MPDB-Mobile offset progressive deformable barrier
A new approach to cover compatibility and offset testing

Volker, Sandner
Andreas, Ratzek
ADAC e.V
Germany

Paper Number 15-0389

ABSTRACT
For more than 25 years the German Automobile Club ADAC is conducting tests to show the consumers and Industry the compatibility of passenger cars. With the upcoming off road vehicles in the 90’s, the structural and mass difference between the compact and the small executive cars according the Off roaders was huge. The geometries in the vehicle front structures were totally different and did not align in case of a frontal impact. In combination with less performing structures for offset crashes the outcome in a car to car offset frontal impact tests was dramatically worse. Not only the smaller and lighter car showed poor performance also the crash structure of the large off roader failed. A decade later the passenger cars have become much safer due to consumer test programs and regulatory demands. But still these cars are showing a different behaviour in a car to car impact than in a car to barrier impact.

The different results of ODB tests, car to car impacts and the accident analyse showed that there is a need to find a test solution which will show this performance in a full size crash and allow analysing and rating the result. Several tests with vehicles, barriers and different test conditions have been carried out to find a solution to reproduce real life behaviour and a possibility to rate the vehicle according its aggressiveness and compatibility, which lead to a mobile barrier solution with a progressive deformable element.

INTRODUCTION
Passenger cars have become much safer over the last years, not least thanks to comprehensive consumer testing programmes. The vehicles comply with most of the requirements of the Euro NCAP standard crash configurations.

The Euro NCAP frontal impact assesses the vehicle’s self protection potential under the precondition that the car’s supporting structure is ideally hit in the crash. Since single-vehicle accidents account for over 50%[1] of road deaths and over 40% of severely injured occupants, self protection is a decisive aspect of passive safety. ADAC accident research data shows, however, that severe injuries may be due to the fact that the supporting vehicle structures fail to meet. To ensure optimal accident protection, it is essential that the supporting vehicle structure is hit and that the crumple zone absorbs energy while the cabin remains stable. However, ADAC accident research data shows that this is not always the case. In many collisions, e.g. the longitudinal member is not hit (Figure 1) or the cross member detaches from the frame. In such case, the crumple zone cannot be fully utilised and the cabin deforms. This reduces survival space which means that the restraint systems fail to prevent the occupants from hitting the steering wheel or dashboard and sustaining severe injuries.
In 2010, ADAC introduced a new test set-up to assess the compatibility of vehicles. The test procedure should address the majority of the collisions not covered by the standard. In the test, the test vehicle impacts a special, honeycomb-shaped element, leaving a characteristic indentation whose surface is scanned for evaluation after the test. The indentation scan allows an assessment of a vehicle’s sensitivity to nonstandard crash constellations. Moreover, the test assesses the partner protection of the vehicle’s crumple zone and the load the vehicle causes to smaller vehicles in a collision. This vehicle to mobile barrier test with a progressive deformable Element was named ADAC compatibility test or MPDB test.

To achieve additional reductions in the injury risk of car occupants, extended research into passive safety will be required. Assessing a vehicle’s self protection potential under ideal load conditions will no longer be sufficient. The effective interaction of different vehicles (“compatibility”) and a large front-end shield are becoming increasingly important.

ACCIDENT STATISTICS

In 2009, 183,785 car occupants [1] were in a road accident involving a maximum of two parties: approx. 64% of them were in a car-to-car accident, 23% in single-vehicle accidents, 9% in accidents involving HGV and buses and approx. 4% in accidents involving other road users.

Considering exclusively accidents causing severe or fatal injuries, the percentage of single-vehicle accidents increases considerably (see Table 1 and Figure 2).
Table 1:
Car occupants involved in accidents in Germany by crash opponent and injury severity

<table>
<thead>
<tr>
<th>Crash opponent</th>
<th>Car occupants (single-vehicle and two-vehicle accidents)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of occupants involved in accidents</td>
</tr>
<tr>
<td></td>
<td>killed</td>
</tr>
<tr>
<td>Single-vehicle</td>
<td>42,773</td>
</tr>
<tr>
<td>Passenger car</td>
<td>118,173</td>
</tr>
<tr>
<td>HGV, bus</td>
<td>16,425</td>
</tr>
<tr>
<td>Other</td>
<td>6,414</td>
</tr>
</tbody>
</table>

Figure 2: Car crash opponents (top left) and crash opponents by injury severity of car occupants
According to ADAC accident research data, the vehicle class only has a minor influence on the severity of the injuries car occupants sustain (Table 2). There are two reasons:

- ADAC accident research concentrates on severe accidents; approx. 39% of them are single-vehicle collisions and 14% involve utility vehicles. In these two types of accidents, the vehicle’s self protection potential is essential while the high vehicle weight and a more rigid front end have little advantage. The only asset is the larger crumple zone of large cars.
- The analysis considers all types of collisions. Large vehicles have the greatest advantage in front-end collisions.

| Table 2: Percentage of slightly, severely and fatally injured car occupants (ADAC accident research; vehicles built in 2000 or later) |
|---------------------------------|----------------|----------------|----------------|
|                                 | Supermini      | Family         | Luxury         |
| Slightly injured                | 37%            | 38%            | 45%            |
| Severely injured                | 60%            | 60%            | 53%            |
| Fatally injured                 | 3%             | 2%             | 2%             |

Considering exclusively two-car front-end collisions, it becomes obvious that injury severity is relatively strongly affected by vehicle mass. Figure 3 shows that the risk of getting seriously or fatally injured in a crash is approximately twice as high in very light vehicles (<950kg) (over 27%) as in very heavy vehicles (>1750kg).

![Figure 3: Percentage of severely and fatally injured in car-to-car front-end collisions by vehicle mass](image-url)
WHAT DOES COMPATIBILITY INCLUDE

Compatibility refers to the interaction of colliding vehicles. The following issues are especially important:

- **Weight difference:**
  When two vehicles of different weight crash into each other at identical speed, both vehicles will move in the heavier car’s direction of travel. While the impact causes the lighter car to brake to a standstill and then accelerate rearward, the heavier car is braked from its speed of travel to a residual speed.

  Vehicle deceleration depends on the change in speed during the crash (\(\text{delta } v = \text{pre-crash speed of travel} - \text{post-crash residual speed}\)) and is a decisive factor for determining accident severity and the occupants’ injury risk. Since speed change is smaller in the heavier passenger car, loads on the occupants are lower in the heavier than in the lighter vehicle.

- **Different front-end rigidity:**
  The test set-up used for vehicle approval based on ECE R94 and the Euro NCAP frontal impact includes an offset collision between two cars of identical weight which travel at the same speed. For this test, it is essential that impact energy is absorbed by the crumple zone before the cabin starts to deform. To ensure that the vehicle’s own “pushing” mass causes only the crumple zone to deform, heavy vehicles have higher front-end stability than light vehicles. Although heavy vehicles usually have a longer deformation distance, the structural force required to cause front-end deformation is significantly higher in heavy vehicles than in light vehicles.

  If two different vehicles crash into each other, the crumple zone of the lighter car will be the first to deform because of the vehicles’ different rigidities. As a result, the load on the small vehicle may become too high relatively quickly while the crumple zone of the larger vehicle remains mostly intact.

*Figure 4: Upon impact, the heavy SUV causes the light supermini to skid rearward*
Different front-end geometries:
The deformable element used in the Euro NCAP frontal impact and the ECE R94 vehicle approval is comparatively soft and absorbs only little energy while maximum load is exerted. Modern vehicles penetrate the element (blue in Figure 6), and the longitudinal member transfers the impact energy directly to the metal plate behind.

Longitudinal member position and dimensions as well as transverse member stability (cross members connecting the left and right longitudinal members; red in Figure 7) are of minor significance. In this standard crash, even a single longitudinal member jutting out of the vehicle like a spear can transfer the impact energy to the large metal plate behind the deformable element.
Figure 7: The dimensions and position of supporting structures in modern cars vary considerably

More often than not, cars colliding head-on cannot support each other because their supporting structures do not meet, causing the crumple zone to remain mostly intact while the cabin deforms. In most cases, this results in very severe injuries to the occupants (Figure 8). The smaller the front-end overlap and the higher the collision speeds, the more serious are the consequences of geometric discrepancies. An approach by IIHS is covering exactly this kind of small overlap situation, by using just 25% of the vehicle width.

Figure 8: If the supporting vehicle structure is not hit in a crash, the impact energy causes cabin deformation
DEVELOPMENT OF CAR TO MOBILE DEFORMABLE BARRIER TEST

As the car to car impact was the starting point the initial setup of the car to barrier test should be close as possible. The impact speed of 56kph and the overlap of 50% of the small car were taken over. In several European projects, such as APROSYS, the actual average mass of passenger cars in Europe were discussed for the side impact barrier. While taken into account the number and type of cars actual on the market as well as actual selling numbers, the compact car class, shows the highest number actual on European roads. In driving condition these class will be approximately 1400kg heavy. The mass of the mobile barrier was set to this weight, which is already covered by the FMVSS 208 side impact barrier, which is the base for the impacting trolley.

First impact tests

The initial starting point for the test specification was the car to car impact test between two cars of the same mass range and size. This test was carried out according the actual car to car impact specifications with 50% overlap of the small car and 56kph impact speed. In this test, also the vehicles were out of the same vehicle class, both longitudinal did not match (see Figure 9)

Figure 9: car to car impact at 56kph

In a second test the yellow car was replaced by the mobile barrier equipped with the PDB Element. All other parameters were not changed (see Figure10)
Comparison of deformations:

A direct comparison between the vehicle pulses, the vehicle deformations and the 3D measurement showed that the MPDB test loaded the tested vehicle in a different way than in the car to car impact.

Differences detected after the impacts were are more or less undeformed footwell area, the trans facia beam and A-pillar section showed rupture, the instrument panel intruded the passenger compartmented. Compared to cases of the ADAC accident research and also compared to the car to car test those deformations are quite uncommon and lead to the decision to implement changes in the test setup and improve the performance of the test results.

The top of the PDB element is compareably high (appr. 900 mm) and in the upper part more or less undeformed. So it is quite likely that the upper part of the PDB is stiffer than an average car. During the test, the PDB put a lot of energy into the car, especially in the area of the waist line. Following changes were applied to the barrier due to that fact.

1. reduce the ground clearance of the PDB by 75 mm
2. reduce the overall height of the PDB by 135 mm
3. **reduce the test speed to 50 kph**

A second impact test with the changes mentioned was performed and the vehicle pulse as well as the 3D measurement and the deformation of the car were quite close and comparable see deformation pictures in Figure 12.

![Deformation comparison](image)

**Figure 12: Comparison of deformations car to car test (left picture), new car to MPDB test (right picture):**

The overall result of the new test setup could be recognized after the detailed analyses of the vehicle tested according the new boundaries. Not only the overall picture shows a comparable deformation, also the detailed view below the dashboard, the deformation of the A-pillar and the intact trans facia beam offer no big differences between the 2 tests. But there are still less deformations in the footwell area of the MPDB tested car. The conclusion is, that deformations of the PDB are more homogeneous – the upper part is also loading the tested vehicle.

**Test setup car to MPDB**

The new test setup of compatibility crash test simulates a head-on collision with a 50% overlap between the vehicle to be assessed and an approx. 1400kg moving trolley with a PDB, made of alloy, representing a typical, widely used small family car (see Figure 13). The vehicle and the trolley are travelling at identical speed.

The ground clearance of the PDB barrier is 150mm while the height of the barrier is 750mm above the ground and one alloy box with a stiffness of 0.34MPa and a second block with progressive stiffness, both covered with an alloy sheet.
To assess the occupants’ injury risk, two 50% H3 dummy on each of the two front seats and restrained a Q6 child dummy in an appropriate CRS on the right rear seat were installed. Dummy installation and instrumentation as well as vehicle load and measurement were in compliance with the Euro NCAP test protocol. Also the Dummy assessment was carried out according Euro NCAP assessment protocols.

**METHODE OF THE COMPATIBILITY ASSESSMENT**

The compatibility assessment includes the analysis of the indentation the colliding vehicle leaves on the deformation element upon the impact as well as the change in trolley speed. The assessment comprises the steps below:

1. **Determining the assessment area:**
   
The first step includes determining the area of the PDB that is relevant for assessment in dependence of the vehicle dimensions and other framework conditions:

   **Width** Ideally, the front-end shield spans the entire width of the passenger car to be able to absorb impact energy in the crumple zone also in accidents where overlap is minor. To take this into account, the assessment area represents 45% of the vehicle width.

   Because of the crash kinematics (rotation of the vehicle and trolley), force is exerted on the side edges of the deformation element which, as transverse load, causes unrealistic deformation to the honeycomb structure. As a result, the edges cannot be assessed and the assessment area ends 200mm from the PDB’s side edges.

   **Height** To ensure that the structures of the colliding vehicles meet upon the impact and to lower the risk of overriding or underriding the barrier, the supporting structure must be mounted between 250 and 650mm above the ground. This takes the different vehicle classes into account and complies with additional requirements (e.g. RCAR bumper test, HGV underrun protection).
Figure 14: Determining the assessment area

650mm

45% of the vehicle width

250mm

200mm
2. Assessing indentation homogeneity/geometry:

Ideally, the vehicle front end should have homogeneous rigidity in the entire assessment area (see Figure 14). Both very rigid longitudinal members that penetrate the colliding vehicle like a spear and very soft areas that do not provide support for the colliding vehicle and barely dissipate or absorb energy are a disadvantage. A vehicle meets the above criteria if it leaves a homogeneous and large indentation in the PDB.

The homogeneity assessment comprises a statistical evaluation of the intrusion depth in the area under assessment. For this purpose, the average intrusion depth and the standard deviation (a measure for the mean variation of the measured values around the average) are determined. A greater standard deviation means a more inhomogeneous deformation of the barrier and results in a poorer homogeneity rating.

3. Assessment of the energy impacting on the colliding vehicle:

Two criteria are used to assess front-end rigidity and the energy impacting on the colliding vehicle:

- **Energy impacting in the PDB assessment area:** Great differences in the rigidity of colliding vehicles may cause impact energy to be absorbed only by the less rigid vehicle while the crumple zone of the more stable vehicle remains intact. Very high front-end rigidity therefore has a detrimental effect on partner protection. PDB deformation depth enables the assessment of front-end rigidity and impact energy. To lower the risk of excessive loads on the colliding vehicle, it is essential that the vehicle tested absorbs kinematic energy in its own crumple zone.

- **Change in trolley speed:** Since for technical reasons impact energy assessment focuses only on the assessment area as defined above, we do not consider the entire amount of energy impacting on the colliding vehicle in our test. Therefore, we also assess the change in trolley speed. While a change by less than 50kph is a plus, a change by more than 50kph is a drawback.

**Examples of different front structures**

The following tables will show the results of 3 family cars tested in the last test series and according the latest version of the assessment. All cars have been tested also by IIHS according the small overlap test. The results in the compatibility test are showing very different behaviour of front structures. In the 1st example the vehicle shows a single load path of extreme stiffness and a very weak cross member. While example 2 has several load paths in height and is also covering the outside areas of the longitudinal. This vehicle scores well in the small overlap and the compatibility test. The 3rd vehicle shows also 2 load paths in the front, but also a weak cross member. The longitudinal is too stiff, but less aggressive than in example 1. The 3rd car has a good rating in small overlap tests too.

**Table 3:**

<table>
<thead>
<tr>
<th>Example 1 family car</th>
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<tbody>
<tr>
<td><strong>Post-crash vehicle</strong></td>
</tr>
</tbody>
</table>
Post-crash PDB

PDB deformation upon the impact is extremely inhomogeneous with the longitudinal member punching a deep hole into the barrier and the engine block causing strong deformation to the PDB edges (on the right in the photo). Where the vehicles front wheel impacts the PDB, intrusion of the PDB which absorbs approx. 93kJ is, however, minimal. The PDB trolley’s maximum deceleration upon impact was 35g. The change in speed was 63kph.

Digitised post-crash PDB front

This illustration shows the entire front of the PDB and the different intrusion depths. Intrusion depth colour scheme:
- Orange 0 to 160mm
- Yellow 160 to 320mm
- Green 320 to 480mm
- Red >480mm

Post-crash PDB assessment area

This illustration shows the PDB area that is relevant for compatibility assessment.

The green area of the indentation left by the Audi’s front end is well-suited to absorb energy in a crash, while the red area is much too rigid. On the other hand, the yellow and orange areas are too soft.
Table 4:  
Example 2 family car

| Post-crash vehicle | The vehicle is a family car with a relatively homogeneous crumple zone. It consists of three horizontal planes connected on the right and left with vertical profiles:
|                   | - The main load path consists of two longitudinal members interconnected by a steel cross member. There is an additional connection from the longitudinal members to the suspension strut domes in front of the wheels.
|                   | - A steel lock support of somewhat weaker dimensions is located above the main load path and is connected to the suspension strut domes on either side.
|                   | - Below the main load path is another steel cross member which spans the width of the longitudinal members.
|                   | What makes the vehicle design unique are its structures located outside the longitudinal members and in front of the front wheels. These structures are intended to dissipate the impact energy over a large area and absorb energy in crashes with little overlap.
|                   | Maximum deceleration of the vehicle upon the impact was 71g. The change in speed was 58kph. |

| Post-crash PDB    | Rather large areas of the element are deformed by the impact. There are no major holes in the surface, but the individual members on the vehicle front have left visible indentations. The PDB trolley’s maximum deceleration upon impact was 29g. The change in speed was 58kph. The barrier absorbs 76kJ of energy in the crash test. |
This illustration shows the entire front of the PDB and the different intrusion depths. Intrusion depth colour scheme:
- **Orange**: 0 to 160mm
- **Yellow**: 160 to 320mm
- **Green**: 320 to 480mm
- **Red**: >480mm

### Table 5:
**Example 3 family car**

<table>
<thead>
<tr>
<th>Post-crash vehicle</th>
<th>The front end of the vehicle comprises several load paths:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• The main load path consists of two longitudinal members connected by a steel cross member.</td>
</tr>
<tr>
<td></td>
<td>• Underneath the longitudinal members, there is an additional steel cross member whose outer edges rest on the chassis sub-frame.</td>
</tr>
<tr>
<td></td>
<td>• In front of the suspension strut domes, the vehicle has two additional short, longitudinal members (shotguns) stably connected to the main load path. These members are intended to protect the cabin in crashes with little overlap.</td>
</tr>
<tr>
<td></td>
<td>Maximum deceleration of the Vehicle upon the impact was 33g. The change in speed was 51kph.</td>
</tr>
</tbody>
</table>

| Post-crash PDB     | The main load path of the vehicle leaves a vertical bend and a much deeper indentation than the other supporting structures. In this test, the PDB element absorbed 92kJ of energy. The PDB trolley’s maximum deceleration upon impact was 38g. The change in speed was 58kph. |
CONCLUSIONS

Compliance with Euro NCAP frontal impact requirements is essential for good occupant protection. However, even vehicles with a very inhomogeneous front-end design may pass this test. In the event of a two-vehicle accident (or single-vehicle accident such as vehicle-tree collision), poor front end structural design may result in excessive local loads on the vehicle or its opponent and serious injuries for the occupants. Vehicle designers must therefore take additional requirements into account:

- **Adapted front-end geometries**

  In today’s vehicles, there is no standard for the mounting height of front-end supporting structures, i.e. mounting height may vary greatly from manufacturer to manufacturer and from car model to car model. Cross members are usually very flat and do not span the entire width of the vehicle. In addition, they are unstable, failing to dissipate the impact energy. As a result, there is poor energy absorption potential for the colliding vehicles.

  Equipping a vehicle with a front shield consisting of wide multiple cross members (see Figure 15) may dramatically improve partner protection and self protection (e.g. when crashing into a tree). It helps dissipate the impact energy throughout a large area so that most of it is absorbed in the crumple zone. The shield should protect the area between 250mm and 650mm above the ground and ideally span the entire width of the vehicle. This construction will not only help for partner protection, also small overlap scenarios will be addressed with this construction.

![Figure 15: Frontal impact protection: disadvantageous (left) vs. advantageous (right) front-end construction](image)

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[Digitised post-crash PDB front]

This illustration shows the entire front of the PDB and the different intrusion depths. Intrusion depth colour scheme:

- Orange 0 to 160mm
- Yellow 160 to 320mm
- Green 320 to 480mm
- Red >480mm
Adapted front-end stability

Vehicle mass has no influence on the deformation distance required to keep vehicle deceleration at an acceptable level. The long nose of a large and heavy vehicle can therefore be divided into a soft partner protection area and a rigid self protection area. This ensures that in a head-on collision with a light vehicle, the crumple zone of the large vehicle is able to absorb most of the energy rather than the small vehicle.

If the vehicle designers bear the above issues in mind, they will contribute to considerably lowering the injury risk in single-vehicle and car-to-car accidents. The risk of getting seriously or fatally injured is likely to decrease by approx. 7%.[1] This would prevent over 150 road deaths and some 2100 serious injuries to car occupants on German roads each year.

The Euro NCAP roadmap for 2017-ff will also include an updated frontal impact scenario and will have to deal with the question self and partner protection. Possible frontal scenarios were examined in the last 5 years which will be taken into account for a new consumer frontal impact test scenario in 2020.

REFERENCES