

What is the Benefit of the Frontal Mobile Barrier Test Procedure?

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ABSTRACT

Frontal impact is still the most relevant impact direction in terms of injury causation amongst car occupants. Especially for car-to-car frontal impacts the mass ratio between the involved vehicles has a significant impact on the injury risk (the heavier the opponent car the higher the injury risk). In order to address this issue frontal Mobile Deformable Barrier test procedures have been developed world-wide (for example the MPDB procedure that was fully described during the FIMCAR Project). The objective of this study was to investigate how vehicles of different weight classes perform in a mobile barrier test procedure compared to a fixed barrier test procedure (the full width rigid and offset deformable barrier test). Beyond that, the influence of vehicle mass and vehicle deformation on injuries was evaluated based on real world accident data.

Five vehicle types were selected and tested in a fixed offset test procedure (ODB), a full width rigid barrier test procedure (FWRB) and a mobile offset test procedure (MPDB). For the accident analyses data from the German In-Depth Accident Study (GIDAS) was evaluated with a focus on MAIS 2+ injured belted front row car (UN-R 94 compliant cars) occupants in frontal impact accidents.

Test data indicates higher dummy loadings, in particular for the head acceleration and chest acceleration, in the MPDB test for the vehicles with a mass lighter than the trolley (1,500 kg) compared to the FWRB test. The trend of increased vehicle stiffness (especially illustrated by tests with the MPDB and small cars) shows the need of a further improvement of passive restraint systems to reduce the occupant loading and with it the injury risk.

The analyzed GIDAS data confirm the higher injury risk for occupants in cars with an accident weight of less than 1,500 kg compared to those with a crash weight above 1,500 kg in car-to-car and car-to-object or car-to-HGV, respectively. Furthermore the injury risk increases with decreasing mass ratio (i.e., the opponent car is heavier) in car-to-car accidents. Independent from the higher injury risk, the risk for passenger compartment intrusion in frontal impact appears not to be independent on the crash weight of the car.

INTRODUCTION

Frontal impact is still the most relevant impact direction in terms of injury causation [1]. While the stability of passenger compartments has been improved in Europe substantially in recent years, the performance of the restraint system becomes now even more important [2]. In the traditional restraint system test, the vehicle is crashed between 40 and 56 km/h against the rigid wall independent of the vehicle mass. This is a test procedure used in many countries all over the world. In real-world car-to-car impacts a light vehicle is more likely to be hit by a heavier vehicle and due to the principle of conservation of momentum, the lighter of the two vehicles has to withstand higher loading than the heavier vehicle. Higher loading not only affects cabin integrity, but also cabin acceleration as the lighter of the opponents suffer from a greater change of velocity (Δv) due to the conservation of momentum. A test with a frontal mobile barrier would reflect these circumstances and was discussed several times in the past [3], [4] and [5]. For the present investigation the frontal mobile test procedure as defined by the FIMCAR

Project [5] was used, because the mass of the trolley and the stiffness of the barrier represents a European midsize car [6–8].

Current accident studies show that many injuries are caused by high vehicle acceleration in frontal impacts compared to injuries caused by intrusions into the passenger compartment [2]. It was also stated that the accidents with acceleration loading induced injuries had a high overlap. On the other hand crash tests with a low overlap at the corner of the vehicle are discussed in other consumer information programmes or regulatory bodies [3, 9–11]. However in Europe, crash tests with a high overlap seem to have a higher priority [12].

With the analyses of real world accident data the following questions should be answered. Have occupants in smaller vehicles (less than 1,500 kg) a higher injury probability in frontal impacts compared to occupants in vehicles heavier than the crash trolley? And if so, is this due to the passenger compartment stability (intrusions) or due to higher occupant loads as a result of the crash pulse and the restraint system?

The different loading in terms of vehicle deformation, vehicle acceleration and injury assessment values for vehicles with a mass lighter and heavier than the mobile barrier should be investigated with the help of crash test data. It is assumed that lighter vehicles have a higher loading with a frontal mobile offset barrier compared to a fixed barrier test (FW / ODB) and that heavier vehicles have a lower loading.

METHODS

Methods Accident Data

For the accident analyses, data from the German in-depth accident study (GIDAS) was evaluated with a focus on MAIS 2+ injured belted front row car occupants¹ in frontal impact accidents. To ensure that only UN-R 94 [13] compliant vehicles were included, only vehicles with a date of first registration in 2003 or later were considered. Furthermore only completely coded and reconstructed accidents up to 2013 were included in the study to guarantee that not only EES but also delta-v was available. The GIDAS sampling method is explicitly explained in [14]. The final data set consisted of 98 cases including 112 front seat occupants with MAIS 2+ injuries.

The accident severity was evaluated using the reconstructed delta-v and EES values. The deformation of the vehicle was classified using the overlap and the CDC classification. The overlap is in percentage and it is important to note that the overlap is coded independently from the involvement of the vehicle corners (e.g., a center pole impact with a pole having a diameter of 20% of the vehicle width is coded as 20% overlap). That distinction was necessary to separate between accidents with a small overlap at the edge of the vehicle and pole impacts. For the analysis it was estimated which kind of frontal impact test procedure would cover best the accident scenario. Here the four possibilities pole, small overlap, half overlap and full frontal were considered. The accident scenarios were identified by separating between offset crash (30 % to 50 %) and large overlap crash (80% to 100%), see also Figure 2. All cases were manually checked in regard to the deformation classification with the help of the accidents pictures.

The collision opponents were classified, on the one hand, as vehicles and, on the other hand, as fixed structures (e.g. road side barriers, walls), poles (trees, traffic lights, street lamps) and others.

The injury severity was coded for the whole person by the official police classification (not injured, slightly injured, severe injured (hospitalization for more than 24 hours) and fatally injured (fatality as a direct result of the accident within 30 days after the accident)). All injuries were separately analyzed using the AIS 2005 classification. The vehicle mass was described with the estimated crash weight of the specific vehicle at the time of the first impact.

Methods Crash Test Data

Crash test data from different vehicle models were obtained in the test configurations: offset test according to the Euro NCAP test protocol (ODB), Full Width Rigid Barrier test (100% overlap, FWRB), and against a Mobile barrier with the Progressive Deformable Barrier attached (MPDB). To evaluate the injury risks Hybrid III

¹ MAIS = Maximum Abbreviated Injury Scale, injury severity classification according to AIS 2005

50% dummies on the driver seat were used. Table 1 is showing the vehicles used, including the acronyms, the test masses and the data source the test is obtained from.

Table 1 Test vehicles, acronyms and data base used for the analyses

Vehicle acronym	DS	VU	SI	VT	VX
Test mass	1164 kg	1050 kg	1181 kg	1900 kg	2400 kg
ODB	Euro NCAP	Euro NCAP	Euro NCAP	Euro NCAP	Euro NCAP
FWRB	BASt	BASt	BASt	n.a.	n.a.
MPDB	BASt	BASt	BASt	FIMCAR	FIMCAR
Description	Compact car, four doors, cheap	Super mini, two doors, new vehicle design	Compact car, two doors, popular	Midsize SUV	SUV

The ODB test was conducted with a test speed of 64 km/h and an overlap of 40% using a deformable barrier face as defined in [13]. The FWRB had a test speed of 50 km/h, with 100% overlap and without a deformable barrier face [15]. The MPDB test procedure is explained in detail in [7] including the specifications for the test trolley. The closing speed was 100 km/h and the mass of the trolley was 1,500 kg. These values were not changed for the different vehicles. The progressive deformable barrier used for the MPDB is bigger and significantly stiffer compared to the ODB barrier. This makes barrier bottoming out much more unlikely. The barrier is specified in [16].



Figure 1 Crash trolley used of the test with mobile barrier specified in [7] using the PDB v8.0 XT

To analyze the loading on the vehicle the maximum acceleration measured at the b-pillar driver side was measured. Additionally the OLC (Occupant Loading Criterion, [17]) was calculated based on that acceleration signal. OLC predicts the relative motion of the dummy and vehicle and calculates the average acceleration experienced by the dummy when its relative position is in the interval between 65 mm and 235 mm. The structure of the vehicle was evaluated based on the a-pillar displacement (at waist line) measured after the test.

The restraint performance was evaluated using the following indices: belt forces measured at the upper shoulder belt between shoulder and the upper anchorage point (B3) and - if available - measured at the lap belt between the hip and the lower anchorage point (B6). Furthermore the airbag deployment time², the airbag contact time³ and the seatbelt pretensioner time⁴ was analysed. The time points were determined based on the high speed videos.

² Airbag deployment time = Timing correlating with first frame in the high speed film when the Airbag cover breaks

³ Airbag contact time = Timing correlating with first frame in the high speed film when the dummy head contacts the airbag

⁴ Seatbelt pretensioner time = Timing correlating with first frame in the high speed film when the seatbelt moves

For the analyses of the loading on the occupant the injury criteria from the HIII dummy were used. The focus was on the criteria which are sensitive to assess the loading from the vehicle acceleration: head acceleration (3ms value, HIC within 36ms), chest compression, chest acceleration (3ms value) and pelvis acceleration (peak). The injury criteria were scaled to the ratio of 100% injury assessment reference values (IARVs) to provide a better overview and to enable a better comparison according to UN-R 94 where possible [13, 18–20] [18]. For the chest and pelvis acceleration 60g as 100% were defined, see also Table 2.

Table 2 Injury assessment reference values used for the analyses of the occupant loading

Injury Criteria	Pelvis acceleration	Thorax Acceleration	Thorax deflection	Head acceleration	Head injury criterion
Acronym	Pelvis Acc	Thorax Acc	Thorax Defl	Head a3ms	HIC 36
IARV	60g	60g	42mm	80g	1000
Notes	peak value	3ms value	max. value	3ms value	within 36ms

RESULTS AND DISCUSSIONS

Accident Data

The following picture (Figure 2) shows the distribution of the overlap crash scenarios for the 98 cases. Almost half of the accidents had a very large or a full overlap. The other three crash scenarios (offset, small overlap edge, small overlap in the middle) were almost equally distributed with values between 15% and 20%.

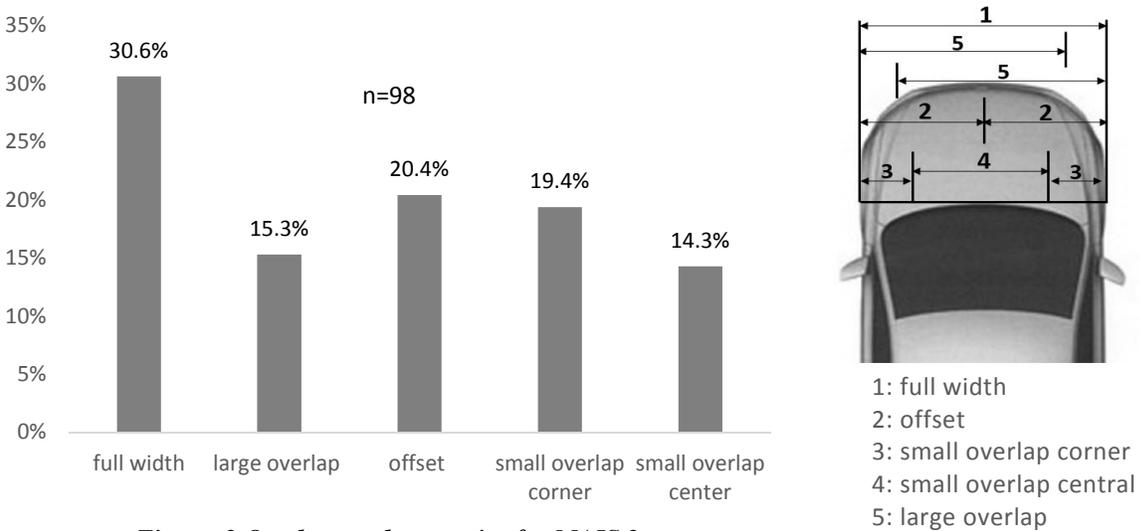


Figure 2 Overlap crash scenarios for MAIS 2+

Of the 98 cases, 52 accidents involved another vehicle and in the other cases the opponent was an object. Figure 3 shows the mass distribution (left) and mass ratio (right) of the vehicle opponents. The mass ratio was calculated by dividing the crash weight of the case vehicle by the crash weight of the opponent vehicle. Thus a mass ratio smaller than one indicates cases with the opponent being heavier than the case vehicle and vice versa. The mass was categorized in 300 kg steps starting with 800 kg. The mean value of the vehicle opponent mass was at 1,472 kg which is very close to the mass of the crash test trolley used (1,500 kg). With regard to the mass ratio it can be seen (Figure 3, right) that in the groups with a mass ratio around 1 (0.8 to 0.99 and 1.0 to 1.19) the injury risk was similar. However, there was a higher injury probability in vehicles with a mass ratio be-

tween 0.6 and 0.79 (the vehicle opponent was heavier) compared to the group with a mass ratio 1.2 to 1.39. It is believed that the numbers for the groups with a mass ratio beyond are too small.

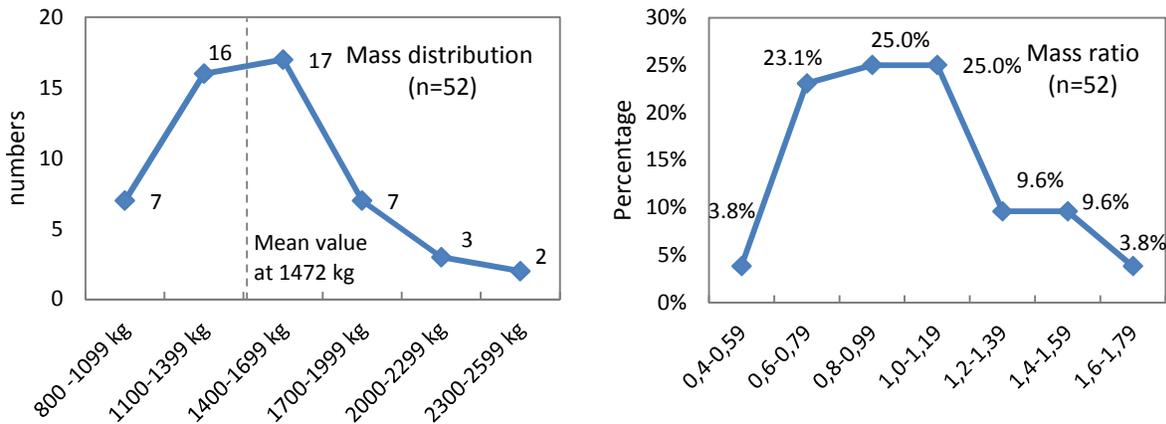


Figure 3 Distribution (left) and ratio (right) of the mass for the vehicle opponents (n=52); vehicle opponent is heavier (ratio < 1), vehicle opponent is lighter (ratio > 1)

The influence of intrusion to the passenger compartment with regard to the mass ratio was evaluated and is illustrated in Figure 4. Intrusion is defined as stability loss in the a-pillar or the firewall. In general passenger compartment intrusion is observed in a small number of cases of car-to-car accidents only – when intrusion was observed it was mainly in accidents against objects and Heavy Goods Vehicles (HGV). Looking at the car-to-car impacts there were 4 cases in crashes with a mass ratio > 1 (the opponent vehicle was lighter) and 2 cases in crashes with a mass ratio < 1 (the opponent vehicle was heavier).

When looking at the 13 cases with a large weight difference between the accident vehicles (mass ratio between 0.6 and 0.79) in only one accident vehicle intrusion was observed. This indicates that intrusion seems not to be the major injury factor when a heavier vehicle crashes against a lighter vehicle as already postulated by Thompson et al. [2].

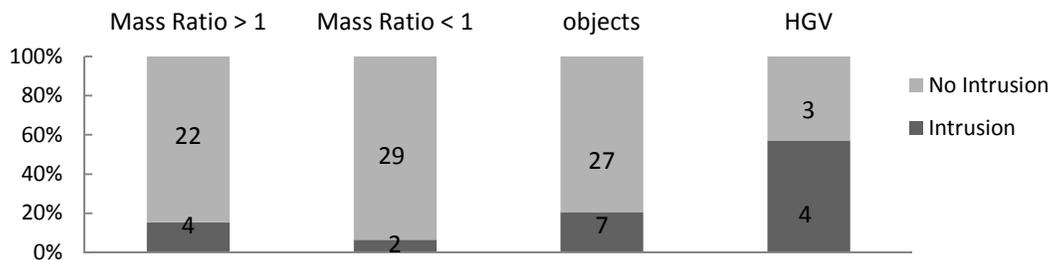


Figure 4 Influence of intrusion in regard of the passenger compartment identified for the vehicle to vehicle accidents with a certain mass ratio and the vehicle to object accidents

Figure 5 illustrates the number of injured front seat occupants categorized in slightly injured, seriously injured and killed according to their own vehicle mass. As only cases with MAIS 2+ injuries were selected there were no uninjured occupants in this data set. On the left side there are crashes against all opponents (vehicles and objects). There were almost more than double of seriously injured occupants in lighter vehicles compared to heavier vehicles. While the left side of Figure 5 shows all accident scenarios the right side considers only car-to-vehicle accidents (including car-to-HGV). The data suggest that the injury risk is increasing when the vehicle is

lighter than the mean mass. However, there is a bias because heavier vehicles are more likely to be newer. Also, heavier vehicles are more likely to be a luxury vehicle having a more advanced restraint system.

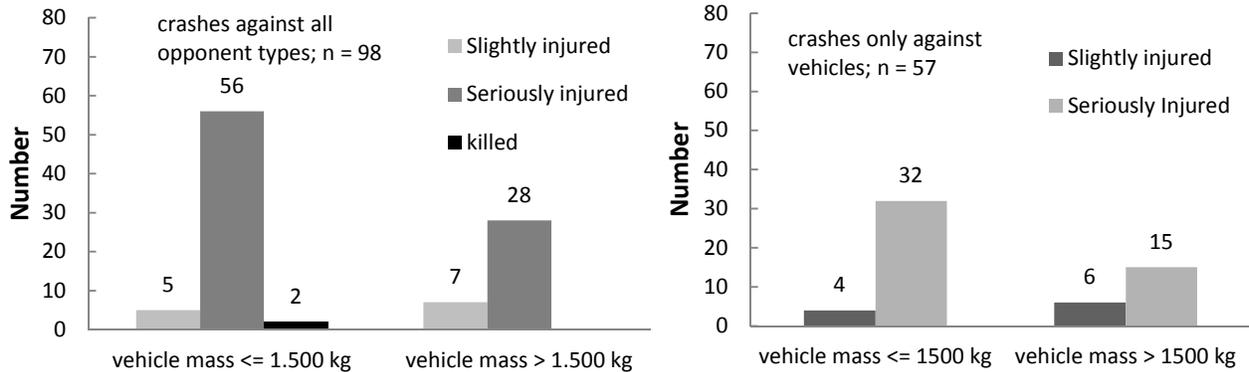


Figure 5 Number of vehicles with MAIS2+ car occupants in regard to their injury categorization and their own vehicle mass; left: against all opponent types (n=98), right: only vehicle to vehicle crashes (n=57)

The analyses of real world accident data suggests that occupants in smaller vehicles (less than 1,500 kg) have a higher probability on injuries in frontal impacts compared to occupants in vehicles heavier than the crash trolley. Although the numbers were low in regard to the mass ratio, the numbers were very clear when only the own vehicle mass was considered. The accident data also suggest that the higher injury probability is not due to the passenger compartment stability, but rather due to the occupant loading due to the crash pulse and the restraint system.

Crash Test Data

To compare the loading on the vehicles in the different test configurations the maximum acceleration measured at the b-pillar driver side, the OLC and the maximal plastic deformation measured in x-direction at the upper a-pillar were evaluated.

Figure 6 shows the acceleration together with the OLC for the different crash tests. There is a strong linear correlation between OLC and maximum cabin b-pillar acceleration ($R^2=0.93$). It is important to note that the OLC was developed and is mainly valid for full frontal tests. However, for the MPDB tests, the maximum acceleration has a relatively higher increase compared to the OLC. The OLC values for the fixed barrier tests (FWRB and ODB) were in a range between 22.3 g and 32.4 g. The values were for lighter vehicles in the mobile barrier tests (MPDB) much higher 34.8 g and 46.6 g.

Eickhoff [21] has evaluated the OLC values for different vehicles using the NHTSA database. There, the majority of values were between 25 g and 38 g, which indicates that the OLC values for the lighter vehicles in the MDPB test are relatively high compared to conventional design levels.

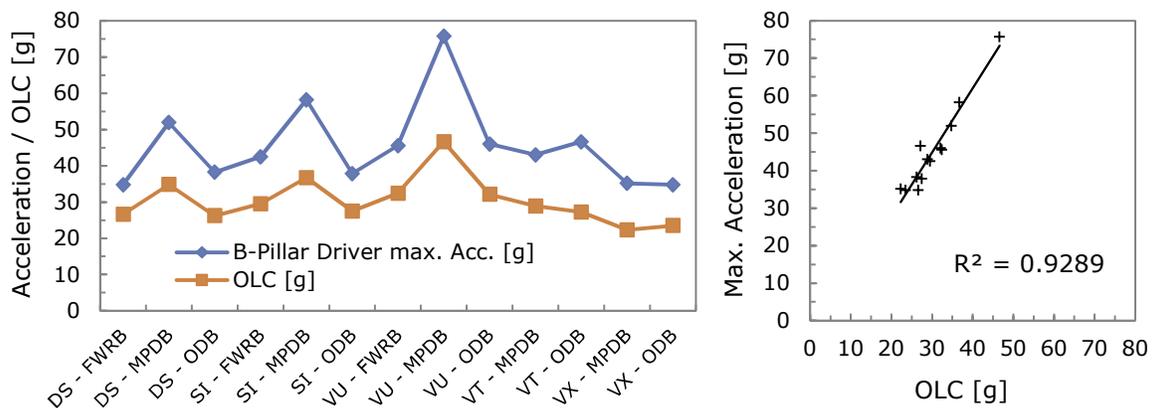


Figure 6 Vehicle accelerations and occupant loading criterion (OLC)

The maximum accelerations measured at the b-pillar driver side are shown in Figure 7. It is apparent that the maximum acceleration levels for vehicles lighter than 1,500 kg were much higher in the test against a mobile barrier (MPDB) compared to the test configurations with a fixed object (ODB, FWRB). Acceleration values for the vehicles in the ODB and FWRB test were in general between 30 and 40 g, while the acceleration values for the lighter vehicles in the MPDB test were over 50 g and in one case reaches up to 76 g. However, the acceleration values for the heavier vehicles were similar when comparing MPDB test and ODB tests for the same car. Previous research showed that the acceleration level for fixed PDB tests are considerable higher compared to ODB even for heavy vehicles [5]. The combination of PDB barrier face and mobile barrier with a fixed weight could explain why the acceleration of the heavy cars is similar between ODB and MPDB. This is most likely due to the different barrier stiffnesses (ODB vs PDB) and the fact that the vehicles are not optimized for the MPDB test procedure. The vehicle VX had a test mass of 2,400 kg and had almost no differences in the MPDB accelerations compared with the ODB test. The vehicles front structure is differently loaded by the PDB element comparing to the FWRB or the ODB tests. This counts in particular for vehicles with an inhomogeneous vehicles front (Figure 7, right).

Note: In previous projects it was criticized that the mobile barrier would not generate enough loading for the heavier vehicle which could potentially lead to insufficient compartment strength in single vehicle accidents [5].

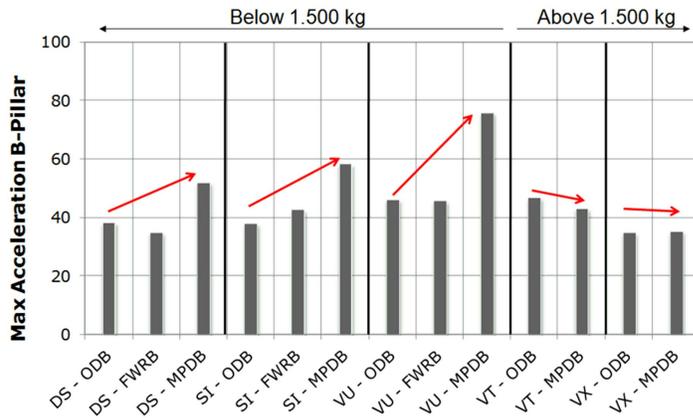


Figure 7 Maximum vehicle accelerations for the vehicles measured at b-pillar driver side; right: example of the vehicle structure which is not optimized for the PDB barrier

In Figure 8 the a-pillar displacement on the driver side measured at waist line is shown. Almost no deformation was measured for the vehicles in the FWRB tests. This was expected as the objective of this test is to generate a high acceleration pulse to assess the restraint systems. The vehicle's front structure is symmetrically loaded in the FWRB and the crash structures can deform in a perfect manner. Even for the other configurations the deformation was relatively small. The vehicle DS had the largest deformations between 40 mm (ODB) and 50 mm (MPDB). Generally there is no clear trend which test set-up (MPDB vs. ODB) results in higher compartment intrusions – for some tests larger intrusions were measured for the MPDB and for others in the ODB test. Previous research [5] furthermore indicated that the deformation patterns are different between ODB and PDB (i.e. the PDB appears to load the upper region of the car more than the ODB test). Therefore the intrusion depth might be influenced by the combination of deformation pattern and barrier stiffness.

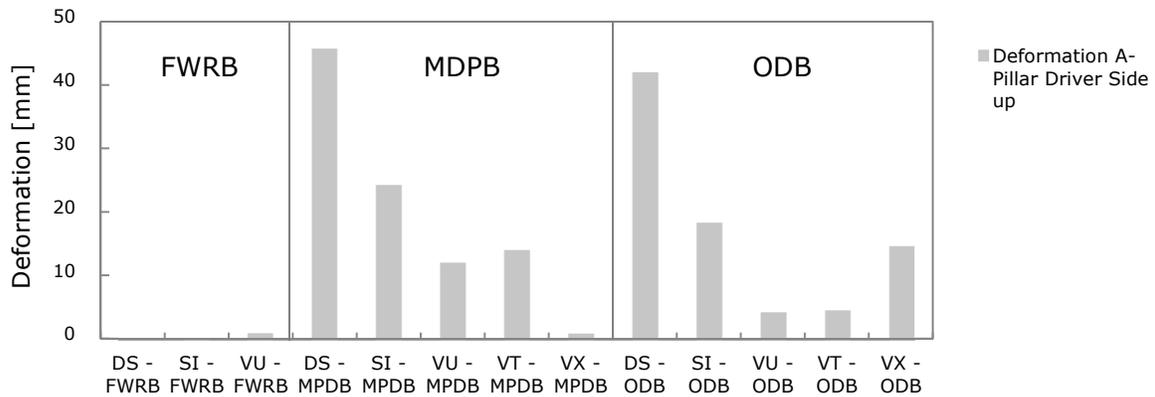


Figure 8 Deformation of the vehicles measured in millimeter at the a-pillar of the driver side in the height of the waist line.

The maximum vehicle acceleration was compared to the thorax acceleration [3ms], pelvis peak acceleration and the belt force measured at the outer lap belt (B6). As expected the acceleration measured at the dummy is similar to the vehicle acceleration and therefore a possible indicator for evaluating the loading on the dummy in the crash test. Nevertheless, the force measured on the belt had even a higher correlation ($R^2=0.84$) in regard to the vehicle acceleration.

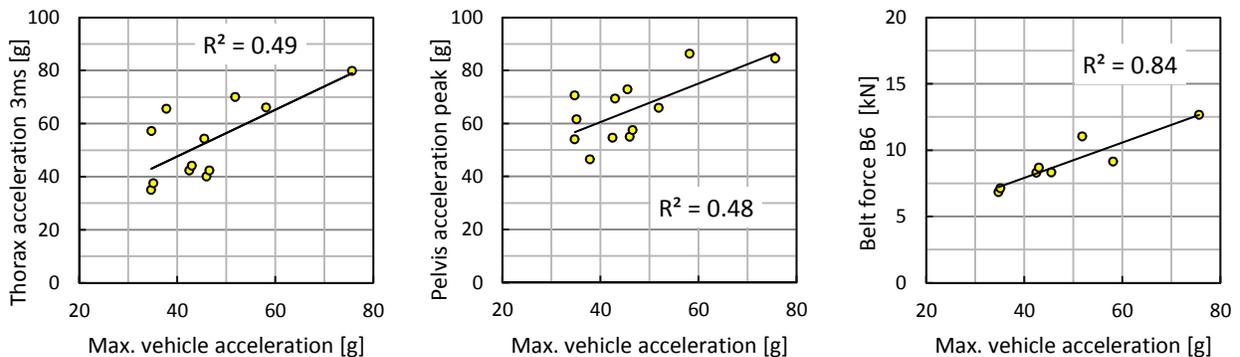


Figure 9 Vehicle acceleration measured at a-pillar versus thorax acceleration, pelvis acceleration and lap belt force (B6).

The injury criteria measured at the dummy are shown in Figure 10. In general the head acceleration was higher in the MPDB test procedure compared to the fixed barrier tests for all vehicles. It should be noted that the values in particular for the two lighter vehicles (VU and DS) were much higher, up to $a_{3ms} = 136$ g. Nevertheless, head bottoming out and chest contact with the steering wheel was not observed. Also the thorax deflection was higher in the MPDB than in the FWRB test (approximately 10 to 20 %), while the thorax deflection in the ODB test was the lowest. The thorax and pelvis acceleration were much higher in the mobile barrier test and, in general, very close to or above the IARV.

For the heavier vehicles (VT and VX) the dummy values were equal or slightly higher in the MPDB test procedure. For the lighter vehicles the relevant IARVs in regard to UN-R 94 (HIC_{36} , a_{3ms} , thorax deflection) were slightly higher in the FWRB test, but still well below the limits. However, the pelvis and thorax acceleration were much closer or above the limits. The stronger loading on the lighter vehicles in the mobile barrier tests can be clearly seen in all IARVs. It has to be noted, that the restraint systems are optimized for Euro NCAP and are not adopting to the new crash pulse.

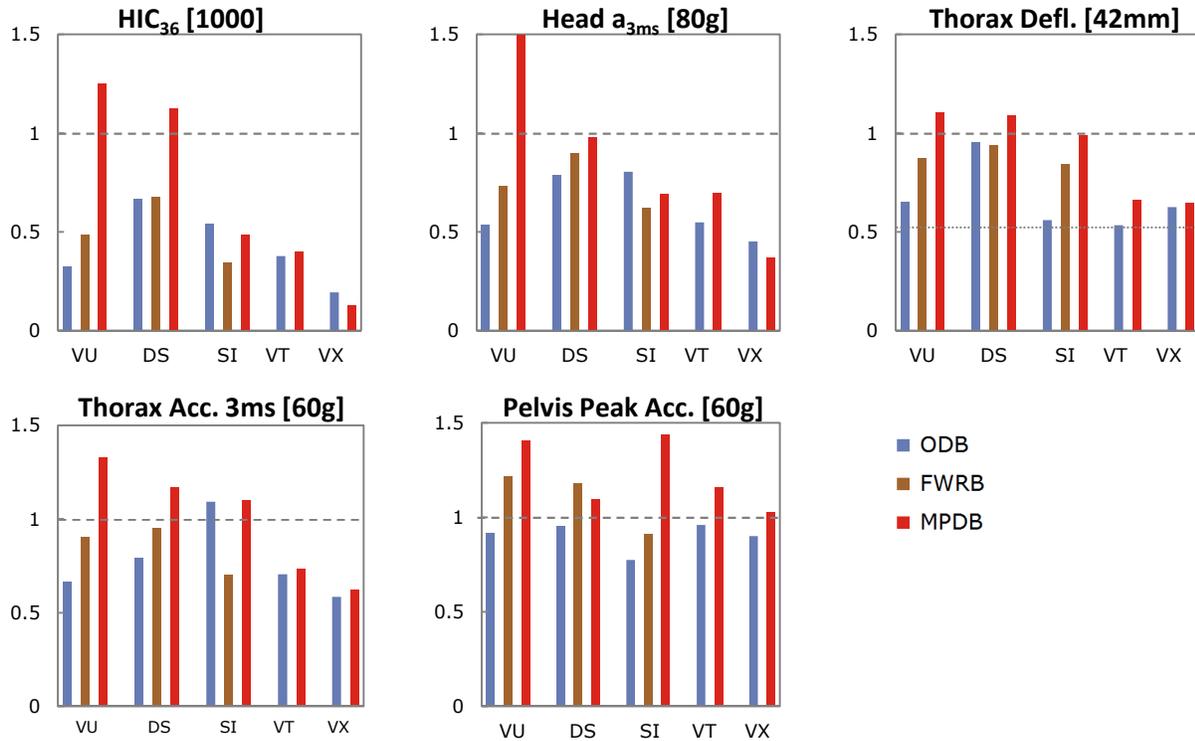


Figure 10 Ratio of relevant injury assessment reference values for the vehicles in the test configurations ODB; FWRB and MPDB.

The different loading in terms of vehicle structure, vehicle acceleration and injury assessment values for vehicles with a mass lighter and heavier than the mobile barrier should be investigated with the help of crash test data. It is assumed that lighter vehicles experience a higher loading with a frontal mobile offset barrier compared to a fixed barrier test (FW / ODB) and that heavier vehicles show a lower loading.

The vehicle crash test data with regard to vehicle deformation, vehicle acceleration and injury assessment values were analyzed. It has been shown that the assumption that lighter vehicles are subjected to a higher loading in a frontal mobile offset barrier test, compared to a fixed barrier test (FW / ODB), can be supported not only with regard to vehicle structural performance but also in regard to injury assessment values. On the other hand it has been that the vehicle acceleration and the injury assessment values were not substantially lower for the heavier vehicles. The delta-v is much lower for the heavier vehicles in MPDB tests but the PDB barrier is much stiffer and most of the vehicles are not designed for this test.

LIMITATIONS

It has to be noted that the number of tested vehicles was limited. Furthermore, only one test per configuration was carried out.

It is important to note that not all vehicles were tested in the same test laboratory which could result in minor differences. However, the test configurations for the ODB test (Euro NCAP protocol) and the MDPB were among themselves the same.

With regard to the analyses of accident data, the data sample was carefully selected to address the appropriate accident configurations. However, this leads to a limited number of accident cases.

CONCLUSIONS

The accident data show that the injury severity of car occupants is higher for lighter vehicles in car-to-car, car-to-HGV and car-to-object accidents. The influence of intrusion seems not to be the major factor for injuries in particular for car to car accidents. Accidents with large overlap are dominant. For impacts with a small overlap it is important to separate between impacts including one vehicle edge and centered impacts.

With the mobile deformable barrier test the loading conditions were seen more realistic in terms of real world car-to-car accidents. This was in particular true for the lighter vehicles. However, the loading on the light and stiff vehicles produces a very high acceleration pulse in the mobile barrier test procedure. The acceleration pulse was also influenced by the different deformation of the vehicle front structure when crashing against the PDB barrier. With regard to the IARVs, the vehicles had much higher head accelerations and thorax deflections in the mobile barrier test procedure. The data suggests that thorax and pelvis accelerations could be important and relevant indicators if the loading due to the vehicle pulse needs to be evaluated.

It was seen that the crash test with the mobile crash barrier induced a rotation to the vehicle which occurred relatively late in the impact. This motion induces high accelerations at the dummy head in the rebound phase, when the head hits the b-pillar. A dummy movement during the forward motion apart from the driver airbag due to the rotational effects of the MPDB test procedure has not been identified, though.

The benefit of the mobile deformable barrier test is the higher loading for smaller vehicles in particular in regard to the crash pulse. In addition, the PDB offers potential for the compatibility assessment of the vehicles structure. The trend of increased vehicle stiffness (especially illustrated by tests with the MPDB and small cars) shows the need of a further improvement of passive restraint systems to reduce the occupant loading and with it the injury risk.

As the measurement of the thorax loading with the chest deflection of the HIII dummy is not ideal, the evaluation of the loading in the mobile barrier test procedure with a more appropriate dummy is recommended.

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