAR project, the Consortium established a list of the critical compatibility requirements [5]. A total of 8 main priorities were identified, but the ones that need to be evaluated in the off-set procedure are:

- Load spreading
- Structural alignment: over-ride/under-ride, small overlap and fork effect were found predominant in cases with injuries and fatalities
- Single vehicle collision compartment strength evaluation
- Evaluate restraint systems for different pulses (combined with full width FW procedure)

FIMCAR has analyzed existing crash compatibility data from previous research projects, Euro NCAP and ECE R94 tests. Previous research projects indicated that load cell measurements in off-set procedures are not appropriated to assess load distribution, so FIMCAR decision was to concentrate in PDB procedure and assess the barrier face deformation. This cannot be done in the ODB because the barrier is normally overcrushed and the vehicle contacts the rigid barrier face.

The PDB barrier was divided in three areas for evaluation (Figure 3):

- Upper area: This area is above Primary Energy Absorbing Structures (PEAS) and secondary Energy Absorbing Structures (SEAS) for most of the vehicles.
- Middle area: Includes the Common Interaction Zone (CIZ). For most vehicles is where the PEAS are located.
- Lower area: This area is below PEAS for most of the vehicles, but in some cases is where SEAS are located.

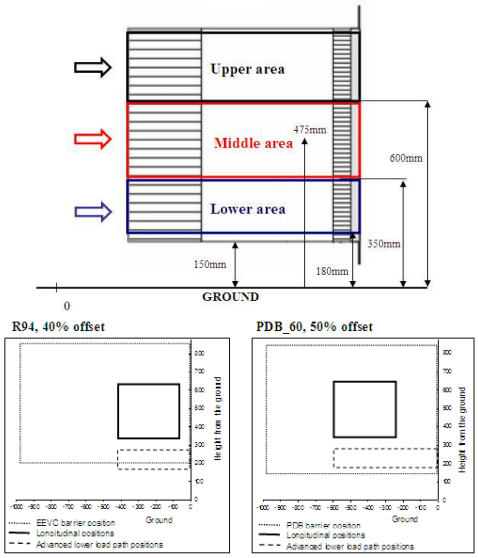

Figure 3. Areas of assessment of the PDB Barrier and differences in ODB and PDB structures location

Significant longitudinal deformations in the upper area will increase the risk of over-ride/under-ride issues. Homogeneous deformations in the middle area are promoted to improve partner-protection issues such as “fork effect” and the small overlap. Deformations in the lower area are also promoted to improve compatibility issues as well.

During the initial development phase of the PDB metric, the development was supported by a database of 37 PDB tests at 60 km/h performed in previous research projects (e.g. VC-COMPAT). FIMCAR contributed to this database with 7 additional tests to develop the new metric. Therefore, a total of 44 cases were available to develop this metric.

In a first phase, the barriers were classified following a subjective approach, only considering the barrier deformation and not the vehicle data. This subjective classification is shown in Figure 4.

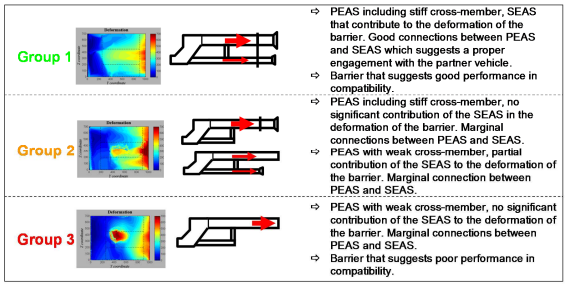

Figure 4: Subjective classification by groups

In the second phase the classification of the barriers based on the subjective evaluation was modified to focus in the main objectives defined by the FIMCAR Consortium:

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

The proposed metric was based on the PASS/FAIL approach shown in Figure 5. In a first phase the presence of a load path is analyzed, and then the characteristics of the load path in terms of spreading loads through the barrier are considered.

The aim of the criteria is to identify the structures capable to significantly deform the barrier. The 3D measurements of the barrier allow the identification of the vehicle load paths that will be detected if certain quantile values are above certain limits. Regarding the load spreading, different criteria were considered: Total Variation criteria (TV), Smooth Deformation Index (SDI), Area of significant deformations and Horizontal Load Spreading. For its simplicity and some promising correlation results, the horizontal load spreading was considered the best option for evaluating the load spreading of a detected PEAS and SEAS.

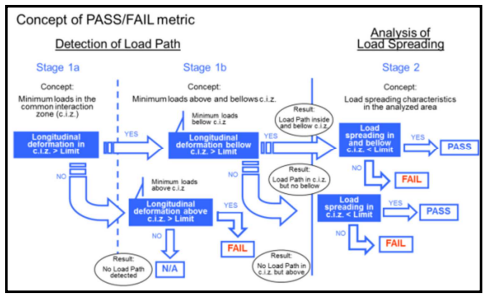

Figure 5. Proposal for metric.

RESULTS

PDB metric description

A total of 44 cases were considered to develop the PDB metric, including 37 cases from previous research projects and 7 cases conducted within the FIMCAR project. The PDB barrier deformation was taken as a reference for the metric development. In a first phase a subjective classification described in Figure 4 was considered and then a criterion based on load path detection and load spreading characteristics was defined.

The PDB was vertically divided in two main zones, the area for assessing PEAS and the area for assessing SEAS. The area for assessing the PEAS was identified as the priority for evaluating the load spreading and it was decided that should include the CIZ of Part 581 (406 to 508 mm from ground) for harmonization purposes with the FW procedure. Finally an area from 330 to 580 mm from ground was selected (Figure 6).

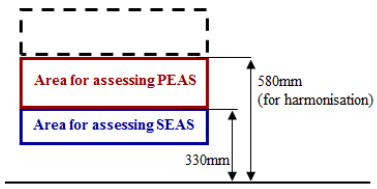

Figure 6. PDB areas of assessment.

For the calculation of the PDB metric calculation the following steps need to be follow:

- Scan the PDB
- Pre-process the PDB scanning
- Criteria calculation: Load path detection and Load Spreading characteristics
- Metric calculation: PASS/FAIL threshold definition

Both the PDB definition and certificate and the PDB scan procedures are detailed in the FIMCAR

Deliverable D2.2 [6]. Different pre-processing methods were investigated: Ray Tracing method and Deformation Projection method. Although both methods presented reasonably consistent results, VTI method was adopted for further PDB analysis due to the most consistent filtering of the data and having deformation gradient less susceptible to small tears or folds.

Then, the load path was evaluated by the deformations based on the 3D measurements of the barrier, which allow the identification of the vehicle's load paths. The load path detection was assessed by the Longitudinal Deformation of the barrier using the developed (d) criterion. This criterion is based on statistics characteristics of the deformation at a defined zone, taking coefficients of the barrier longitudinal deformations. Figure 7 shows an example of limits for detecting load paths. The stiffness of the vehicle is also evaluated, limiting the maximal longitudinal deformation.

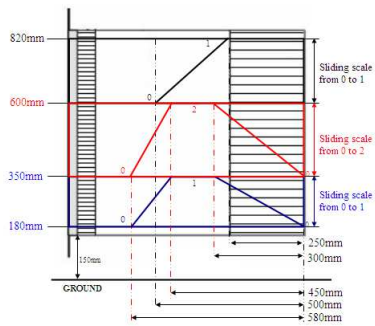

Figure 7: Load path detection, longitudinal deformation

The area of the barrier considered for horizontal load spreading could be divided in N equal sub-zones. Vertical limits were set from 330 to 580mm from ground while the horizontal limits will vary depending on the vehicle's width.

The differences of longitudinal deformations and relative distances between them are analyzed using different parameters:

- D is the average of longitudinal deformation of the complete area
- Di (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
- DDY, Digital Derivative in Y direction, based on change of slope or gradient

And some criteria have been developed using these parameters:

- D/Di esimates of the horizontal variation of the i sub-zone compare to the total average
- ei=D-Di is the deviation of a sub-zone from the overall average of deformation
- Statistics of DDY (i.e. max DDY, 99%ile DDY and STD DDY)

The DDY calculation on the entire longitudinal area was the best candidate to evaluate the load spreading.

$$\text{For } y=1 \text{ to } Ny,\ z=1 \text{ to } Nz \quad DDY(y,z) = \left| \frac{X(y,z)-X(y-1,z)}{\text{mesh size}} \right|$$

Figure 8. DDY equation

Different options for the metric development were considered:

- Lateral limit: (W/2-100mm), 80%, 70% and 60% of vehicle width
- Vertical definition: CIZ of Part 581 and Row 3&4
- DDY criteria: max DDY, 99%ile DDY and standard deviation of DDY
- Mesh dimensions: 1,3,5,10 mm

The 99%ile DDY calculated in the defined area gives an estimation of the homogeneity of the barrier. Lower values correspond to small variations in the analyzed area, therefore more homogeneous vehicle deformation.

The horizontal limits of investigation are fixed at 150 mm from the center of the vehicle and extend laterally to the side of the tested vehicle. A limit of 60% of the vehicle width was proposed.

The assessment area that provided best correlation with the subjective classification and showed acceptable repeatability and reproducibility results consisted of:

- 330-580 mm (row 3 and 4 in the full width (FW) tests
- 60% of the vehicle width
- 99% DDY with a threshold of 3.5

In Figure 9 the subjective classification against the 99%ile DDY in the previously described evaluation area is shown. Using a threshold value of 3.5, the 99%ile DDY discriminated between vehicles with an even (homogeneous) deformation pattern, G1, and barrier with localized holes, G3.

The criterion had a good sensitivity to discriminate vehicles according to the subjective rating although there were some borderline cases that request further review. It can be seen that the criterion showed good repeatability for the different Supermini 2 tests with all the values around 0.6. Acceptable R&R in terms of PASS/FAIL assessment was found for the cases studied in previous projects, except the left and right hand versions (cases 9 and 19 in Figure 9). Differences are due to the asymmetric powertrain structures and should be considered in a "worst case" condition for testing. The metric was also consistent with the modification of vehicles for compatibility. Vehicle 56 was modified to create vehicle 54 for compatibility and the metric result changed accordingly and correlated with the PASS/FAIL results.

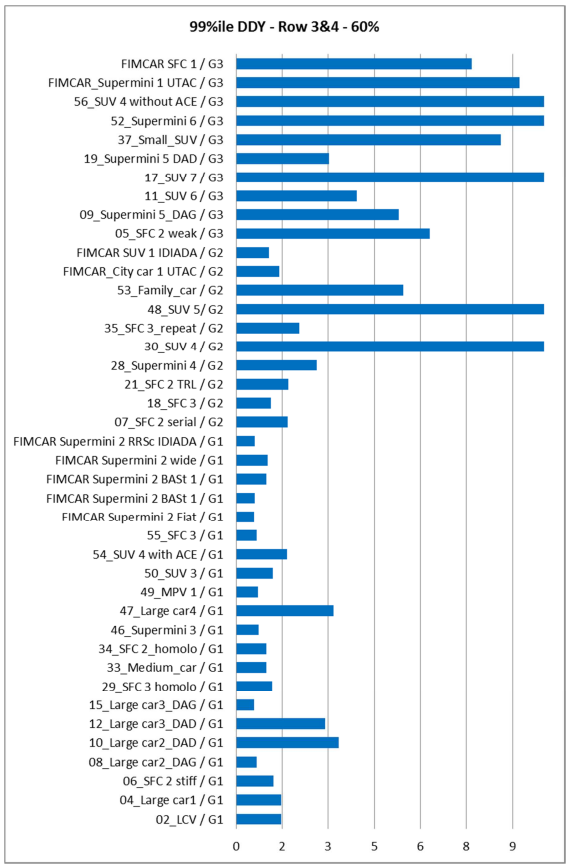

Figure 9. 99% DDY, Row 3&4, 60%.

Simulations

In order to investigate the robustness of the metric and assessment criteria and to identify potential for misuse in vehicle design some simulations using 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.

- 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

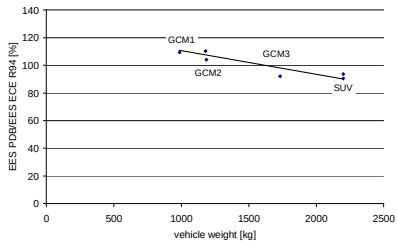

Figure 10. EES dependency on vehicle weight

The models were tested following the PDB 60 km/h and the ODB 56 km/h 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. Simulation results showed a clear tendency of decreasing requirements for the PDB tests when increasing the vehicle weight (Figure 10).

PDB tests

A total of 7 tests were performed using the PDB procedures. Figure 11 shows the complete test matrix and the main objective of each test. This testing program support the final development of the assessment procedure and support the repeatability and reproducibility (R&R) evaluation of the PDB approach. A detail description of these tests can be found in D2.2 of the FIMCAR Project [6].

Vehicle to test	Laboratory	Test Date	Test configuration	Objective	Partner-protection
Supermini 2	FIAT	Jun 2011	PDB60	Test severity validation (self-protection) and comparison with other test modes (FWRB and MPDB)	Good performance expected
City Car 1	UTAC	Sep 2011	PDB60	Comparison with Supermini 2 in terms of the vehicle performance	Good performance expected
Supermini 1	PSA	Nov 2011	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	Marginal performance expected
Supermini 2	BASt	Jan 2012	PDB60	Repeatability issues	Good performance expected
Supermini 2	BASt	Apr 2012	PDB60	Repeatability issues	Good performance expected
SUV 1	IDIADA	May 2012	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	Good performance expected
Small family Car 1 (SFC 1)	IDADA	Jun 2012	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	PASS/FAIL limit investigation

Figure11: PDB test matrix

In order to address the compartment strength, the pulse, intrusion and dummy readings were considered. The PDB scanning was also analyzed in order to evaluate the Structural interaction of the vehicle (load spreading).

Pulse The vehicle pulse gives an estimation of test severity in terms of deceleration (higher pulse indicates higher severity and shorter duration also suggests higher severity). This pulse was measured at the B-pillar base of the vehicle. The pulses for all the PDB tests are shown in figure 12. This figure shows that small vehicles reach higher deceleration peaks than heavy vehicles.

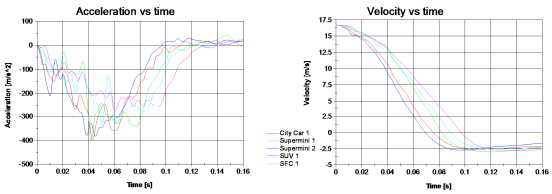

Figure 12: Tested vehicles pulses

The maximum mean acceleration (maximum Delta V divided by the time to reach this maximum Delta V) was used to compare the level of severity between the vehicles. The Supermini 2 test was more severe in terms of deceleration pulse compared to the others and the lowest values were reached by the SUV1 and the SFC.

Intrusion The residual displacement of structural components in the passenger compartment (intrusion) provides an indication of the level of self-protection offered by the tested vehicle. For instance, the presence or not of rearward displacement of the A-Pillar will indicate a level of self-protection of the tested vehicle. European vehicles produce a very low A-pillar rearward displacement in off-set test (R94, Euro NCAP or PDB) and the same behavior was observed in the FIMCAR tested vehicles, where the A-pillar intrusions were always below 30mm.

Dummy readings Dummy measurements are a direct indicator of vehicle's self-protection. This measurements were performed using a Hybrid III 50%tile male dummy (ECE R94) and the injury parameters obtained were compared to Euro NCAP rating to provide an estimation of the level of protection provided by the vehicle and compare PDB and Euro NCAP rating.

Figure 13: PDB vs Euro NCAP ODB dummy readings for Sumpermini 2 test

As the PDB test represents a more severe test for the Supermini 2 compared to the Euro NCAP one, higher injury values were obtained in the PDB compared to the test performed by Euro NCAP.

PDB Scanning PDB procedure serves to investigate the level of partner-protection provided by the tested vehicle and in particular, the PDB assessment is focus on load spreading issues, measured through the scans of the tested barriers. The PDB scans obtained in the 7 tests performed were included in the development of the PDB metrics as explained in the PDB metric description.

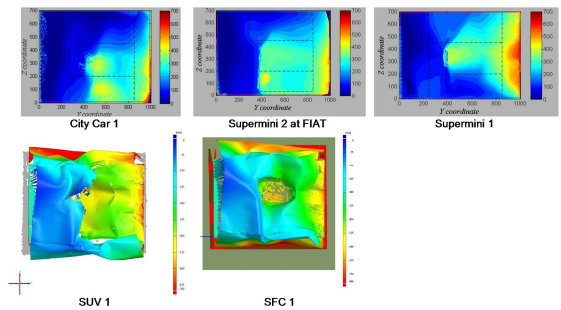

Figure 14: PDB scans

Validation of the PDB metric

The validation of the PDB metric involved PDB and the associated car-to-car tests to show that the vehicles that showed "compatibility" problems failed the metric and those without these issues were addressed appropriately by the PDB metric.

Three series of car-to-car crashes were used to support the off-set assessment proposal, the PDB metric (PASS/FAIL definition) and the final validation of the PDB metric:

- Supermini 2, aligned and misaligned
- Supermini 1, aligned and misaligned
- SUV 1 vs. SFC 1, aligned and misaligned and SUV 2 vs. SFC 1 aligned

In these tests the main issues addressed were the under-ride/over-ride and also the "fork effect" in the aligned conditions, where no under-ride was present. The reference test used for FIMCAR was the Euro NCAP test.

In the car-to-car tests, the Supermini 2 in both the aligned and misaligned crash tests was OK in the load spreading. Therefore, the Supermini 2 test series suggests that the tested vehicle should be a clear PASS the load spreading metric. In the Supermini 1 case, the aligned car-to-car test presented acceptable results for both tested cars, but the misaligned situation showed a bad performance in the lowered car compared to the other vehicles (aligned and raised), which was identified as an "incompatible" situation (under-ride of the raised vehicle) probably due to the absence of SEAS, or other structures to support vertical load spreading. High injuries for the driver and high vehicle intrusions were measured. The PEAS of the Supermini 1 worked well in alignment conditions so should PASS the metric.

Finally, the last car-to-car test series showed better results in the SUV 1 vs. SFC 1 (aligned and misaligned) compared to the SUV 2 vs. SFC 1 (aligned), this last test was classified as an "incompatible" situation due to a fork effect.
As conclusion, the SUV 1 will be a clear PASS vehicle, while the SUV 2 and SFC 1 need to be further evaluated in order to understand the final reason of the fork effect and the main responsible of the "incompatible" situation.

Repeatability and reproducibility

In order to study the repeatability and reproducibility of the procedure, it was decided by the FIMCAR Consortium to perform three tests of the Supermini 2 in two different laboratories (FIAT and BAST). The results of the acceleration vs time and velocity vs time are shown in figure 15.

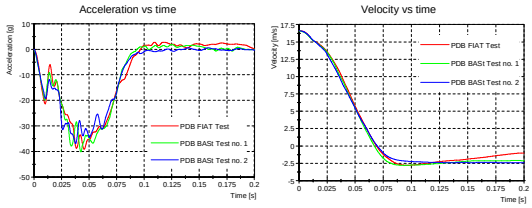

Figure 15. Supermini 2 test pulses.

A barrier separation at the outer part of the PDB was observed in the FIAT test. The issue seemed to be caused during the vehicle rebound phase (Figure 14, time 150ms). It affected the PDB analysis when extended to 70% or 80%, so a limit of 60% was proposed. In terms of dummy readings, comparable results were obtained in FIAT and BAST test 2 (BAST test 1 was not compared since the restrain systems was not fired).

MPDB tests

The Mobile Progressive Deformable Barrier (MPDB) procedure consists in the assessment of the vehicle with a moving trolley equipped with a deformable barrier in a frontal configuration. The same barrier used in the PDB was used for the MPDB tests as the development of a new barrier was out of the scope of FIMCAR.

The two parameters used in the tests to define the test severity were:

- Test speed: 50 km/h (test were also conducted at 45 and 56km/h)
- Trolley mass: 1500 kg (simulations were also performed with 1300 and 2200 kg of trolley mass)

All tests were conducted using Hybrid III 50%tile except that a Hybrid III 5%tile female was used on the passenger seat to investigate the protection level for these type of occupant. Figure 16 shows the test matrix for the MPDB tests.

Lab	Number	Vehicle	Vehicle mass [kg]	Trolley mass [kg]	Vehicle speed [km/h]	Trolley speed [km/h]	Offset [%]	Driver	Passenger
Reference tests: Velocity 50 km/h / Trolley mass 1500 kg / Offset 50%									
TTAI	F114204	Supermini 3	1136	1503	50.4	50.4	50	50th	5th
TTAI	F112902	Citycar 1	1159	1503	50.1	50.1	50	50th	5th
Fiat	17204A	Supermini 2	1225	1512	50	50	50	50th	50th
BAST	FM06C3MB	Supermini 1	1301	1500	50.1	50.1	50	50th	5th
IDIADA	111410CF	Small Family Car 2	1482	1500	50.4	50.1	50	50th	5th
TTAI	F103904	Small Family Car 2	1484	1512	49.8	49.4	50	50th	50th
IDIADA	122701CF	SUV 1	1907	1500	50.4	50.4	51	50th	50th
UTAC	AFFSEP1202056	SUV 2	1912	1500	50.5	50.5	50	50th	50th
TTAI	F105005	SUV 4	2440	1510	49.8	49.4	50	50th	5th
Low speed tests: Velocity 45 km/h / Trolley mass 1500 kg / Offset 50%									
TTAI	F114303	Supermini 3	1136	1503	44.7	44.8	50	50th	5th
TTAI	F114203	Citycar 1	1156	1503	45.1	44.9	55	50th	5th
TNO	F054801	Small Family Car 2	1403	1500	45.1	45.1	50	50th	50th
TNO	F055001	Small Family Car 2	1405	1500	45.2	45.1	50	50th	50th
High speed tests: Velocity 56 km/h / Trolley mass 1500 kg / Offset 50%									
TNO	F084003	Supermini 2	1161	1514	56.1	55.8	50	50th	50th
BAST	FM01OPMB	Small Family Car 2	1446	1533	56	56	56	50th	50th

Figure 16. MPDB test matrix.

For all the vehicles a baseline test was carried out at a speed of 50km/h and a trolley mass of 1500kg, showing, in some cases an acceleration range slightly higher than the current Euro NCAP tests. The duration of the pulses is significant shorter than UN-ECE Regulation 94 or Euro NCAP tests, as trolley and vehicle are both moving. To study effect of velocity, tests at different speeds (45, 50 and 56 km/h) were carried out using the Small Family Car 2.

To compare all the results for all vehicles, the maximum mean B-pillar acceleration of the MPDB tests are presented in Figure 17. The maximum mean acceleration has been defined as:

$$\max mean\ acc = \frac{\max Delta - v}{time\ to \max Delta - v}$$

In general, lower B-pillar accelerations are measured in heavier vehicles. However for all vehicles with a reference test, the MPDB B-pillar acceleration is higher than in Euro NCAP tests. For the Small Family Car 2 and SUV 4, the MPDB is more severe than the fixed offset test. For the delta-v and due to the test configuration, it can be observed that the delta-v of the MPDB is depending of the mass of the tested vehicle. In the case of the static tests, the delta-v is higher due to the vehicle rebound.

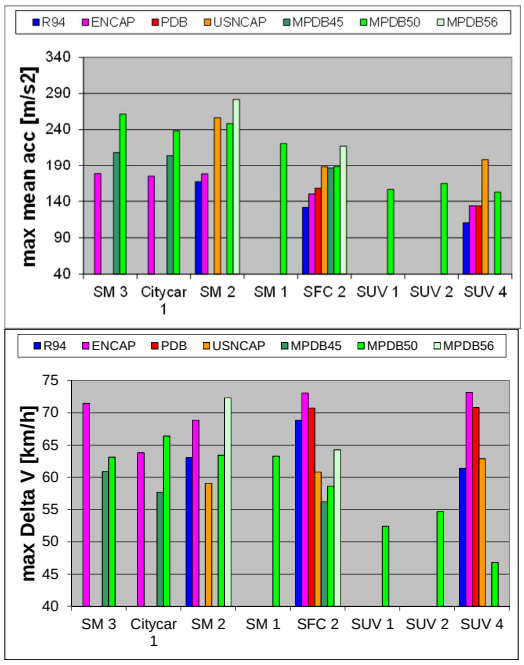

Figure 17. MPDB tests - maximum mean acceleration and delta-V results.

After the tests, vehicle deformations were measured. For small and average size vehicle the A-Pillar deformations were higher in the baseline MPDB that the reference tests, being the MPDB more severe for the compartment strength than the R94 and the Euro NCAP. However, all vehicles except the Citycar 1 were below 50mm of A-Pillar intrusion.

For the dummy readings in the MPDB tests, it needs to be taken into account that the restraint systems are not yet designed/optimized for this test mode (airbags are triggered earlier than in PDB or Euro NCAP tests), so better dummy results than the obtained in the FIMCAR tests are expected in the future. In general dummy results are worse than Euro NCAP results for light vehicle and comparable to Euro NCAP scores the heavy ones.

One of the main results of the tests was the deformation of the PDB. The details of the scanned barriers can be found in D4.2 of the FIMCAR Project [7]. Based on PDB assessment metric, the metric for the MPDB was developed. The metric based on the slope, or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate. 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 (higher results are worse than lower ones) could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localized holes. The assessment results are shown in Figure 18.

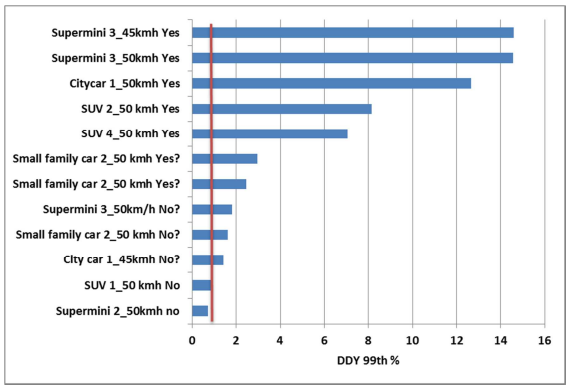

Figure 18. MPDB assessment results.

The remarks "yes / no" refer to whether or not a good spreading of the load was obtained during the test based on the judgment of an expert of the PDB deformation. The results presented in Figure 18 show a good correlation between the expert view during the development phase and DDY 99th% values. The question marks referred to situations where the expert has no clear view about the required results. For the metrics these unclear observations are located between real "yes" and "no" observations. The red line shows the proposed target value of 3.5 based on the PDB results analysis.

CONCLUSIONS

Two off-set candidates were evaluated during the FIMCAR project, the ODB and PDB test procedures. The PDB procedure was identified at the start of the project as the one with more potential to evaluate the issues and priorities defined in FIMCAR, but still some open issues need be addressed in order to be considered for the assessing of frontal impact crash compatibility.

	Structural Interaction		Front End Force / Deformation		Compartment Integrity		Restraint System	
	Alignment	Load Spreading	Deforma-tion force	Energy Absorption	Sufficient for self-protection	Enhanced for light vehicles	Different pulses	Restraint Capacity
Priority	1	1	2	1	1	2	1	1
Can be addressed by? (FIMCAR conclusions)								
ODB	N	N	N	-	Y	N	-	-
PDB	Y	?	Y	-	?	Y	-	-
	Metric development				Test procedure characteristics			

Figure 19. ODB and PDB compatibility assessment comparison.

Activities carried out during the project to develop the structural interaction assessment criteria using PDB data included 7 PDB tests, 15 MPDB tests and car-to-car tests. A new assessment metric for assessing compatibility using PDB tests was proposed. In addition, the PDB definition and certification and PDB scan procedures were developed in order to harmonize the analysis of the test procedure.

Different metrics have been investigated for assessing compatibility issues using the PDB procedure. The proposed metric is based on the DDY criterion, a vehicle mass independent criterion calculated from the PDB barrier's deformations. More specifically, it calculates the barrier's slope in the lateral (Y) direction and penalizes vehicles producing high slopes such as those occurring at the edges of holes. However, the metric still needs to be developed further and validated. Finally, R&R issues have been analysed for the PDB test procedure using the FIMCAR Supermini 2 PDB data. Three different tests were performed in two different FIMCAR laboratories showing repeatable results.

A draft protocol for the MPDB test has been set up. Tests were conducted in various laboratories showing the feasibility of reproducing the test configuration. A trolley mass of 1500 kg and test speed of 50 kg/h is proposed to define the required test severity. For vehicles outside the range between 1000 kg to 2200 kg, for example light electrical vehicles or heavy SUV's, an update of these specifications must be considered in the future. The metric for horizontal load spreading based on the deformation of the PDB barrier is also suitable for MPDB tests

The full scale tests performed showed that the PDB represents a reasonable severe test compared to the Euro NCAP test, which is considered the reference today in Europe. The vehicle pulse and dummy values measured in the PDB tests showed comparable results to the Euro NCAP reference.

Further validation is needed for vehicles with masses over 2000 kg.

The PDB and MPDB tests are currently the only configurations that can potentially assess horizontal load spreading. Candidates for assessing load spreading have been identified but there is still validation and repeatability issues that must be resolved before the candidates can be forwarded to rule makers.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the European Commission that co-funded this project through the FP7 programme (Grant Agreement no. 234216). The authors wish to acknowledge the Partners of the FIMCAR Consortium for their contributions.

The members of the FIMCAR consortium are: Technische Universität Berlin, Bundesanstalt für Straßenwesen. Chalmers tekniska hoegskola AB, Centro Recerche Fiat S.C.p.A., Daimler AG, FIAT Group Automobiles Spa, Humanetics GmbH, IAT Ingenieurgesellschaft für Automobiltechnik mbH, IDIADA Automotive Technology SA, Adam Opel GmbH, Peugeot Citroën Automobiles SA, Renault s.a.s, TNO, TRL Limited, UTAC, Volvo Car Corporation, Volkswagen AG, TÜV Rheinland TNO Automotive International BV.

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