Methodological physical analysis of FWDB and PDB test procedures regarding incompatible physical phenomena observed in real car accident

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ABSTRACT

Many studies have been performed in the field of compatibility between cars. Two test procedures with assessment have been developed to evaluate the compatibility level. The FWDB test is conducted at 56km/h against a 100% overlap rigid wall with deformable elements. The PDB test is a 50% overlap test at 60km/h against a Progressive Deformable Barrier. Assessment criteria are based on the force for FWDB test and on the deformation of the barrier for the PDB test.

If new assessment criteria are often proposed, few outcomes are provided concerning test procedures themselves, even though a lot of open issues still exist.

The aim of this paper is not to review all of them, but to conduct a methodological and physical analysis of both candidate test procedures. "Physical analysis" because it is based on the three incompatibility physical phenomena responsible for real car incompatibility (geometry, energy and stiffness mismatching). And "methodological" because both test procedures are studied using physical tests and virtual testing. Assessment criteria are therefore not considered.

Moreover, as a general agreement exists today that multiple load path with connections could help car front-ends to interact, PSA will present component tests and virtual testing with or without lower load path. Significant outcomes are provided concerning the efficiency of the technical procedures:

1) Both procedures can detect a geometry change such as the absence of load path.

2) Both procedures can measure a global force. However, its interpretation for the FWDB test is difficult due to the very limited deformation of the front-end undergone in this test.

3) Only the PDB test is able to draw up an energy absorption statement which is the only way to evaluate the car crash severity. For the FWDB test, this point represents a major difficulty because energy absorption by deformable elements is significant, about 50kJ.

INTRODUCTION

Compatibility is now studied for many years. Different research programs have therefore developed test procedures and assessment criteria in order to evaluate the compatibility level of cars. For several years, it could be observed that activities in these research programs are mainly addressed to develop assessment criteria, for each test procedures still candidate. During 2004-2006, the compatibility international context has changed for the following reasons.

First of all, the decision taken by the US to implement possible new requirements on compatibility in several steps has lead to a catalyst effect. In concrete terms, a self commitment concerning the height of the longitudinal has been applied has a first step. The following steps would have been based on full rigid width test with dynamical requirements, but the NHTSA has announced in 2006 that it would be very difficult to conclude this program.

Secondly, a new global approach, based on the PDB barrier is supported by the French since 2003 ([1], [2], [3]). This proposal is based on the current ECE R94 regulation. Three main changes are advised: a replacement of the current EEVC barrier by the PDB one, an increase of the test speed from 56 kph to 60 kph and an increase of the overlap from 40% to 50%.

Thirdly, the European VC Compat program has studied both test procedure (FWDB test and PDB test) and possible assessment criteria. The official report of these studies will be available in 2007.

So, due to the evolution of the context and due to the progressive consolidation of criteria assessment, it appears necessary to review in a first step the ability of both procedures to measure the main physical aspects that govern compatibility before considering assessment criteria.

PHYSICAL ANALYSIS OF VEHICLE/VEHICLE COLLISION IN REAL CAR ACCIDENTS

Many incompatibility accident cases could be observed in real car accident. Three main physical aspects are involved during such collision: geometry, energy and force. The analysis of all incompatibility cases show that each time, at least one of them could be identified as the best probable reason of the mismatching.

First physical aspect: Geometry or structural interaction

The lack of structural interaction between the front-end of the two cars leads to an overriding phenomenon (see Figure 1).

Figure 1. Overriding phenomenon illustration.

A front-end is made of several load paths such as the longitudinals, the sub frame and sometimes a lower load path. This "geometrical aspect" must therefore allow an interaction between these different load paths of both vehicles, in order to avoid such overriding phenomena.

Second physical aspect: Energy

Among the real car incompatible accidents, it could be regularly observed that the "reference" deformation mode of the front-end is not reproduced during some vehicle/vehicle collision. The "reference" deformation mode corresponds to the optimised front-end behaviour for which the vehicle has been designed for regulation or consumers test procedure (EEVC barrier for example). Figure 2 illustrate, for two different cars, a longitudinal not deformed after a head-on car-to-car collision.

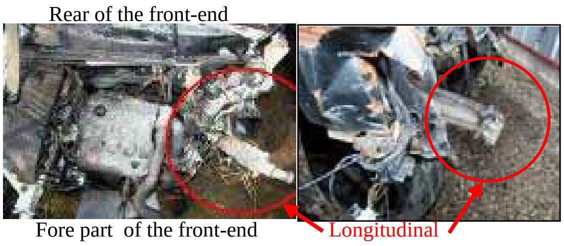


Figure 2. Energy absorption deficit illustration.

The front-end energy absorption ability is therefore under used, this will increase the passenger's compartment intrusion further in the crash if the collision is severe.
Front-end should be able to absorb a maximum energy to limit deceleration and intrusion for the occupants. This "energy aspect" must therefore insure that each vehicle has the minimum ability to absorb its own kinetic energy.

Third physical aspect: Force

A common well known requirement in order to balance the deformation in both cars involved in the collision consists in defining:

1) A passenger's compartment strength for both vehicles greater than the two front-ends one.
2) A passenger's compartment strength quite equivalent for both vehicles in order to equilibrate intrusion.

Many incompatible accident cases involving two cars with an important mass difference exist (4x4 or SUV against conventional car for example). But incompatibility linked to the force can also appears without mass difference as shown in Figure 3 with a collision case between the same cars, but from different generation (1993 & 1998):

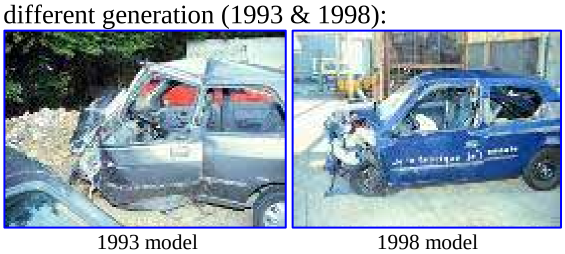


Figure 3. Incompatible passenger's compartment strength.

The interaction force between both cars is increasing during the crash. When this force reaches the force level of the weaker passenger's compartment, the remaining crash energy will be absorb by this vehicle. Therefore intrusion is not fairly distributed between cars after crash.
This "force aspect" must therefore insure that a vehicle has a sufficient passenger's compartment strength to limit its intrusion when opposed to another compatible vehicle.

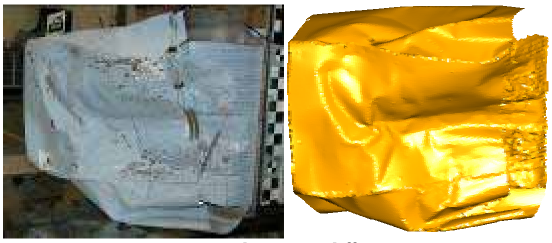
Conclusion on these physical aspects

When considering the real car incompatible accident cases, three main physical aspects (geometry, energy, force) are involved. According to the crash severity and vehicles characteristics, one or several aspects could be observed. They could even be combined (geometry incompatibility, then incompatibility energy and at last force incompatibility). That is the reason why geometrical aspect is widely recognised as the priority to improve compatibility between cars. Without considering any assessment criteria with defined thresholds, a candidate test procedure for compatibility must therefore be able to measure these three aspects.

TECHNICAL REVIEW OF BOTH CANDIDATE TEST PROCEDURES

PDB test procedure

This test procedure is based on a new Progressive Deformable Barrier (PDB barrier) which has been designed to represent the average strength of modern cars. Its 700mm depth allows avoiding bottoming out effect for most vehicles. The test is performed at a speed of 60 km/h with an overlap of 50 % in order to represent an average car to car frontal accident.
The barrier deformation represents the main measure of the PDB test. This deformation is digitalised after the crash. A view of a barrier after crash and its digitalisation is given figure 4.



Note: angle view is different.

Figure 4. View of a real PDB barrier after impact and its digitalisation.

The compatibility level should be evaluated according to deformation characteristics as local perforation, deformation homogeneity, average height of deformation, average depth of deformation, etc. The starting point for developing any assessment criteria is therefore the barrier deformation after crash.
Self protection can also be evaluated with the PDB test procedure, but this aspect will not be developed in this paper [4].

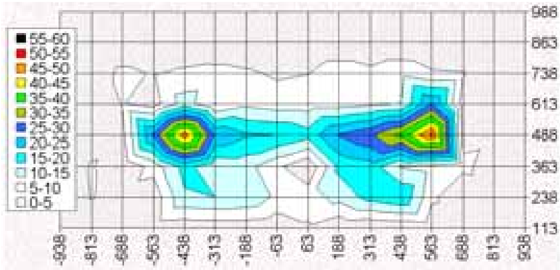
FWDB test procedure

This test procedure is based on the force measured by a wall of 128 load cells. The test is conducted at a speed of 56 km/h with an overlap of 100%. Moreover, a deformable element of 300mm is placed in front of the wall in order to reduce engine load peak without spreading the force on several cells.
The evaluation of the compatibility is based on the force measure, thanks to force cartography measured by the 128 cells.

Figure 5 (a) is an example of force cartography based on the maximum force measured by each cells during the crash. Figure 5 (b) is an illustration of the same force cartography with an interpolation of the force between cells.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
0	1	6	5	6	7	6	4	5	8	6	8	6	5	2	1
0	2	5	2	12	5	9	8	8	8	9	10	25	3	2	1
1	3	3	26	48	24	21	20	17	25	29	36	51	3	4	1
1	5	1	7	17	11	12	6	0	16	18	9	8	6	3	0
1	5	3	2	14	15	14	9	8	12	17	20	6	1	3	0
2	1	1	2	1	1	2	1	4	1	0	1	1	1	1	0

(a) View of a cartography of force



(b) View of an interpolated force cartography

Figure 5. Two different ways of presenting the results of a FWDB test: (a) Cartography of force (b) Interpolated force cartography.

Different kinds of cartography could be used. For example, at a given time of impact, with the maximum force measured by each cell during the crash, or during a particular crash period.
These cartographies are the main measures on FWDB, from which assessment criteria could be developed to evaluate force homogeneity of the front-end.

Aim of the study

The aim of the study carried out by PSA Peugeot Citroën is to evaluate the ability of each test procedure (PDB and FWDB) to "measure" the three physical compatible aspects: geometry, energy and force. Some tests and virtual testing had therefore been performed (funded by ACEA, by a French consortium or directly by PSA Peugeot Citroën as presented in table 1). The analysis consists in evaluating the sensitivity of each procedure to different loadings (barrier deformation for PDB test and force cartography for FWDB test).
Assessment criteria are not considered in this study.

METHODOLOGY USED

The methodology is mainly based on physical testing and virtual testing conducted on both procedures, PDB and FWDB. In order to have different kinds of loadings, different types of vehicles have been used (see table 1).

Table 1. List of vehicles tested and their sources of funding.

Vehicle type	Test source
Mini car	PSA Peugeot Citroën
Small family car	PSA Peugeot Citroën
Family car #1	ACEA program
Family car #2	French program (UTAC, Renault and PSA Peugeot Citroën)
Family car #3	French program (UTAC, Renault and PSA Peugeot Citroën)
Component tests #1 on family car with lower load path	PSA Peugeot Citroën
Component tests #2 on family car without lower load path	PSA Peugeot Citroën

City car, small family car and family car tests correspond to non-modified vehicles.
Components tests are based on a family car, which has been "simplified" by removing some components difficult to simulate by virtual testing. Moreover, the influence of the lower load path has been quantified in these component tests.

All the tests performed by PSA Peugeot Citroën have also been analysed by virtual testing according to the following approach:

1) The PDB barrier and the deformable element for FWDB test have been validated thanks to several physical component compression tests.
2) The vehicle numerical model used has been validated thanks to usual crash configuration such as full-width frontal test and EEVC barrier (ECE 94 or Euro NCAP protocol).
3) Analysis of each physical test and improvement of the virtual testing correlation.
4) Additional virtual testing to complete the analysis.

As virtual testing could always been discussed, this paper will focus on presenting the physical test results and will present additional results from virtual testing only to complete the information when necessary.

CANDIDATE TEST PROCEDURE ANALYSIS

For each physical aspect (geometry, energy, force), the ability to be detected by PDB and FWDB tests will be analysed.

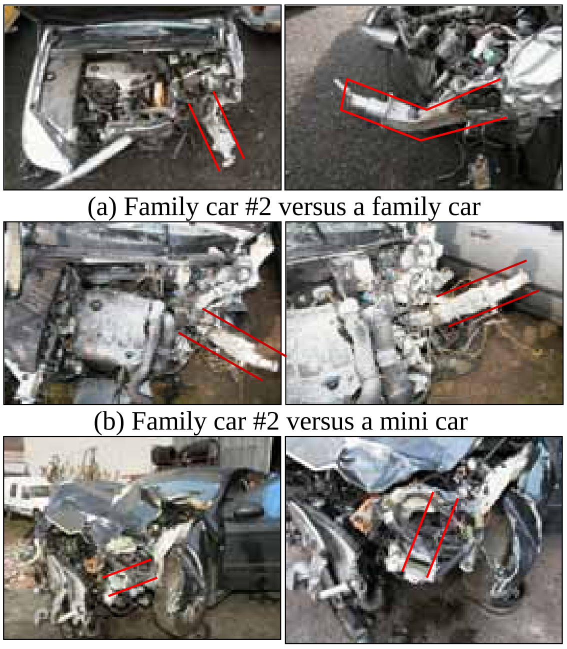
Capacity to detect structural interaction (Geometry aspect)

For this aspect two notions have been distinguished:

1) The ability to detect aggressiveness of a longitudinal as seen in a real-life car accident.
2) The ability to detect different front-end geometries in terms of homogeneity.

Ability to detect aggressiveness

The accident data analysis shows that family car #2 is sometimes "aggressive" in real car accidents. Three cases are presented in Figure 6.



(a) Family car #2 versus a family car

(b) Family car #2 versus a mini car

(c) Family car #2 vs. a small family car

Figure 6. Typical deformation of Family car #2 during a real-life car-to-car accident against different cars: (a) versus a family car, (b) versus a mini car (c) versus a small family car.

On the contrary, the longitudinal of the family car #3 never appears as aggressive in real-life car accidents as illustrated in Figure 7 with eight car-to-car collisions.

Figure 7. Family car #3 involved in eight car-to-car accidents.

The non aggressiveness of the longitudinal of the family car #3 is due to a very stiff crossbeam. Even a car-to-pole and a car-to-tree frontal impact are not able to detect a failure of the crossbeam as shown in Figure 8.

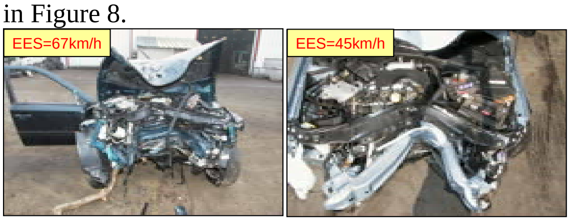


Figure 8. Family car #3 involved in two car-to-pole accidents.

In the frame of the French research program on compatibility, both family car #2 and #3 have therefore been tested in PDB test and FWDB test to see whether or not the two procedures are able to detect these real car accident statements.

PDB tests results

The deformation of the barrier for the family car #2 test clearly shows that the longitudinal is very stiff and remains undeformed after the accident (see Figure 9).

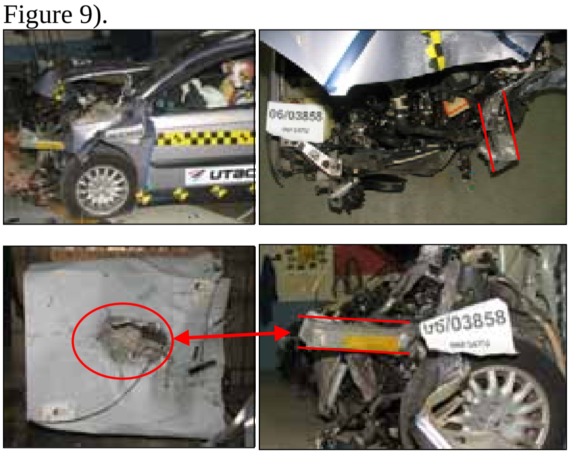


Figure 9. PDB test results of family car #2.

The deformation of the barrier for family car #3 test clearly shows that the crossbeam is very stiff, without failure phenomena (see Figure 10).

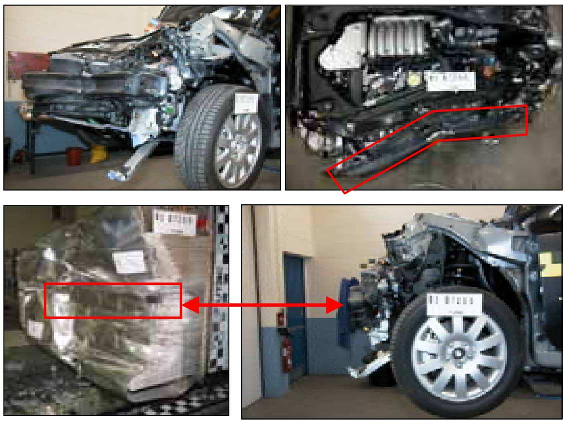


Figure 10. PDB test results of family car #3.

PDB tests results are therefore fully in line with the real-life car accidents statements.

FWDB tests results

The deformation of the deformable element for the family car #2 is shown in Figure 10.

(a) Family car #2 after FWDB test

(b) View of the deformable element

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2	2	3	6	6	9	5	6	5	8	3	6	5	2	3	0
3	3	8	8	7	4	2	7	5	3	6	8	9	8	2	2
2	4	16	36	33	18	3	4	5	6	17	49	24	10	4	2
1	1	3	9	5	5	8	5	5	7	16	9	7	4	0	0
0	0	4	2	0	5	5	6	4	8	3	7	3	1	0	1
0	0	0	2	2	0	3	4	2	5	0	4	0	2	0	0

(c) Maximum [0-40ms] force cartography

Figure 10. Family car #2 FWDB test results (a) View of the car after impact, (b) View of the deformable element, View of the maximum [0-40ms] force cartography.

This cartography only detects a concentration of force corresponding to the longitudinal pushing. The crossbeam is totally invisible. It is interesting to notice that the longitudinal is well deformed in this test.

The deformation of the deformable element for the family car #3 is shown in Figure 11.

(a) Family car #3 after FWDB test

(b) View of the deformable element

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	1	2	4	4	6	7	4	4	6	5	6	4	4	4	1
0	1	2	7	7	3	3	5	4	3	6	4	6	2	1	1
1	1	12	28	26	20	9	6	6	7	24	25	32	20	2	1
0	1	6	22	22	10	6	3	3	5	8	18	20	8	0	0
1	1	6	12	14	7	4	2	3	3	7	7	12	3	0	0
2	2	1	1	1	2	1	1	1	2	1	1	1	1	2	0

(c) Maximum [0-40ms] force cartography

Figure 11. Family car #3 FWDB test results (a) View of the car after impact, (b) View of the deformable element, (c) View of the maximum [0-40ms] force cartography.

An important bending of the crossbeam due to the stiffness of the deformable element is observed. This test may therefore be interpreted as the crossbeam is too soft whereas real car accidents indicate that the crossbeam is very stiff.
In comparison with the results of the family car #2 equipped with a weak crossbeam, FWDB test does not make a significant difference between these two vehicles. The force corresponding to the cells located in front of the crossbeam is about 5 kN for the family car#2 (see figure 10c) to be compared with 7 kN (see figure 11c) for the family car#3. This is opposed to real car accidents observations previously presented.

<u>**Ability to detect homogeneity**</u>

In the same way, homogeneity will be evaluated by testing the different vehicles (see table 1) against PDB and FWDB and then analysing the response of the barrier deformation or force cartography measured.

PDB tests results

The mini car front-end has been widely deformed. Intrusions in the passenger's compartment are also observed due to the pushing of the engine on the dashboard and the front left wheel on the sill.

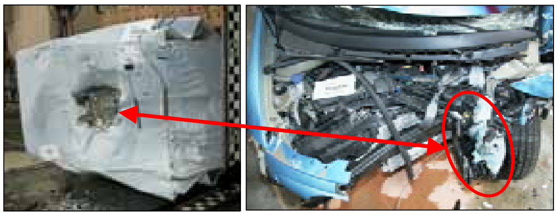


Figure 12. Mini car - PDB test results.

The barrier has been perforated. This result is not surprising due to the weak crossbeam present on this vehicle. Homogeneity of the front-end appears therefore very limited.

The small family car front-end has also been strongly deformed. In this test too, intrusion in the passenger's compartment could be observed due to the engine and front left wheel.

Figure 13. Small family car - PDB test results.

In that test, the barrier deformation does not suffer from local perforation and the homogeneity seems to be very good. Notice that this small family car is equipped with an advanced lower load path.

The result of the PDB test with the family car #1 is shown in Figure 14 has already been presented by ACEA in 2004.

Figure 14. Family car #1 - PDB test results.

The barrier deformation shows a large localised deformation due to the very stiff crossbeam of this vehicle but without local perforation. Homogeneity of the barrier deformation is therefore not quite good. The front-end is also well deformed with a contribution of the engine. Passenger's compartment intrusion could also been noticed.

The component test #1 corresponds to a family car "simplified" with a lower advanced load path.

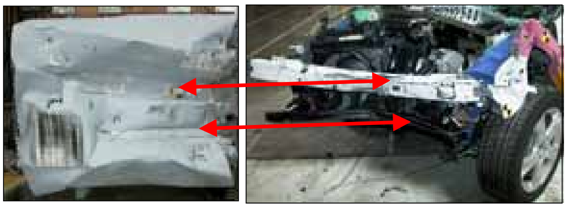


Figure 15. Component test #1 PDB test results.

As shown in Figure 15, the barrier deformation clearly detects the pushing of the stiff upper crossbeam and lower crossbeam. The lower advanced load path is therefore well detected. Barrier deformation homogeneity is judged as relatively good when knowing that no bumper, headlight and bonnet were present during this test.

The component test #2 corresponds to the same test that the previously one, except the removal of the lower advanced load path.

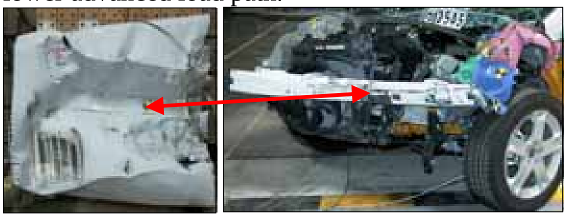


Figure 16. Component test #2 - PDB test results.

The barrier deformation clearly detects the advanced load path removal. The barrier is indeed less deformed at the bottom and the deformation due to the upper crossbeam is deeper than previously. The barrier deformation homogeneity is therefore less good than with the advanced lower load path.
The results of this test series confirm that the PDB barrier is a very good validated tool to check front-end behaviour. Changes in the front-end design are clearly detected by the barrier deformation. For information, a pushing of the engine has also been observed during these component tests #1 and #2.

FWDB tests results

For FWDB tests, as there exist many ways to display force cartographies, tests results will be presented in several manners:

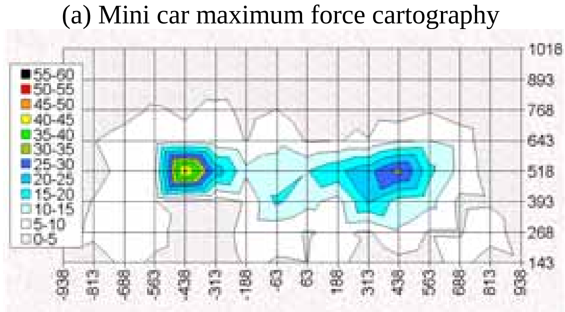
1) Two types of cartography display will systematically be shown. The first display will be the maximum force measured by each cells without any force interpolation. The second will be the same measurement but with an interpolation.

2) Moreover, as the TRL proposes now to analyse the force only on the first 40ms of the crash, force cartography will first be drawn during the entire crash and secondly during the first 40ms of the crash.

<u>Force cartographies during the entire crash</u>
The mini car cartography is characterised by the pushing of the longitudinals. The maximum forces measured on the left side and on the right side are quite different (see Figure 17).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0
1	0	3	6	4	7	3	5	2	5	3	2	4	2	0	0
0	5	8	6	7	6	5	9	4	5	5	9	10	8	1	2
1	2	7	10	46	23	11	11	15	19	23	31	16	8	2	0
0	5	5	5	3	2	5	16	12	8	20	13	12	4	4	0
1	7	6	7	2	3	6	6	5	6	4	9	5	4	9	1
3	0	7	4	2	1	6	5	5	7	1	4	2	8	0	4

(a) Mini car maximum force cartography



(b) Maximum force cartography with force interpolation

Figure 17. Mini car FWDB test results (a) Maximum force cartography (b) Maximum force cartography with force interpolation.

The crossbeam seems to be detected on the figure 17(a) in spite of a very low bending stiffness. This is due to the engine pushing that is more visible on the figure 17(b) on the right side.

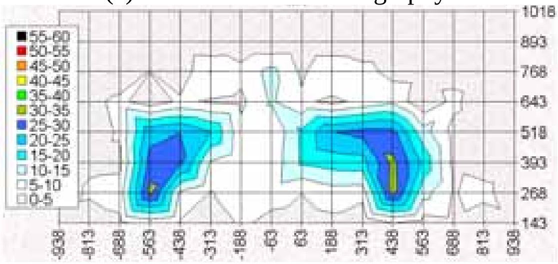
The homogeneity of the front-end seems therefore quite bad.
For information, as usual in FWDB test, the car front-end post test deformation is very limited. The front wheels didn't even touch the sills, as shown in Figure 18.

Figure 18. Post impact deformation of the Mini car after FWDB test.

The small family car cartography is characterised by the pushing of the longitudinals and by the vertical connections between the lower advanced load paths and the longitudinals. The upper crossbeam is nevertheless not detected although is presents a good stiffness in bending. The engine pushing on the right side is also visible (see Figure 19).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	1	1	0	1	1	1	1	0
1	0	1	5	2	10	7	12	4	10	7	3	2	3	2	1
1	4	6	2	6	4	4	11	6	4	6	9	0	7	0	2
0	2	6	23	25	20	7	5	16	25	27	27	12	3	1	0
0	3	4	27	26	9	6	7	16	17	18	31	19	4	1	0
0	6	7	31	9	5	7	7	5	8	7	32	12	5	7	0
2	0	4	7	5	0	6	3	3	4	0	5	3	4	0	3

(a) Maximum force cartography



(b) Maximum force cartography with force interpolation

Figure 19. Small family car test results (a) maximum force cartography, (b) maximum force cartography with force interpolation.

The homogeneity of the front-end appears therefore to be better than the previous mini car one.

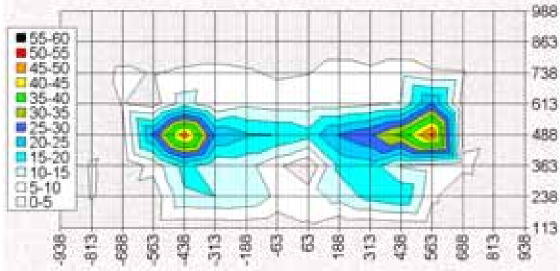
For information, as usual in FWDB test, the car front-end post test deformation is very limited. The front wheels didn't even touch the sills as illustrated in Figure 20.

Figure 20. Post impact deformation of the Small family car after FWDB test.

The cartography of the family car #1 FWDB test is characterised by its very stiff crossbeam and by its lower load path which are well detected (see Figure 21).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
0	1	6	5	6	7	6	4	5	8	6	8	6	5	2	1
0	2	5	2	12	5	9	8	8	8	9	10	25	3	2	1
1	3	3	26	48	24	21	20	17	25	29	36	51	3	4	1
1	5	1	7	17	11	12	6	0	16	18	9	8	6	3	0
1	5	3	2	14	15	14	9	8	12	17	20	6	1	3	0
2	1	1	2	1	1	2	1	4	1	0	1	1	1	1	0

(a) Maximum force cartography



(b) Maximum force cartography with force interpolation

Figure 21. Family car #1 test results (a) maximum force cartography (b) maximum force cartography with interpolation.

The pushing of the engine is not quite visible. The homogeneity of the front-end seems therefore better than the mini car one, but worse than the small family car one.

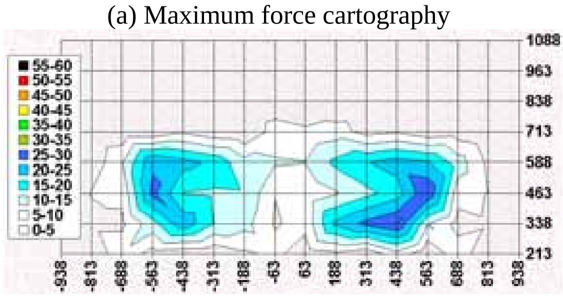
Figure 22. Post impact deformation of the Family car #1 after FWDB test.

Here again, as usual in FWDB test, the car front-end post test deformation is very limited. The front wheels didn't even touch the sills (see Figure 22).

The component test #1 with an advanced lower load path shows the longitudinals and the lower load path on the cartography. The engine, the rigid upper and lower crossbeams are however not clearly visible (see Figure 23).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	2	1	0	0	0	0	0	0	0
0	0	1	1	4	1	0	7	6	7	3	4	1	2	0	0
0	1	10	24	22	19	11	11	10	16	20	22	21	13	4	1
0	5	6	26	15	14	14	5	6	9	14	17	29	7	5	1
0	4	4	13	23	15	12	5	6	21	26	30	10	3	4	1
2	1	9	3	1	1	4	6	2	4	1	8	1	8	1	4

(a) Maximum force cartography



(b) Maximum force cartography with force interpolation

Figure 23. Component test #1 FWDB test results (a) maximum force cartography, (b) maximum force cartography with interpolation.

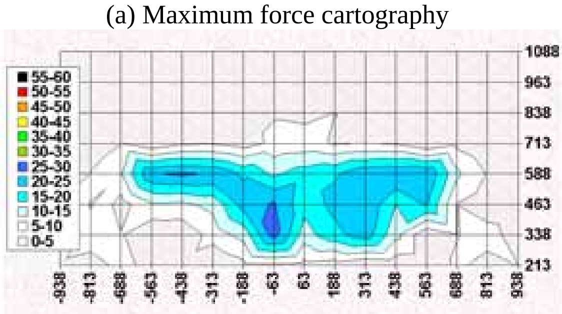
The homogeneity of the front-end appears therefore to be close to the small family car one. As usual, the front-end deformation is very limited without contact between the front wheels and the sills as shown in Figure 24.

Figure 24. Post impact deformation of the Component test #1 after FWDB test.

The component test #2 is very interesting (see Figure 25). Firstly, the removal of the lower load path is well detected compared with the previous component test. Secondly, the crossbeam seems to be weaker than previously even though it has not been changed. This can be explained one time more by the engine. Indeed, as the absorption energy of the front-end has decreased due to the removal of the lower load path, the deformation of the front-end is quite higher, thus leading to a higher pushing of the engine on the crossbeam and therefore on the wall.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0	0	2	0	0	1	0	0
0	0	0	1	0	2	3	5	4	5	2	1	0	1	1	0
1	1	5	1	4	4	2	6	7	4	5	5	0	3	0	1
0	5	10	25	26	24	19	14	18	19	24	25	25	11	5	1
1	10	3	9	9	11	22	26	17	22	24	15	20	5	1	0
1	8	5	1	1	7	12	27	13	18	23	12	1	5	8	2
4	3	6	3	3	0	3	4	3	2	0	1	1	6	3	5

(a) Maximum force cartography



(b) Maximum force cartography with force interpolation

Figure 25. Component test #2 FWDB test results (a) maximum force cartography, (b) maximum force cartography with interpolation.

As usual, the front-end deformation remains limited without contact between the front wheels and the sills as shown in Figure 26.

Figure 26. Post impact deformation of the Component test #2 after FWDB test.

At last, the homogeneity of the component test #2 front-end appears good. Compared the component test #1 equipped with lower load path, the component test #2 homogeneity could even be judged as better. This is opposite to the common understanding of most of the stakeholders involved in Compatibility research groups. According to them, multiple load paths with vertical and horizontal connections should indeed improve the ability of a front-end to interact with others.

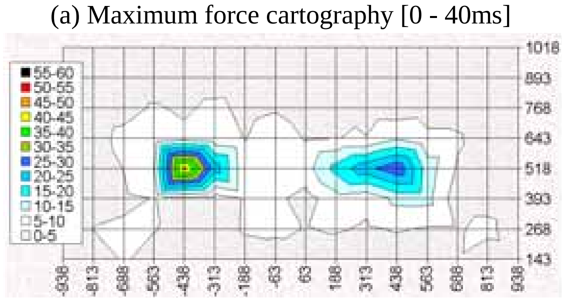
<u>Force cartographies during the first 40ms</u>

This is the new orientation given by TRL in March 2006 during EEVC WG15 / VC Compat meeting.

The mini car cartography is not really affected by this evolution. The engine pushing is less visible, but still exists (see Figure 27).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	2	6	4	7	3	4	1	5	2	2	3	2	0	0
0	2	7	6	7	6	5	9	4	5	5	9	6	6	0	1
0	1	5	10	46	23	6	5	8	17	23	29	12	4	1	0
0	2	4	5	3	2	5	6	3	8	6	11	12	2	2	0
0	5	6	5	2	2	6	6	5	6	4	5	5	4	7	0
2	0	6	2	1	0	2	2	2	2	0	2	1	5	0	2

(a) Maximum force cartography [0 - 40ms]



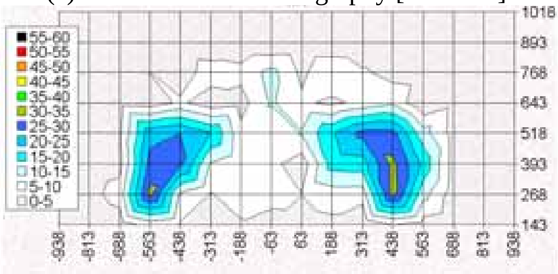
(b) Maximum force cartography [0 - 40ms] with force interpolation

Figure 27. Mini car FWDB test results limited to [0 - 40ms] (a) maximum force cartography, (b) maximum force cartography with force interpolation.

It is exactly the same for the small family car (see Figure 28).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	1	1	0	1	1	0	0	0
1	0	1	5	2	8	7	12	4	10	6	3	2	0	0	1
1	4	3	2	6	2	3	11	6	4	6	9	0	3	0	1
0	1	4	23	25	20	7	5	10	19	27	27	12	3	0	0
0	2	3	27	26	9	6	7	2	17	18	31	19	3	0	0
0	3	7	31	9	5	7	7	5	8	7	32	12	2	3	0
0	0	2	7	5	0	5	3	3	4	0	5	3	1	0	0

(a) Maximum force cartography [0 - 40ms]



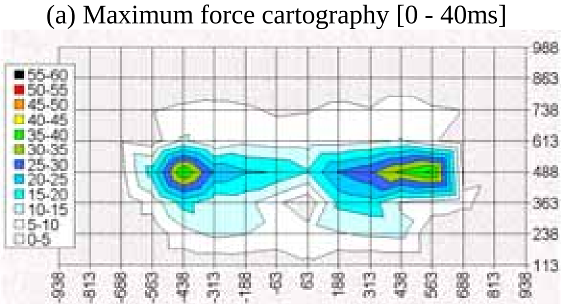
(b) Maximum force cartography [0 - 40ms] with force interpolation

Figure 28. Small family car FWDB test results limited to [0 - 40ms] (a) maximum force cartography, (b) maximum force cartography with force interpolation.

The family car #1 cartography is characterised by the fact that the lower load path (not advanced) is no more visible when only considering the force during the first 40ms (see Figure 29). This result is opposite to the common principle of most of the stakeholders involved in Compatibility research groups who recommend not to penalize multiple load paths.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
0	0	3	5	6	7	6	4	5	6	5	8	6	5	2	1
0	1	4	2	11	5	9	8	8	8	9	10	6	2	2	1
1	2	3	18	40	24	21	20	15	25	29	36	41	3	4	1
1	2	1	7	17	11	12	6	0	16	18	9	8	6	2	0
1	1	2	2	8	11	10	9	8	10	11	11	0	0	1	0
2	1	1	1	1	1	2	1	4	1	0	1	1	1	0	0

(a) Maximum force cartography [0 - 40ms]



(b) Maximum force cartography [0 - 40ms] with force interpolation

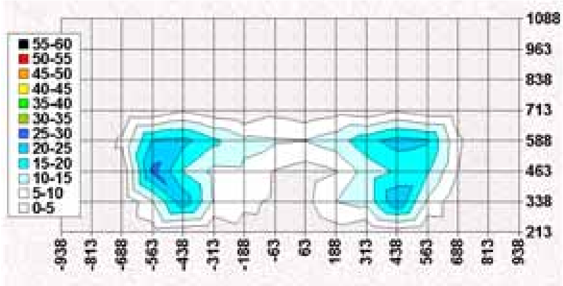
Figure 29. Family car #1 FWDB test results limited to [0 - 40ms] (a) maximum force cartography, (b) maximum force cartography with force interpolation.

We can conclude from Figure 29 that the rigid crossbeam is still visible.

The component test #1 with an advanced lower load path is not really affected by this evolution (see Figure 30).

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	4	1	0	3	2	3	1	4	1	1	0	0
0	1	6	21	22	16	11	11	10	13	18	22	21	6	0	0
0	3	1	26	15	9	9	5	2	5	12	16	16	5	0	0
0	0	0	10	23	10	6	4	3	10	12	24	9	1	0	0
0	0	0	3	1	0	3	4	0	3	0	3	0	1	0	1

(a) Maximum force cartography [0 - 40ms]



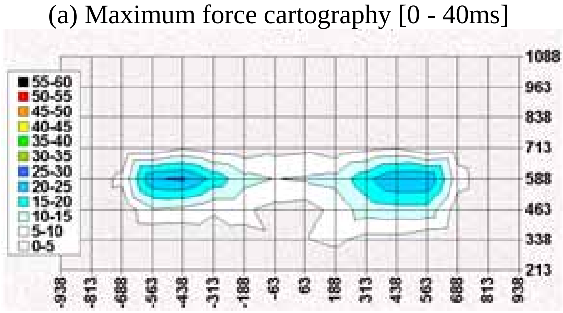
(b) Maximum force cartography [0 - 40ms] with force interpolation

Figure 30. Component test #1 FWDB test results limited to [0 - 40ms] (a) maximum force cartography, (b) maximum force cartography with force interpolation.

It is completely different for the component test #2 without advanced lower load path as shown in Figure 31.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0
0	0	0	0	4	2	1	3	4	2	3	5	0	2	0	0
0	3	6	25	26	18	12	10	11	11	19	25	25	7	1	0
1	2	1	9	9	6	6	4	3	7	12	13	13	2	0	0
0	0	0	0	0	1	4	5	5	6	3	3	0	0	1	0
0	0	0	0	0	0	0	0	1	2	0	1	0	0	0	0

(a) Maximum force cartography [0 - 40ms]



(b) Maximum force cartography [0 - 40ms] with force interpolation

Figure 31. Component test #1 FWDB test results limited to [0 - 40ms] (a) maximum force cartography, (b) maximum force cartography with force interpolation.

Indeed, the limitation of the analysis on the first 40ms does not enable to detect the engine pushing. Homogeneity seems therefore worse than the component test #1 with advanced lower load path.

Multiple load paths are clearly penalized in this case.

Conclusion
Without limitation of time regarding the force analysis, the results of this test series show that FWDB test is able to detect several changes in the front-end design such as the presence or not of a lower load path or vertical connection between it. Nevertheless, these results also show that the engine behaviour is not comparable in all tests. For mini and small family cars, a pushing of the engine is visible, which may give a false conclusion in the homogeneity of the front-end. It is not the case for larger cars. Moreover, when removing a lower load path, homogeneity is detected as to be better. This is due to an increase of the engine pushing, permitted by the decreasing of the front-end absorption energy.

The limitation of the analysis to the first 40ms of crash enables to limit the influence of the engine pushing. It was particularly important for both component tests with and without lower advanced load path, since the engine pushing is not visible even when the lower load path is removed. Nevertheless, this time limitation also leads to a main drawback. It limits one more time the front-end deformation corresponding to the force analysis. Indeed, virtual testing reveals that 40ms correspond to a very limited deformation of the longitudinal as illustrated in Figures 32 to 35.

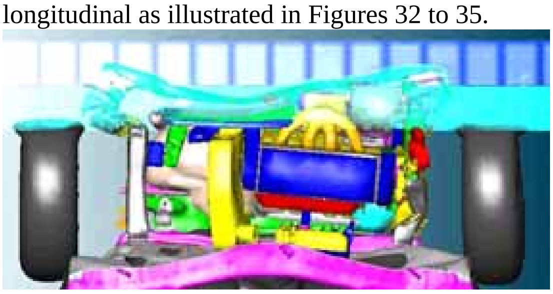


Figure 32. 120 mm longitudinal deformation for the Mini car at 40ms.

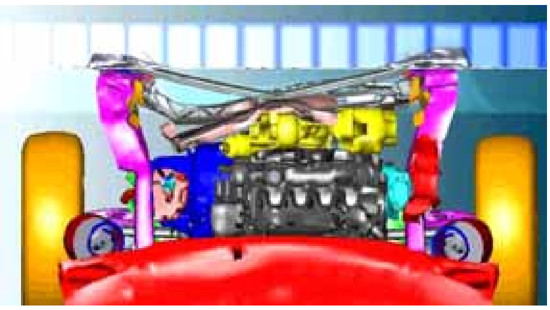


Figure 33. 90 mm longitudinal deformation for the small family car at 40ms.

Figure 34. 140 mm longitudinal deformation for the test component #1 (with advanced lower load path) at 40ms.

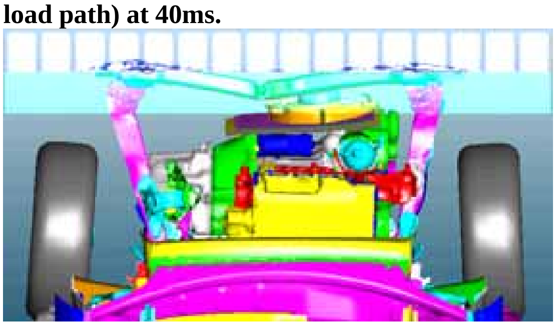


Figure 35. 150 mm longitudinal deformation for the test component #2 (without advanced lower load path) at 40ms.

Moreover, this limitation raises a problem for cars not equipped with advanced lower load path (like the Family car #1 one), because these kind of multiple load path disappears in the cartography and would be therefore penalised in terms of homogeneity.
The problem seems difficult to solve. The aim is to avoid engine pushing. The 40ms limitation goes in the right direction even if engine pushing still exist for mini and small car, but it leads to a very limited front-end deformation, about 90 and 150 mm. Is it sufficient to evaluate geometry interaction in a usual car-to-car accident which highlights incompatible problems?

Such difficulties do not exist in PDB test, since the front-end is deformed significantly for all kind of cars.
The PDB test appears therefore to be more able to detect various type of front-end design than the FWDB test. On top of that, homogeneity changes are fully in line with the common understandings of the main stakeholders involved in Compatibility research programmes.

Capacity to detect energy absorption (energy aspect)

One target of this aspect is to evaluate the ability for a front-end to absorb energy and to detect energy incompatible phenomenon. The better example is given by a longitudinal which could be underused in a car-to-car accident (see figure 2 and 6).

PDB test
The principle is to evaluate the energy level absorbed by the barrier, thus enables to estimate the energy level absorbed by the vehicle.
This evaluation is made from the barrier digitalisation. A theoretical compression barrier law is needed for the different barrier strength zones. The result obtained remains therefore an estimation. However, this method reveals significant changes of the energy level absorbed by the barrier. Results obtained for the two component tests are given in figure 36.

The barrier energy absorbed for the component test #1 with advanced lower load path represents 32.1% of the kinetic crash energy.

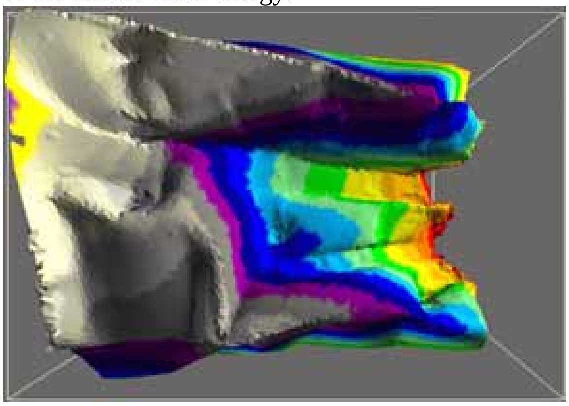


Figure 36. Component test #1 barrier deformation.

For the component test #2 without lower load path, the barrier energy absorption corresponds to 38.4% of the kinetic crash energy (see Figure 37).

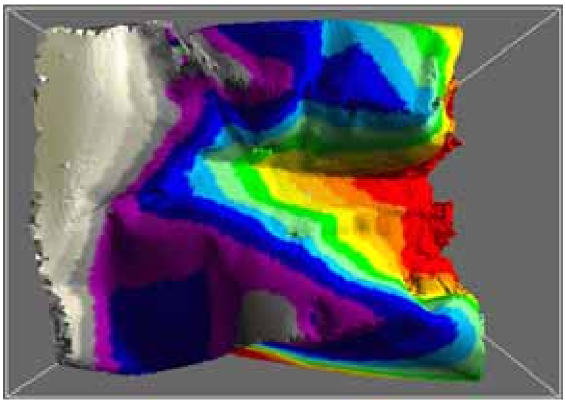


Figure 37. Component test #2 barrier deformation.
Without lower load path, the barrier deformation is deeper.

This results show that with an indicator of this type, PDB test procedure is able to evaluate the level of energy absorbed by the vehicle, and therefore able to check if this level is sufficient to absorb its own kinetic energy in a vehicle/vehicle frontal collision.

FWDB test
As the deformable element is not covered by an aluminium plate, a standard easy digitalisation is impossible.
The estimation of the energy absorption will first require a covering of all the different pieces of the barrier, but will stay even though difficult, because the second honeycomb layer blocks have been observed as unstable during the different tests carried out up to now.

However, in order to have a deformable element energy absorption order of size, ACEA has manually digitalized the barriers of three FWDB test carried out on the family car #1 model.

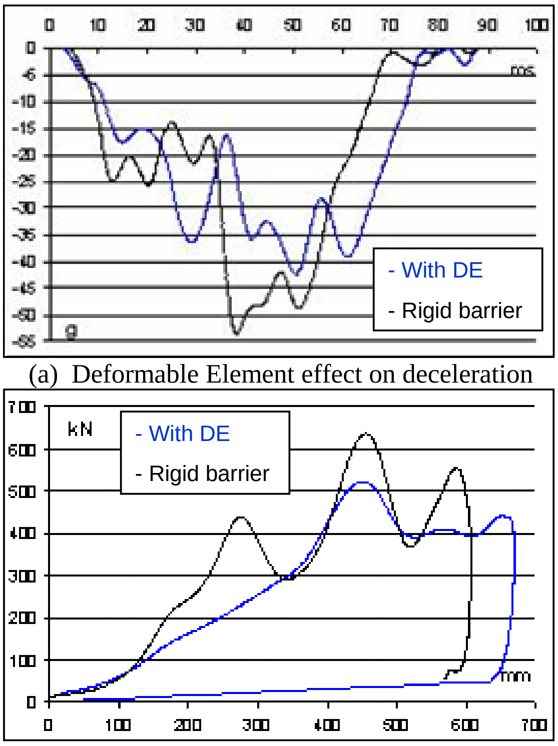
Table 2. Barrier energy absorption for the Family car #1 tests.

Crossbeam	Energy in the barrier	Kinetic energy	% Ek in the barrier
Weak	57 kJ	197 kJ	29%
Serial	59 kJ	195 kJ	30%
Serial test 2	59 kJ	196 kJ	30%
Stiff	60 kJ	196 kJ	31%

The result reveals that the energy absorbed by deformable element is far from being neglected. This is confirmed by virtual testing.

For instance, the energy absorbed by the deformable element for the small family car corresponds to “47.8”kJ.

For information, virtual testing performed with and without deformable element show that the severity of the FWDB test is decreasing when deformable element is present as seen on figure 38 and Table 3.



(a) Deformable Element effect on deceleration

(b) Deformable Element effect on global force

Figure 38. Effect of the deformable element on (a) deceleration, (b) global force.

Table 3. Influence of the deformable element.

Barrier	Max accel.	Max Disp.
With DE	42,5 g	690 mm
Rigid	55,5 g	600 mm
Variation w/wo DE	+ 23 %	+ 15 %

Without any deformable element, the maximum deceleration is 23% higher and the maximum vehicle deformation is 15% increased.

Deformable element could therefore not be considered as non influent on the crash severity. This point must be highlighted when considering the evaluation of occupant restraint system with this test.

Capacity to detect force (force aspect)

PDB test

If the global force during the whole crash is needed for a particular reason, a dynamometrical wall behind the PDB barrier could be implemented. On a physical point of view, this maximum global force does not correspond to the maximum force that the passenger's compartment is able to support. The severity of the PDB test is indeed sufficient to deform totally the vehicle front-end and to begin loading the passenger's compartment. But this severity does not allow checking the maximum force of the passenger's compartment.

FWDB test

The measure of the global force during the crash is obviously possible with this procedure. Nevertheless, the question raised is to know how to interpret it, since the vehicle front-end is so little deformed. The maximum force could therefore not be considered as the maximum force that the front-end could support. And moreover, no information can be obtained with this test concerning the passenger's compartment force.
This global force does therefore not be interpreted as a real characteristic of the front-end or passenger's compartment force. This information does not seem to be relevant.

DISCUSSION ON ADVANTAGES AND DRAWBACKS OF BOTH PROCEDURES

Synthesis of the previous analysis

Following the results of this study, the main results or observations could be resumed for each test procedure.

PDB test

The PDB barrier is confirmed to be a very relevant tool to evaluate structural interaction. Indeed, the real car accident aggressiveness observations concerning the behaviour of a crossbeam or a longitudinal are well reproduced during the PDB test. Moreover, PDB deformation is also able to detect different kind of front-end design, with or without lower load path for instance. It should be highlighted that as the PDB test completely deform the front-end of the vehicle tested, the lower load path is detected even if it is located far from the beginning of the front-end.
The energy absorbed by the barrier after the test can also be estimated from a theoretical compression barrier law. This is an important aspect since this is the only way to evaluate the front-end energy absorption ability of the vehicle. As the deformation mode of the front-end during PDB test is very close to real car accident, this evaluation is all the more relevant.

Finally, the maximum force during the crash could be measured by a dynamometrical wall to be located behind the barrier. For most of the cars, this force corresponds to an average force between the front-end deformation force and the maximum force that the passenger's compartment is able to support.
The three physical aspects involved in incompatibility phenomena could therefore be measured with the PDB test in consistence with the analysis of the real-life car accidents.

FWDB test

The comparison of the front-end deformation mode between the real car accident and FWDB test for same car shows several differences. An important point is the crossbeam behaviour, since a rigid crossbeam detected as such in the real car accident is detected as too soft in the FWDB test (case of the family car #3). Another difficulty concerns the contribution of the engine. According to the size of the car, the engine pushing is different. For instance, the engine pushing is not visible for a large car contrary to what happen for a small car. A good example is the crossbeam of the mini car (see figure 17) which is not detected as weak thanks to the engine pushing. It is even so the case and this is also confirmed by the PDB test result (see figure 12). The engine has therefore an influence not comparable on the force cartography, depending on the car size. This could sometimes lead to wrong conclusions.

The analysis limited to the first 40ms for the force measurement goes in the right direction since the effect of the engine is limited. But in that case, lower load paths located far from the front-end (such as the family car #1 one) are not detected and will therefore be penalized. Moreover, front-end deformation corresponding to 40ms is very limited. The longitudinal deformation is about 120mm. The front wheels do not move back. Is it a sufficient deformation to evaluate the structural interaction that could occur in a car-to-car accident?

To conclude, FWDB is therefore able to detect some changes in the front-end design but could lead to wrong conclusion for some cases (engine effect and lower load path are not always detected). Energy absorption is not measurable and not relevant for assessment in the FWDB test since the front-end is not totally deformed.
The maximum force of the FWDB is available. But as for the energy, its interpretation is difficult due to the low deformation of the front-end.
As far as the virtual testing are concerned, the instability of the second layer observed in physical tests is very difficult to correlate.

Possible actions to improve both test procedure

Geometry

No major problem has been detected for the PDB test. Several additional reproducibility tests may be realized to confirm the stability of the results already observed during 2004 with the family car #1 tests carried out within ACEA.

Concerning the FWDB test, it appears difficult to avoid the engine pushing for all vehicles. In order to have a comparable influence of the engine for all, a possible improvement could be to increase the front-end deformation. This could be obtained by a modification of the procedure in terms of deformable element stiffness, depth or/and impact speed. An improvement of the deformable element appears also necessary to detect correctly a rigid crossbeam in consistence with the real car accident.

Energy

The level of energy absorbed by the PDB barrier is measurable. This requires to define a theoretical barrier compression law from PDB characteristics and dynamical PDB compression tests. Another aspect could be to improve the digitalisation barrier procedure. It seems indeed important to decide for instance if the edges of the barrier should be taken into account or not.

The FWDB procedure is not able to evaluate this aspect. Covering the deformable element by an aluminium plate could be helpful, but it could also affect the force measurement. Moreover, even if this measure was available, the interpretation is not relevant since the front-end is not totally deformed. Due to the lack of energy measurement, another point to highlight is the possibility to limit intentionally the energy capability of the front-end in order to increase the engine pushing and therefore improve the homogeneity as it is measured in the FWDB test. Such an evolution would be counterproductive in the real car accident where the energy aspect could not be neglected.

Force

The maximum PDB force corresponds to an average force located between the front-end deformation force and the maximum force that the passenger’s compartment is able to support. This observation is a general trend.

For FWDB test, the maximum force does not help to evaluate the compatibility regarding the force since this measured force only corresponds to the beginning front-end deformation.

CONCLUSION

The aim of this paper was to conduct a methodological and physical analysis of both candidate test procedures in order to evaluate their ability to measure the three incompatibility physical phenomenon involved in real world incompatibility (geometry, energy and stiffness mismatching).
This study, based on physical and virtual testing, with or without lower load path, enables to draw significant outcomes:

1) Both procedures can detect a geometry change such as the absence of load path. However, for the FWDB test, a rigid crossbeam for a large car should not be detected as enough rigid contrary to real world accident observation. This is due to the high stiffness of the second

layer of the deformable element. On the contrary, a weak crossbeam for a mini car would not be detected so weak due to the engine pushing which is systematically taken in account in the force analysis for small cars. Moreover, the limitation of the force analysis at 40ms will penalise cars not equipped with advanced lower load path as the family car #1. This point is directly link to the procedure itself.

2) Both procedures can measure a global force. However, its interpretation for the FWDB test is difficult due to the very limited deformation of the front-end sustained in this test.
3) Only the PDB test is able to draw up an energy absorption statement which is the only way to evaluate the car crash severity and the front-end absorption capability. For the FWDB test, this point represents a major difficulty because energy absorption by deformable elements is significant, about 50kJ, thus decreasing the severity of the test.

No inconsistencies have been found for the PDB test when comparing the physical and virtual testing with the real word accident. This means that the PDB barrier seems to be a good tool to evaluate compatibility. The next step could therefore consist in confirming its reproducibility.

Several difficulties appear concerning the FWDB test. Improvements are needed on the procedure. The deformable elements are mainly concerned. Firstly because inconstancies have been observed with the real-life car accident and secondly because the instability of the second layer honeycomb blocks makes virtual testing very difficult to carried out. They could therefore be changed in terms of stiffness or/and depth. Another point is also to solve the difficulties linked to the relevancy of the force measured, for instance in the case of rigid plate trolley test. As this point is well known and often discussed, it has not been highlighted in this paper but this problem still exists.

When considering all the results obtained, the PDB test appears therefore to be the best test procedure to evaluate a maximum of physical aspects with only one test.
A general rule to keep in mind is that developing assessment criteria appears completely useless until all test procedure problem have not been solved. The results of this paper show that assessment criteria could therefore now be studied concerning the PDB test. For FWDB test, further improvements are still needed on the procedure itself before being able to work on assessment criteria.

ACKNOWLEDGMENTS

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