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FIMCAR
X – MDB Test Procedure: Test and Simulation Results

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

One of the test modes investigated during the FIMCAR project to improve frontal impact and compatibility is a so-called Moving Deformable Barrier test (MDB test). This is a frontal test with a moving test vehicle and moving trolley equipped with a deformable element. In various initiatives in Europe and the US this type of test is seen as a next step in the future evaluation of vehicle safety with a good possibility for harmonisation. Based on the experience of various projects prior to the FIMCAR project, a test protocol has been drafted in the FIMCAR project. Two main parameters: test speed and trolley mass, key factor to define the severity of the MDB tests, were defined during the FIMCAR program.

Using the draft protocol a number of MDB tests were carried out, the main objectives of the test were:

- Analysis of the feasibility of the test set up and protocol
- Definition of the test severity; trolley mas and impact speed
- Assessment of repeatability and reproducibility
- Development of compatibility metric / horizontal load spreading

The results of 15 MPDB test were used for the FIMCAR investigations. In general terms, the tests according to the draft protocol were feasible in various laboratories using different test trollies. Special attention is needed for the wheel alignment of trolley and test vehicles to avoid incorrect offsets.

For the explored vehicle mass range, kerb weight from 1000kg to 2200 kg, a fixed trolley mass of 1500 kg and a test speed of 50 km/h (for vehicle and trolley) results in an acceptable test severity. For vehicles outside this range, for example light electrical vehicles and heavy SUV’s, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out to date. These series of tests both showed good results, giving an indication for good R&R, however, more tests are needed to make this statement statistically relevant.

Various investigations have been made for compatibility metrics to assess the load spreading of the tested vehicles. It was not possible to define metrics based on load cell wall recordings or trolley accelerations. The metric for horizontal load spreading based on the deformation of the PDB barrier is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm (Row 3 and Row 4 of the Full width Load Cell Wall) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicles with an even (homogeneous) deformation pattern or a barrier with localised holes.

The FIMCAR project proves that the MPDB test is a good candidate for future frontal compatibility test and assessment activities. More tests and studies are needed to define the test severity for light and heavy vehicles and to confirm the R&R results.

International discussions are needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in the shorter term, as it has advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

1 INTRODUCTION

1.1 FIMCAR Project

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

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

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

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

1.2 Objective of this Deliverable

Within the previous deliverable (FIMCAR Deliverable D4.1) [Uittenbogaard 2013 / Section IX] a test procedure was drafted for MDB tests. Based on this test protocol, a series of 12 tests using the PDB as the deformable barrier were conducted by different project partners. The results of these tests, extended with results of 3 tests carried out outside the FIMCAR project and a supportive simulation study, are presented and analysed within this report. This report combines the two originally planned deliverables D4.2 and D4.3 as it appears to be better to combine the experience with the original test protocol and the final test protocol. Furthermore it turned out that the MPDB test protocol according to FIMCAR Deliverable D4.1 does not need any change for the time being.

1.3 Structure of this Deliverable

In Chapter 2 the general boundary conditions of the test series are explained. The different test houses, test vehicles as well as the test matrix are presented. In Chapter 3 the general results are presented not only for the baseline tests, but also for a number of variations in the test specifications. These results include vehicle as well as trolley accelerations, vehicle deformations and dummy readings. The results of the subsequent assessment methods are provided in Chapter 0. A limited investigation on repeatability and reproducibility is presented in Chapter 6. The report ends with a discussion of feasibility and test severity (7.1), compatibility metrics (7.2) and repeatability and reproducibility (7.3) in Chapter 7. Additionally, 1 appendix is added with details of the SUV 3 simulation results.

2 TEST AND SIMULATION PROGRAM

2.1 Test Protocol

As a first step the "Moving Deformable Barrier Test protocol", a draft test protocol for this type of test was set up. This draft test protocol was submitted as FIMCAR deliverable D4.1 [Uittenbogaard 2013 / Section IX]. This test protocol is based on:

- MDB tests as developed and carried out by TNO in an internal R&D project [Versmissen 2006].
- Review of draft test protocols from different continents, evaluated with a European perspective for potential harmonisation.

As the development of a new deformable barrier was out of the scope of the FIMCAR project, the PDB barrier as used in WP2 "Offset test" was selected for the MDB test protocol. Therefore, the MDB tests conducted within this test program are further also addressed as MPDB tests. Two main test specifications could not be fixed in the original FIMCAR MDB test protocol. Too little test information, especially with various test velocities, was available prior to the FIMCAR project to define the optimal test severity. To define the severity during the FIMCAR project, the following parameters were used in the test program:

• Test speed	• 50 km/h - also tests with 45 and 56 km/h are carried out
• Trolley mass	• 1500 kg - also simulations with 1300 kg and 2200 kg respectively are carried out.

For all tests the applicable test speed and trolley mass are mentioned in the test description. All tests conducted within the FIMCAR project are carried out using the FIMCAR test protocol, with one exception. At some point in time during the FIMCAR project it was decided to install the Hybrid III 5th percentile female dummy instead of the Hybrid III 50th percentile male dummy on the front passenger seat. This decision for all FIMCAR test types was taken, to also investigate the protection level of a, so far, neglected group of occupants that still suffer a significant amount of injuries in real life crashes. As a number of MPDB tests were already carried out prior to this decision, both dummies - 50th male and 5th female - are found on the passenger seat in the MPDB test program presented within this report.

2.2 Test Laboratories

During the FIMCAR project MPDB tests were carried out in several different laboratories (see Table 1). For the MDB test, a special test trolley is required. Table 1, also specifies, besides the number of conducted tests, which trolley was used at the respective laboratory.

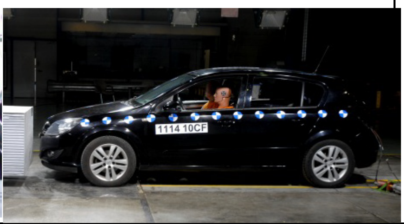
Table 1: FIMCAR MDB Test laboratories.

Laboratory	Number of tests	MDB Trolley
BAST	1	TNO/TTAI trolley
	1	New build trolley, according to TNO specifications
FIAT	1	TNO/TTAI trolley
IDIADA	2	Modified ECE R95 trolley
Renault	1	TNO/TTAI trolley
UTAC	1	Modified ECE R95 trolley
TNO/TTAI	4	TNO/TTAI trolley: Special MDB trolley as developed and build in an internal TNO project

2.3 Test Vehicles

During the FIMCAR program MDB tests with the following vehicles were carried out:

Table 2: FIMCAR MPDB test vehicles.

Supermini		
		
Supermini 2	Supermini 3	Citycar 1
Supermini	**Small family car**	
		
Supermini 1	Small Family Car 2	
SUV / Off road		
		
SUV 4	SUV 2	SUV 1

The vehicles were selected by the consortium, using the following criteria:

- Coverage of the required mass range (kerb weight 1000 kg to 2200 kg)
- Availability of additional (crash) test and/or simulation results e.g. from Euro NCAP
- Access through FIMCAR partners
- Different compatibility design and expected results
- Focus on light and heavy vehicles as they are critical for the definition of a proper test severity

2.4 Test Matrix

The main specifications of the FIMCAR tests are presented in Table 3.

Table 3: FIMCAR test matrix.

Vehicle	Laboratory	Velocity [km/h]	Trolley mass [kg]	Remark
Supermini 2	Fiat	50	1500	Baseline test
Citycar 1	TTAI	45	1500	Effect velocity
Citycar 1	TTAI	50	1500	Baseline test
Supermini 3	TTAI	45	1500	Effect velocity
Supermini 3	TTAI	50	1500	Baseline test
Supermini 1	BAST	50	1500	Baseline test
Small Family Car 2	BAST	56	1500	Effect velocity
Small Family Car 2	IDIADA	50	1500	Baseline test Reproducibility (TTAI)
Small Family Car 2	TTAI	50	1500	Baseline test Reproducibility (IDIADA)
SUV 1	IDIADA	50	1500	Baseline test
SUV 2	UTAC	50	1500	Baseline test
SUV 4	TTAI	50	1500	Baseline test

Additional to the FIMCAR tests, the results of a number of moving progressive deformable barrier (MPDB) tests carried out by TNO, are used in this deliverable, namely:

- Two tests with Small Family Car 2, part of an internal TNO development program
- One test with a Supermini 2, sponsored by the Dutch RDW, for GRSP activities.

The main specifications of these tests are presented in Table 4.

Table 4: Additional MPDB tests.

Vehicle	Laboratory	Velocity [km/h]	Trolley mass [kg]	Remark
Supermini 2	TNO	56	1500	GRSP information
Small Family Car 2	TNO	45	1500	MPDB development Repeatability
Small Family Car 2	TNO	45	1500	MPDB development Repeatability

2.5 Simulation Matrix

To study the effect of trolley mass and test velocity, VCC has carried out a simulation study using a numerical model of SUV 4 and the PDB computer model as developed by Opel as part of the FIMCAR project. The simulation matrix with the main parameter variations is presented in Figure 2.1.

	Simulation	Barrier	Car velocity [kph]	Barrier velocity [kph]	Relative velocity [kph]	Barrier mass [kg]	Car mass [kg]	Initial kinetic energy [kJ]
Baseline	SUV 4	MPDB	50	50	100	1500	2400	376
	SUV 4	MPDB	50	50	100	1300		357
	SUV 4	MPDB	50	50	100	2200		444
	SUV 4	MPDB	56	56	112	1500		472
Euro-NCAP	SUV 4	ODB	64		64			379
R94	SUV 4	ODB	56		56			290
Fixed PDB	SUV 4	PDB	60		60			333

Figure 2.1: Simulation matrix / SUV 4 simulations.

3 TEST RESULTS

3.1 General Information

Only the main results needed for the definition of the test severity and development of the test protocol are presented in this deliverable.

An overview of the main test characteristics is presented in Table 5.

Table 5: Main test characteristics.

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

Remarks:

- All tests are carried out within the tolerances as specified in the test protocol [Uittenbogaard 2013 / Section IX], with three exceptions :
    - Small Family Car 2 high speed test by BAST : offset 56 instead of 50%
    - Citycar 1 low speed test by TTAI : offset 55 instead of 50%
    - SUV 1 baseline test by IDIADA: offset 51 instead of 50%
- The increased offset of these tests is taken into account during the test analysis.

3.2 Vehicle and Trolley Acceleration Results

3.2.1 Baseline Tests

For all vehicles, a baseline test has been carried out with the baseline specifications of a trolley mass of 1500 kg and a speed of 50 km/h. The resulting B-Pillar accelerations on the struck side are presented in Figure 3.1.

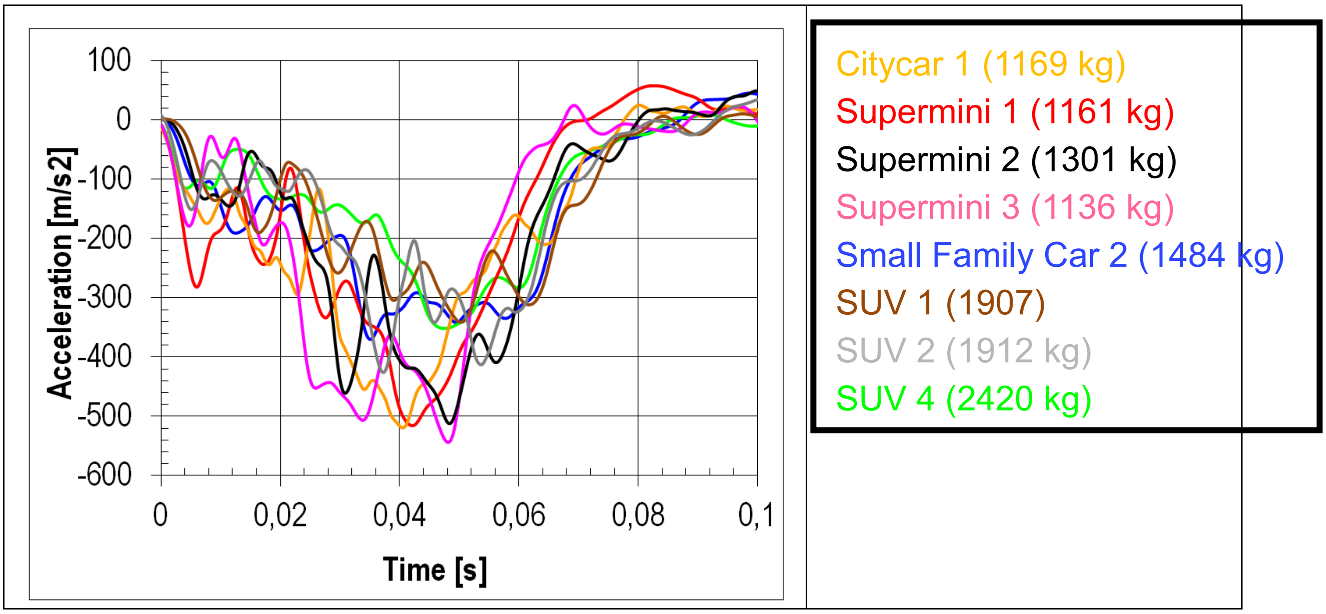


Figure 3.1: B-pillar acceleration / baseline tests.

The acceleration range is in some cases slightly higher or else in line with the results of current Euro NCAP tests such as those plotted by Hynd et al. [Hynd 2010]. Their study shows average Euro NCAP peak accelerations of 30 g. It is clear that the acceleration is mass dependent as light vehicles are pushed back by the trolley and heavy vehicles pushed the trolley backward resulting in higher and lower accelerations, respectively. This is in line with car-to-car impacts between vehicles with different masses. The duration of the pulses is significant shorter than the results of UN-ECE Regulation 94 or Euro NCAP tests, as trolley and vehicle are both moving.

3.2.2 Small Family Car 2 Tests

To study the effect of the impact velocity, additional tests were carried out with Small Family Car 2 - a car with an average mass for the European fleet. For these tests, the trolley mass was kept at 1500 kg and the impact velocity was varied as follows:

- low speed: 45 km/h,
- baseline speed: 50 km/h / two reproducibility tests
- high speed: 56 km/h

The resulting accelerations of the vehicle B-pillar as well as of the trolley are presented in Figure 3.2.

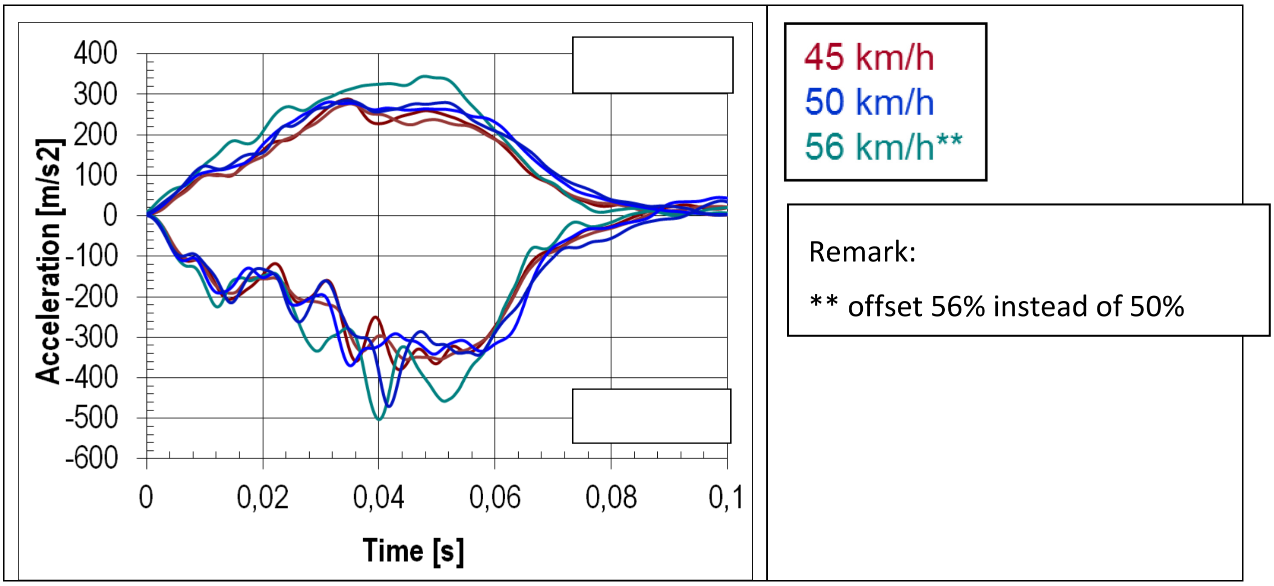


Figure 3.2: B-pillar and trolley acceleration / Small Family Car 2 tests.

Both 50 km/h tests show a good reproducibility. The trolley and vehicle accelerations of the 56 km/h test are significantly higher than the results of the other test. This is mainly caused by the higher offset of 56% instead of 50%.

3.2.3 Citycar 1 Tests

The Citycar 1, a light vehicle, has been tested with a trolley mass of 1500 kg and two impact velocities: 45 km/h and 50 km/h. The accelerations of the vehicle B-pillar and of the trolley are presented in Figure 3.3.

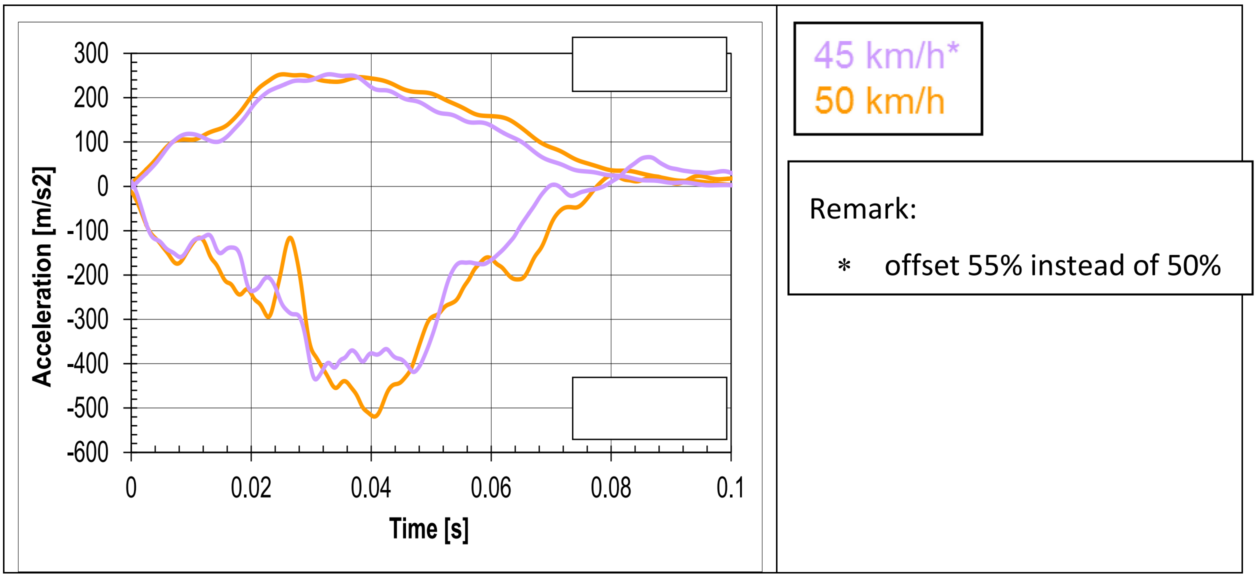


Figure 3.3: B-pillar and trolley acceleration / Citycar 1 tests.

The acceleration of trolley and vehicle are significant higher in the 50 km/h test though the offset in the low speed test is higher, 55% instead of 50%.

3.2.4 Supermini 3 Tests

The Supermini 3, also a light vehicle, has been tested with a trolley mass of 1500 kg and two impact velocities: low 45 km/h and baseline 50 km/h. The accelerations of the vehicle B-pillar and trolley are presented in Figure 3.4

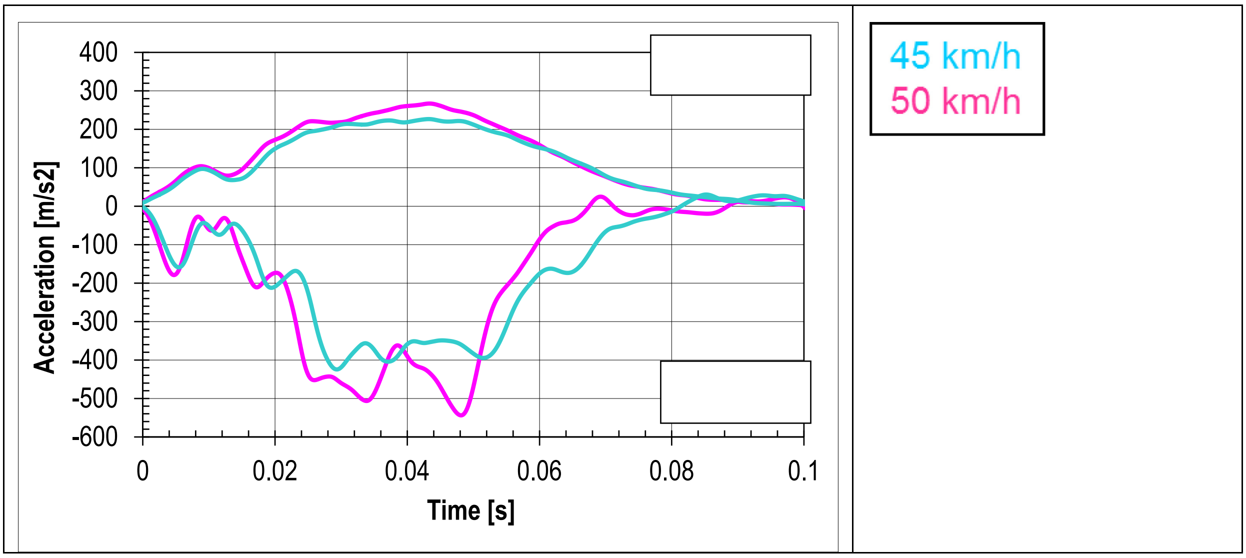


Figure 3.4: B-pillar and trolley acceleration / Supermini 3 tests.

The difference between the accelerations is larger compared to the Citycar 1 tests, as both test are carried out with the correct offset.

3.2.5 Supermini 2 Tests

The Supermini 2, another light vehicle, was tested with a trolley mass of 1500 kg and two impact velocities: 50 km/h and 56 km/h. The accelerations of the vehicle B-pillar and of the trolley are presented in Figure 3.5.

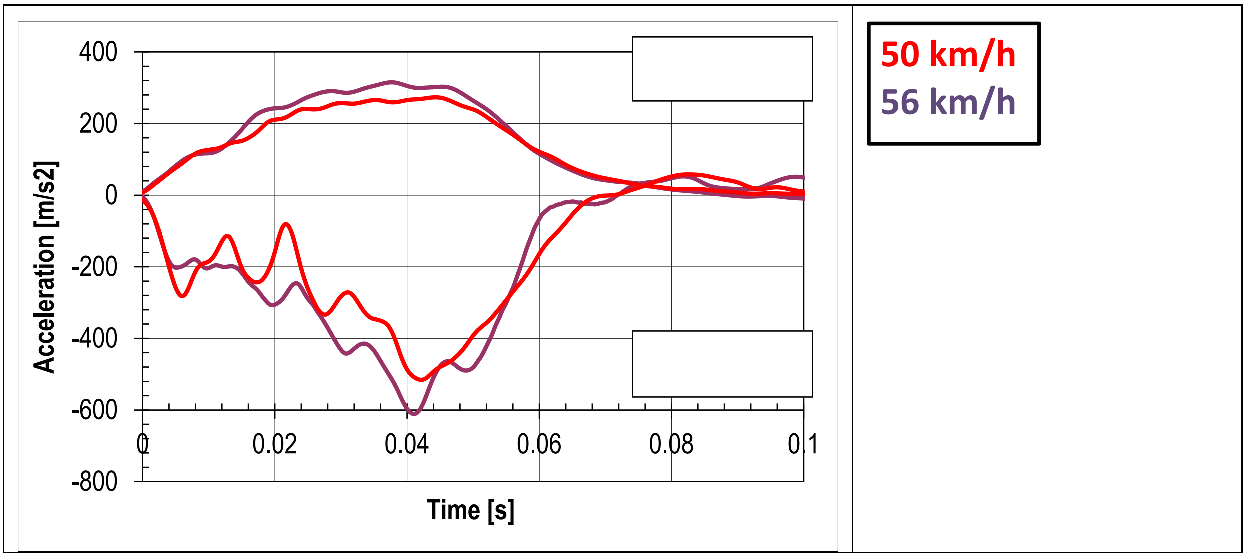


Figure 3.5: B-pillar and trolley acceleration / Supermini 2 tests.

The difference between the accelerations is greater than in the Citycar 1 tests, as both tests are carried out with the correct offset and comparable to the Supermini 3 tests.

3.2.6 Mean B-pillar Acceleration and Delta-v.

To compare all the results of all vehicles, the maximum mean B-pillar acceleration of the MPDB tests are presented in Figure 3.6 and Figure 3.7. The maximum mean acceleration has been defined as:

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

For the Supermini 3, Citycar 1, Supermini 2, Small Family Car 2 and SUV 4 also the results of other test modes, if available, are presented. For the tests carried out in the final phase of the FIMCAR project, SUV 1, Supermini 1 and SUV 2 no reference results are available. It is clear that, in general, lower B-pillar accelerations are measured in heavier vehicles. However for all vehicles with a reference test, the MPDB B-pillar acceleration is higher than in Euro NCAP tests. For the Small Family Car 2 and SUV 4, the MPDB is more severe than the fixed offset test.

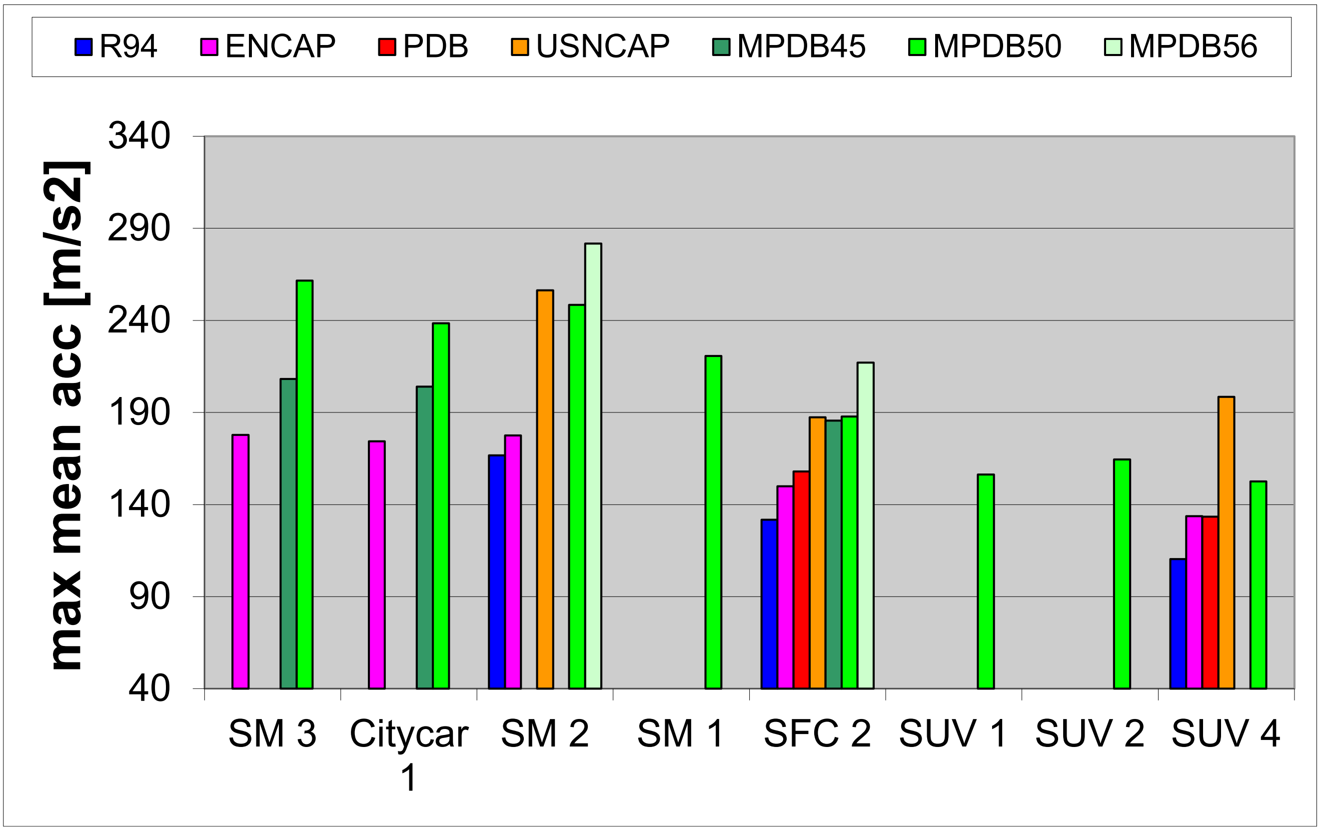


Figure 3.6: Maximum mean B-pillar accelerations.

The velocity changes of the MPDB tests and available reference tests are presented in Figure 3.7. Again for some vehicles the results of reference tests are presented. Due to the test mode, both trolley and vehicle moving, the delta-v of the MPDB is depending on the mass of the tested vehicle. For static tests the delta-v is always higher than the test speed due to the vehicle rebound.

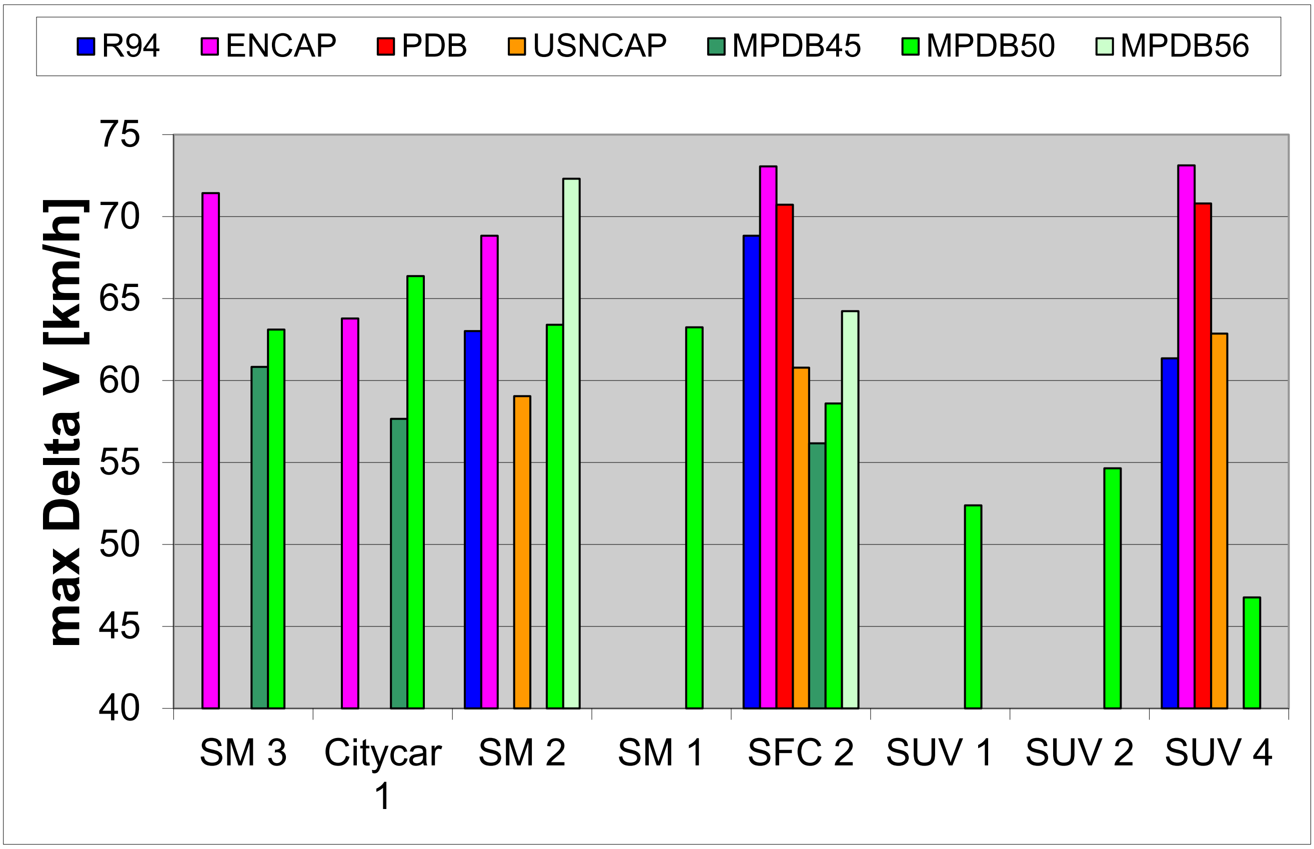
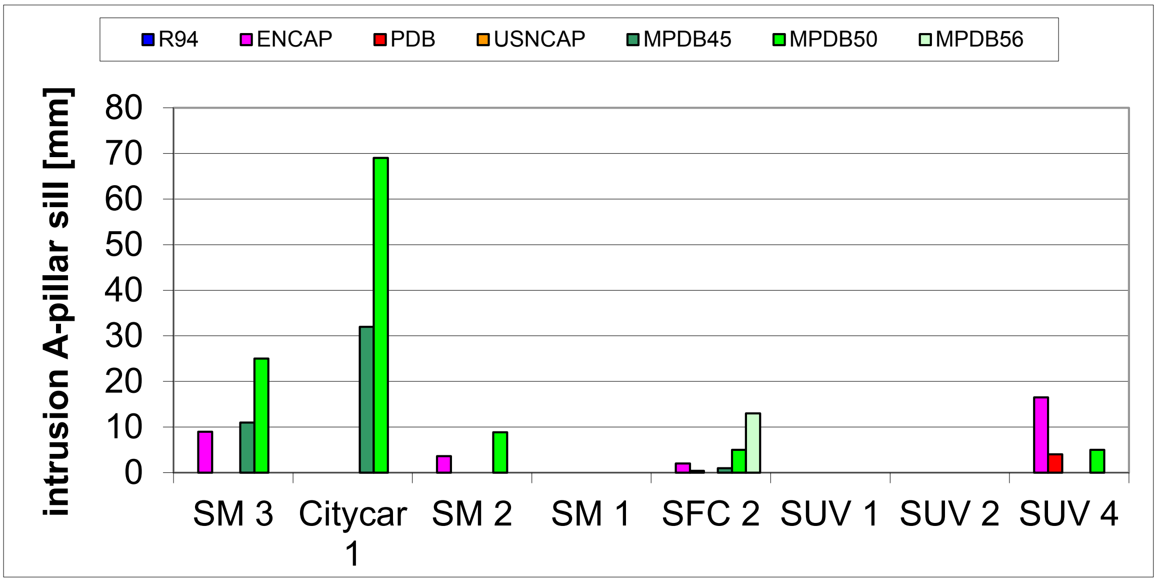


Figure 3.7: *MPDB tests / delta-v results*.

3.3 Vehicle Deformations

After all the MPDB tests, a number of static measurements have been carried out to record vehicle deformations. To compare the MPDB static measurements, the static measurements as specified in the Euro NCAP frontal test protocol measurements were also used. The most relevant measurement to specify for the compartment strength is the displacement of the A-pillar. These results are presented together with the results of available reference tests in Figure 3.8.

It can be seen that for the small, as well as the average sized vehicles, the A-Pillar deformations are significantly higher in the baseline MPDB test compared to the reference test. This test mode is more severe for the compartment strength than UN-ECE Regulation 94 and Euro NCAP. However even with this more severe test mode all values except the ones from the MPDB50 test with the Citycar 1 are below the proposed maximum A-pillar displacement of 50 mm.



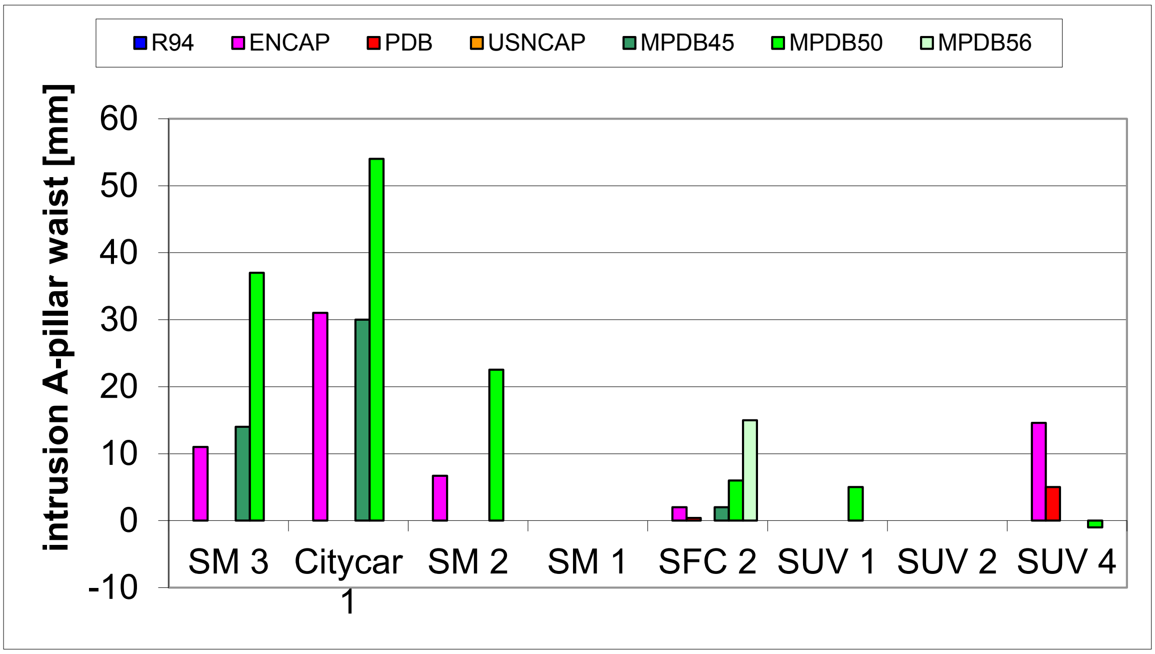


Figure 3.8: Deformation results of the A-pillar at sill and waist level.

3.4 Dummy Results

3.4.1 General

Anthropometric test devices (ATDs), namely Hybrid III impact dummies, were installed in all test vehicles for the tests to give an indication on occupant injury risk during impact. However the sustainable injury risk is not only influenced by the chosen test mode, but also by the configuration of the occupant restraint system, which will be “filtering” a part of the test mode effects. It also needs to be taken into account that the restraint systems are not yet designed/optimised for the MPDB test mode, hence better dummy results are expected in the future when this test may be a part of the vehicle development process. One important issue influencing the effectiveness of the restraint system is its trigger time. As an indication, the airbag trigger time (which is also available for most of the reference tests) was recorded during the MPDB tests - the results are presented in Figure 3.9. In general, during the MPDB tests, the airbags are triggered earlier than in PDB or Euro NCAP tests.

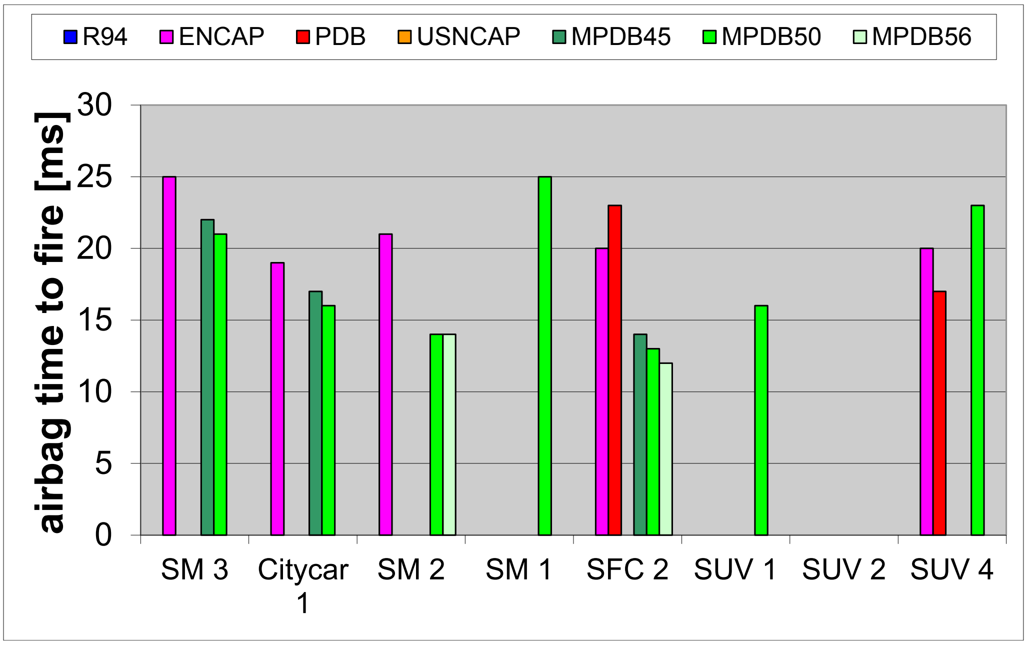


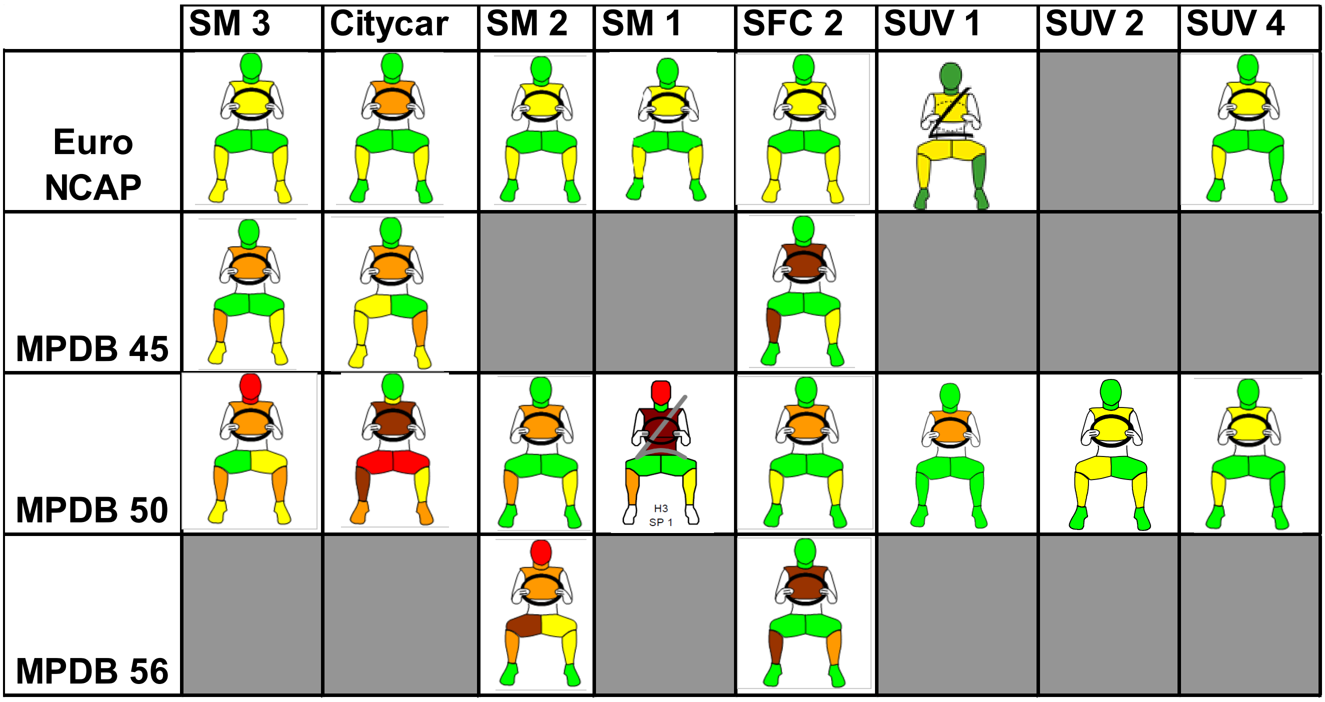
Figure 3.9: MPDB tests / airbag time to fire.

3.4.2 Dummy Results in Euro NCAP Lay Out

Due to the filtering effect of the restraint systems and the variations in airbag firing time, the dummy results are only an indication for the test severity. The total results for the driver presented in Figure 3.10 are prepared in the well-known Euro NCAP colour lay-out including obtained points as calculated based on the Euro NCAP ODB assessment procedure without modifiers. Only the driver's results are presented as in this position in all tests a Hybrid III 50th dummy was installed, so a comparison of the results was possible. The dummy results of light vehicles are worse than the corresponding Euro NCAP scores, the heavier vehicles scores are comparable with Euro NCAP scores.

Remark:

For the SUV 1 the total number of points is comparable although the loads to the different body regions are different. The most probable cause is that leg risks are mainly a result of intrusion and chest risks are mainly a result of car acceleration it appears that there is an higher acceleration in the MPDB but less intrusion.



	SM 3	Citycar	SM 2	SM 1	SFC 2	SUV 1	SUV 2	SUV 4
Euro NCAP	15.1	13.3	15.1	14.38	14.9	13.1		14.8
MPDB 45	11.9	11.4*			9.3			
MPDB 50	6.1	4.6	9.5	0 (capped)	12.7	13.9	13.8	14.9
MPDB 56			4		9.2**			

Figure 3.10: Injury risk indication based on Euro NCAP ODB assessment procedures.

3.4.3 HIC Results

For a number of the tests, a Hybrid III 5th percentile female dummy was installed on the co-driver seat, for these dummies no Euro NCAP scores are available. Therefore HIC values are presented in absolute values for all dummies installed in the MPDB tests, see Figure 3.11 and Figure 3.12.

For most MPDB50 and MPDB45 tests, HIC values are below the R94 requirements of 1000. The HIC values for the drivers in the Supermini 1 and the Supermini 3 MPDB50 tests are above this limit.

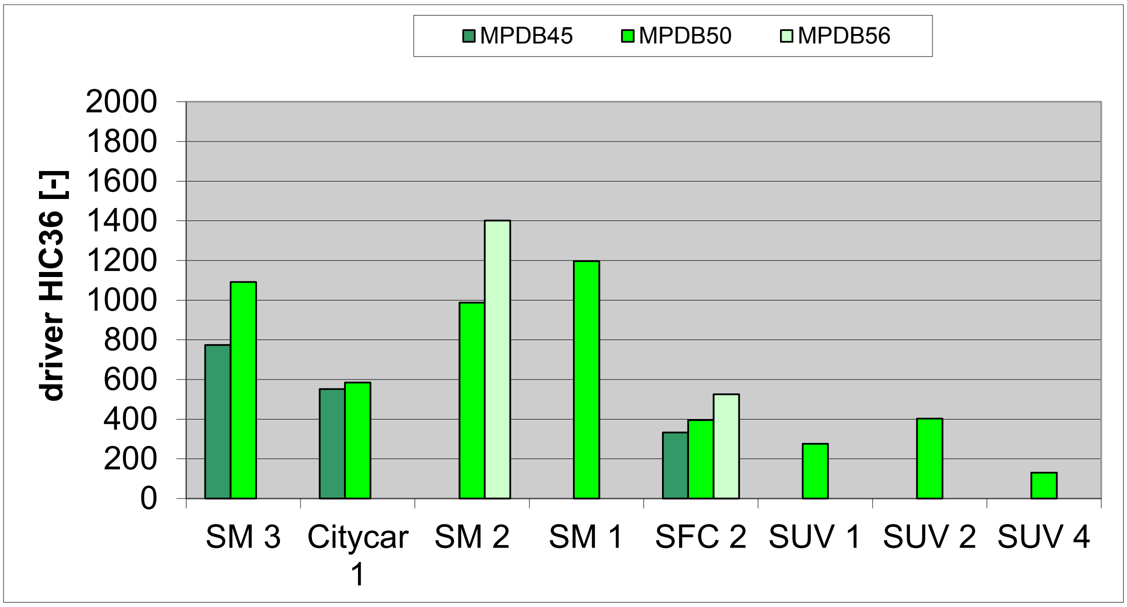


Figure 3.11: HIC results / driver.

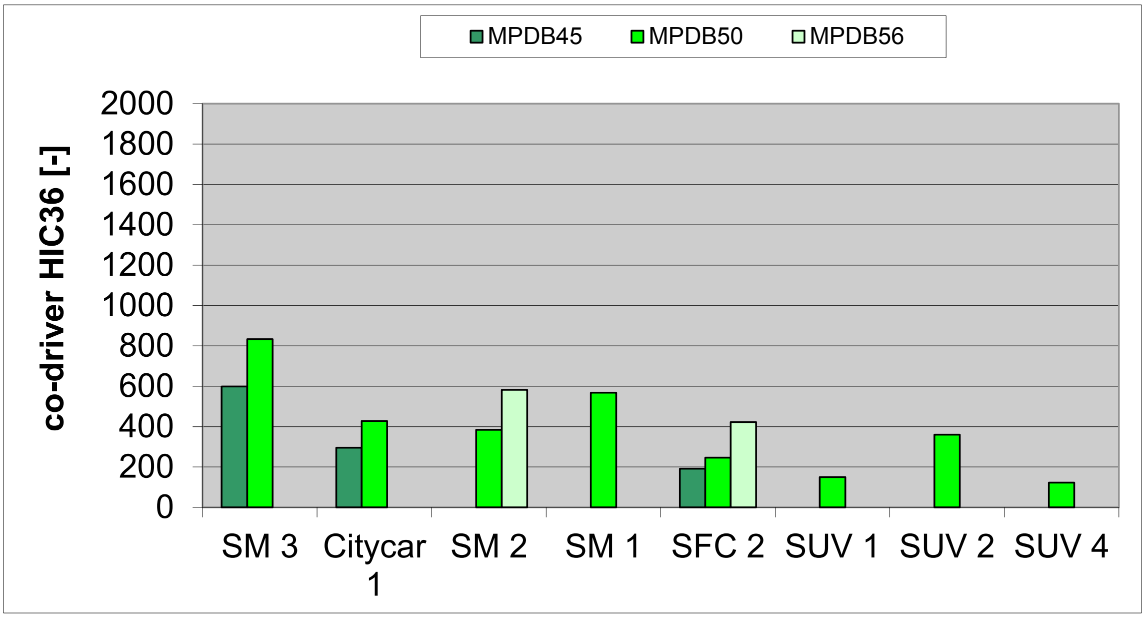


Figure 3.12: HIC results / co driver.

3.5 PDB Deformations

The PDB deformation, which forms the basis for a potential compatibility metric, is one of the main results of the tests. Pictures of the deformed barriers and a view of the scanned results are presented in Table 6 and Table 7, respectively.

Table 6: Barrier deformation results.

	45 km/h	50 km/h	56/km/h
Supermini 2			Not available
Citycar 1			
Supermini 3			
Supermini 1			
Small Family Car 2			
SUV 1			

Table 6: Barrier deformation results. *(continued)*

	45 km/h	50 km/h	56/km/h
SUV 2			
	45 km/h	50 km/h	56/km/h
SUV 4			

Table 7: PDB barrier scan results.

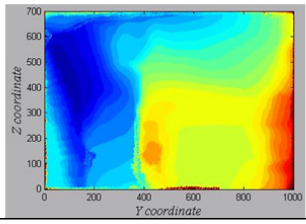
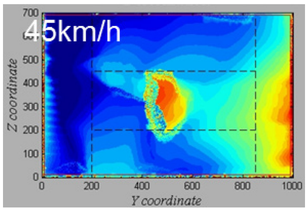
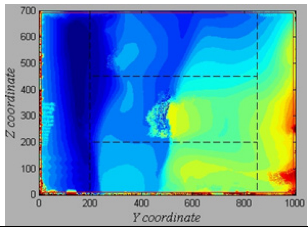
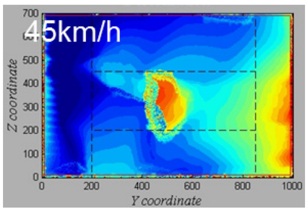
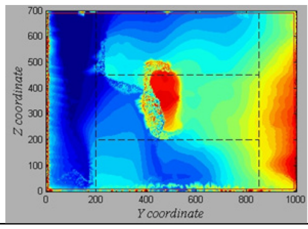
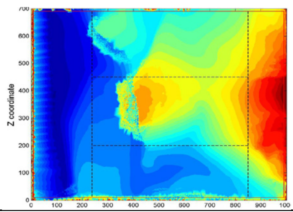
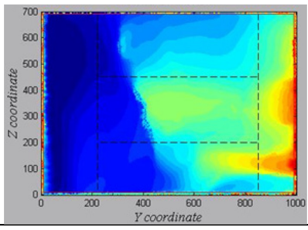
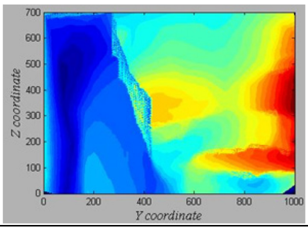
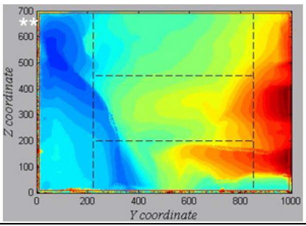
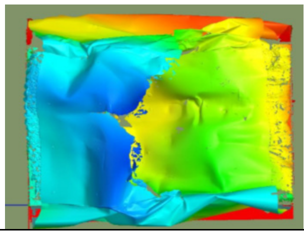
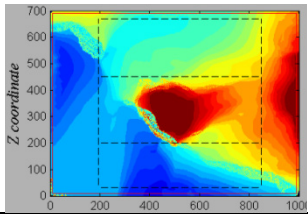
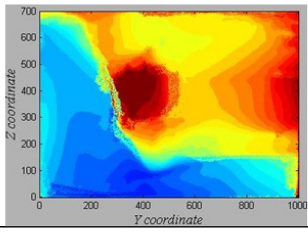
	45 km/h	50 km/h	56/km/h
Supermini 2			Not available
Citycar 1			
Supermini 3			
Supermini 1			

Table 7: PDB barrier scan results. (continued)

	45 km/h	50 km/h	56/km/h
Small Family Car 2			
SUV 1			
SUV 2	45 km/h	50 km/h	56/km/h
			
SUV 4			

4 SIMULATION RESULTS

The SUV 4 simulation results conducted by VCC are presented in detail in Section 0 " A: SUV 4 simulation results" of this report.

The B-pillar acceleration results of these simulations are presented in Figure 4.1. These results show the same trend as the MPDB test results.

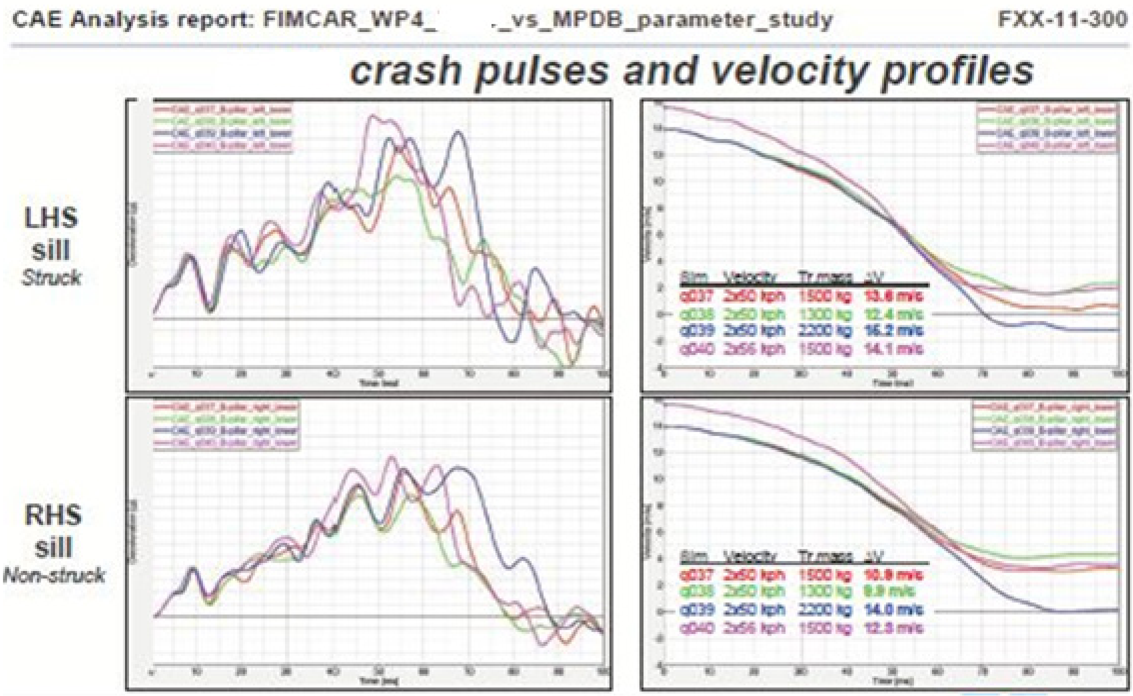


Figure 4.1: VCC Simulations / B-pillar accelerations.

The normalised compartment displacement results are presented in Figure 4.2. All MPDB simulations result in lower compartment displacements as the Euro NCAP tests but higher than the ECE R94 test. The MPDB simulations with 1500 kg trolley mass and 50 km/h test speed is closest to the PDB offset test results.

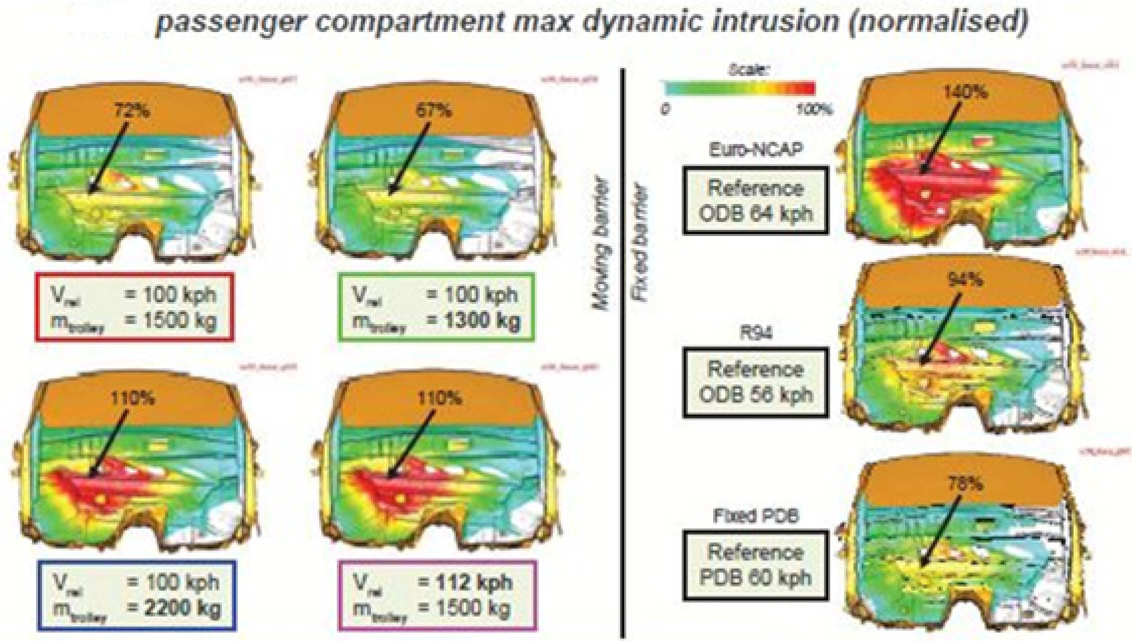


Figure 4.2: VCC Simulations / Normalized compartment displacement.

5 ASSESSMENT RESULTS

5.1 PDB Deformations

The deformation of the PDB barrier was considered for a long time as a potential basis for a metric to assess the compatibility of vehicles. Especially the FIMCAR priority number 1 topic "horizontal load spreading" should be assessed by the PDB barrier deformation. Various potential metrics were developed within the FIMCAR project. As the evaluation of these metrics is one of the main activities addressed by WP2 "Offset tests" which is based on the PDB offset tests, these metrics are described in [Lazaro 2013 / Section V].

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

The deformation profiles could be grouped into three main groups where the horizontal and vertical load spreading distinguished vehicles with good or poor performance. The main focus was the development of an assessment of the horizontal load spreading between the longitudinals. A metric based on the slope, or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm (Row 3 and Row 4 of the Full width Load Cell Wall) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 (higher results are worse than lower ones) could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

The MPDB assessment results of this most promising metric are presented in Figure 5.1.

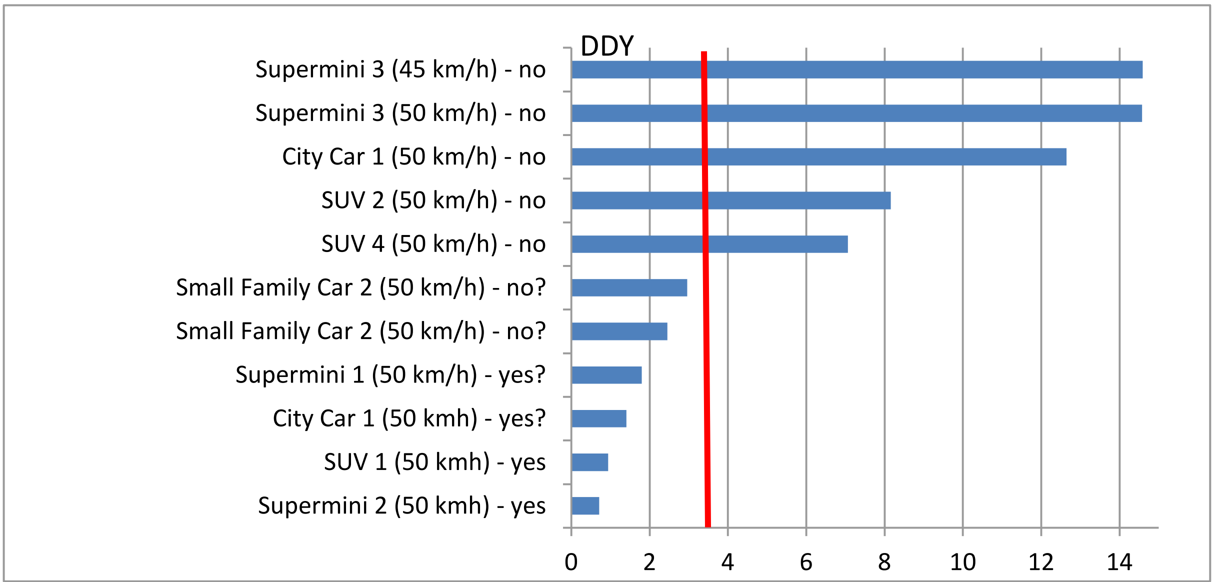


Figure 5.1: MPDB assessment results.

The basic idea of this metric is that a good horizontal load spreading will not cause strong local deformation in form of holes within the assessment zone. The remarks “yes(?) / no(?)” refer to whether or not a good spreading of the load was obtained during the test based on the judgment of an expert of the PDB deformation. The results presented in Figure 5.1 show a good correlation between the expert view during the development phase and DDY 99th% values. The question marks referred to situations where the expert has no clear view about the required results. For the metrics these unclear observations are located between real “yes” and “no” observations. The red line shows the proposed target value of 3.5 based on the PDB results analysis.

5.2 Trolley Acceleration

Investigations were carried out to establish if the trolley acceleration, a recording independent of the vehicle, could be used for compatibility assessment. In Figure 5.2 the PDB deformations, ranked from good to poor compatibility according to an expert are presented with the related trolley acceleration and force. The hypotheses that good compatibility will result in a smooth trolley acceleration, see ranking, could not be confirmed. The results of MPDB tests carried out as part of a development project by TNO were used for this analysis. Based on these negative results it was decided not to repeat this analysis for the FIMCAR tests.

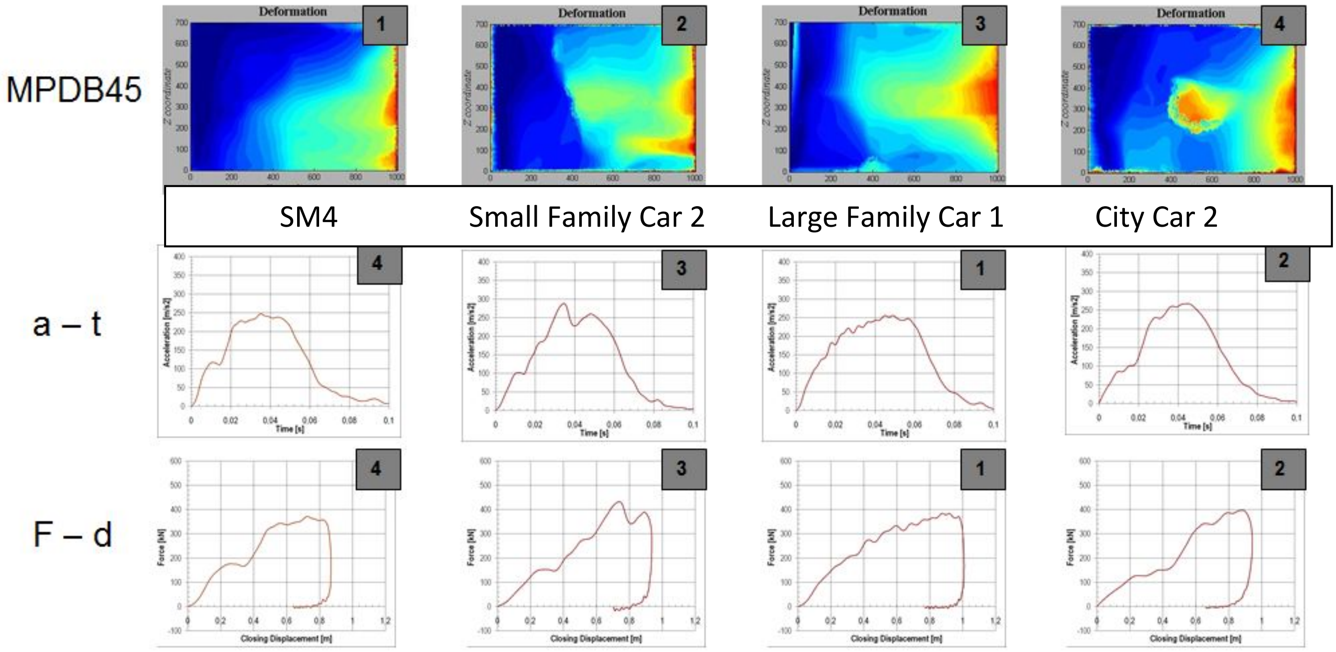


Figure 5.2: PDB deformation / trolley acceleration [Versmissen 2006].

5.3 Load Cell Wall (LCW) Recordings

The TNO/TTAI trolley is equipped with a lightweight Load Cell Wall that has identical load cell dimensions (125 x 125 mm) as the Load Cell Wall used in the full width tests. The main goal of including this load cell barrier is to use the additional information for vehicle development activities. For vehicle assessment purposes the load spreading between the load cells which is highly influenced by the PDB barrier itself is not found sufficiently robust. The use of load cells was already investigated by UTAC during the PDB development activities and was not found to be suitable for this kind of testing [Delannoy 2003].

In Figure 5.3 the load cell wall forces from the Small Family Car 2 and SUV 4 test at the moment of maximum force are presented. Comparing PDB barrier deformations with the recorded loads show that the recorded loads are present in a much bigger area than the local deformations shown in the PDB deformation.

Only the results of MPDB tests carried out as part of a development project by TNO were used for this analysis. Based on these negative results it was decided not to repeat this analysis for the FIMCAR tests.

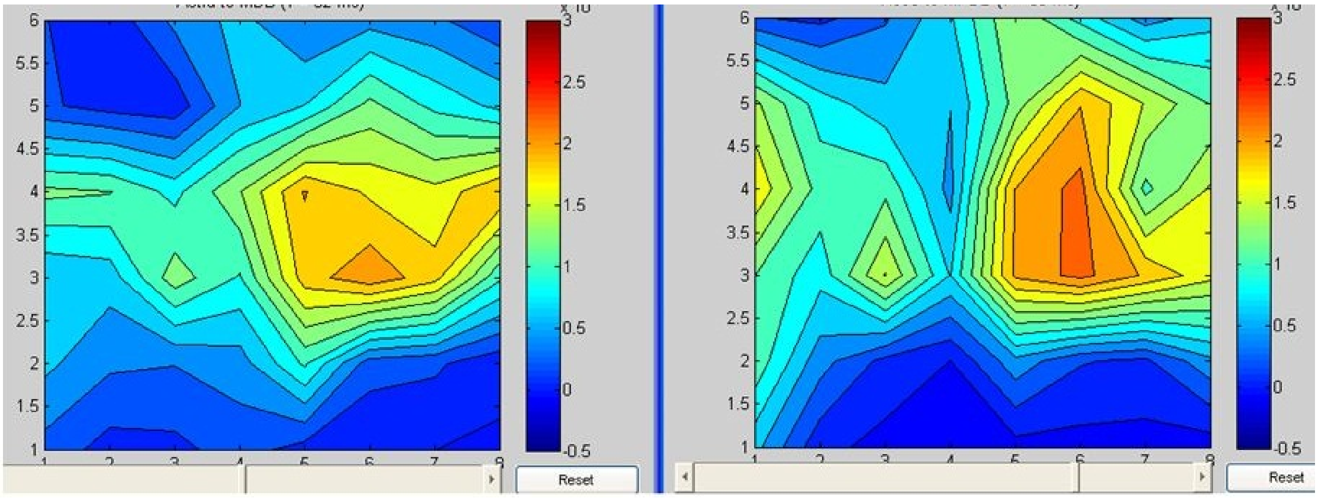


Figure 5.3: Maximum load cell forces MPDB test: Small Family Car 2.

To check the quality of the load cell measurements the total forces were compared by the force calculation based on trolley mass multiplied with the trolley acceleration.

In Figure 5.4 the acceleration of the Small Family Car 2 and SUV 4 MPDB test are presented. The acceleration calculated from the total force measured by the Load Cell Wall shows good correlation with the recorded acceleration.

Small Family Car 2 to MDB

SUV 4 to MDB

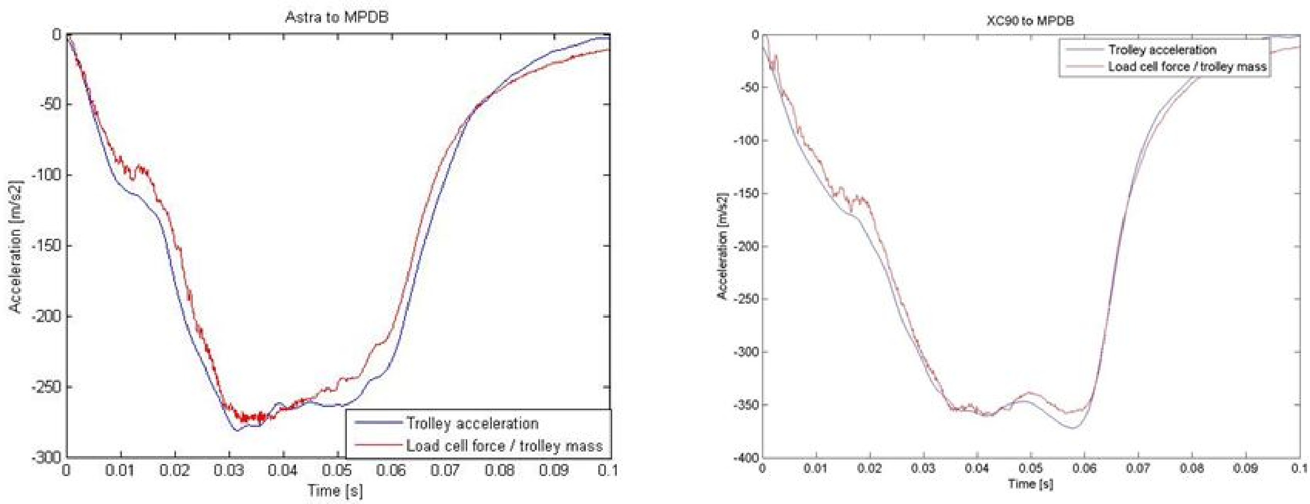


Figure 5.4: Total force results / Small Family Car 2 and SUV 4.

6 REPEATABILITY AND REPRODUCIBILITY (R&R)

6.1 General

To study the repeatability and reproducibility within the limited MPDB test program in the FIMCAR project two sets of tests, carried out with identical Small Family Car 2 vehicles, are compared (see Figure 6.1).

To check repeatability, two tests carried out by TNO as part of the MPDB development project were used. Both tests were carried out with a trolley mass of 1500 kg, a test speed of 45 km/h and with the special developed MPDB trolley from TNO/TTAI.

To check reproducibility two tests of the FIMCAR project conducted at different test facilities were used. Both tests were carried out with a trolley mass of 1500 kg and a test speed of 50 km/h. One test was carried out by TTAI/TNO, using the special developed MPDB trolley from TNO/TTAI. The other test was carried out by IDIADA, using a modified ECE R95 trolley.

Lab	vehicle mass [kg]	MPDB mass [kg]	Closing speed [km/h]	Overlap
TNO F054801	1403	1500	90	50%
TNO F055001	1405	1500	90	50%
TNO F103904	1484	1512	100	50%
IDIADA 111410CF	1482	1500	100	50%

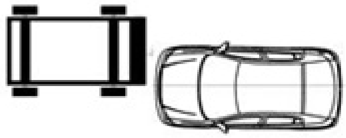


Figure 6.1: MPDB tests used for R&R study.

6.2 Repeatability

The main results of the comparison of the repeatability test results are presented in Figure 6.3 Figure 6.3: Repeatability / B-pillar and trolley accelerations as well as Figure 6.4: Repeatability / delta-v of vehicle and trolley. The deformation of both vehicles are found to be similar, see Figure 6.2.

Figure 6.2: Repeatability / car deformation

All results show a very good repeatability (variations less than 5%) of the Small Family Car 2 tests carried out by TNO.

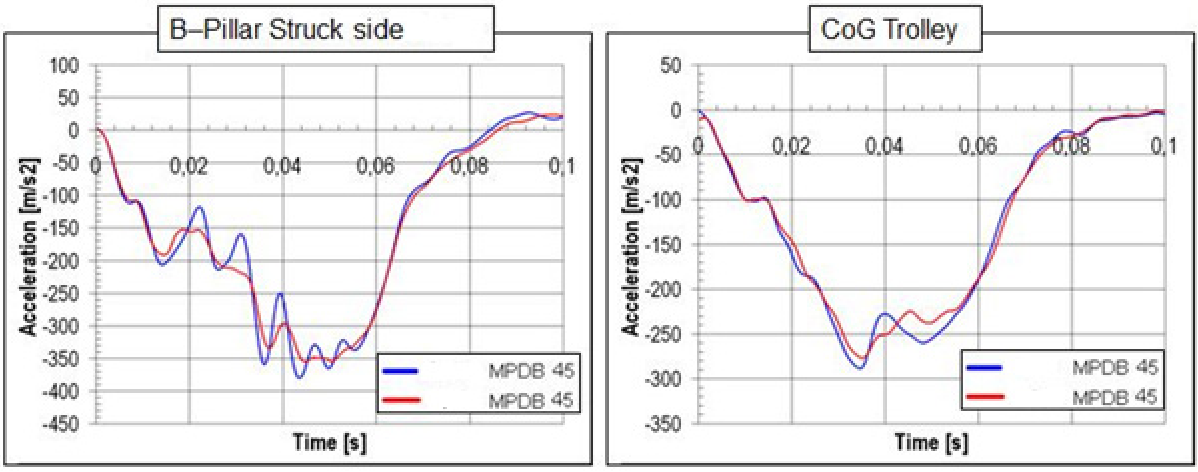
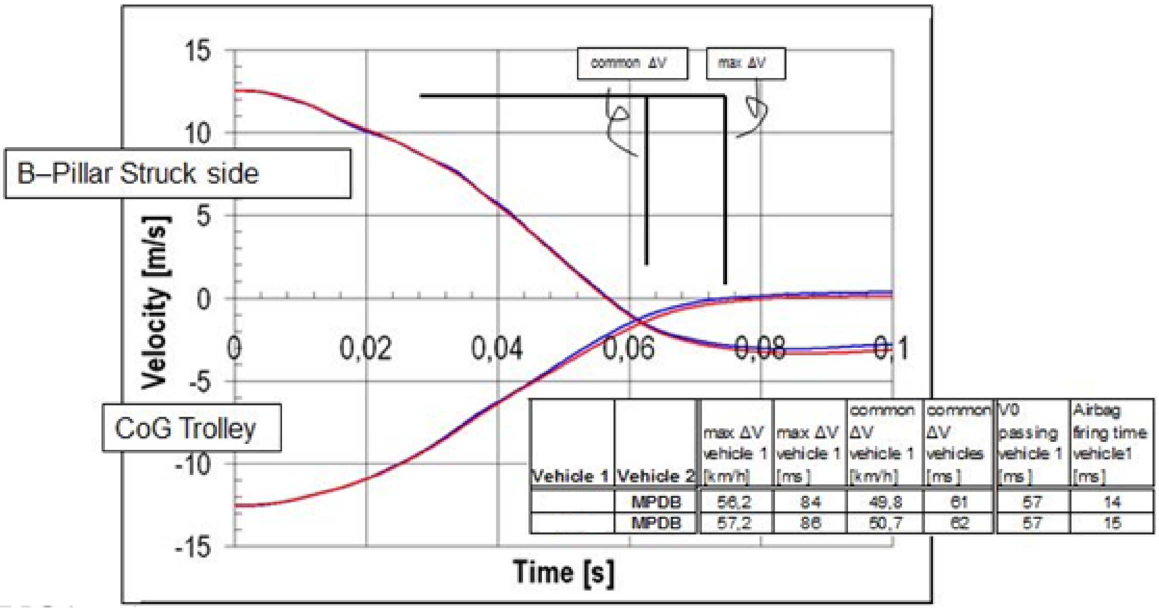


Figure 6.3: Repeatability / B-pillar and trolley accelerations.



Vehicle 1	Vehicle 2	max ΔV vehicle 1 [km/h]	max ΔV vehicle 1 [ms]	common ΔV vehicle 1 [km/h]	common ΔV vehicles [ms]	V0 passing vehicle 1 [ms]	Airbag firing time vehicle1 [ms]
	MPDB	56,2	84	49,8	61	57	14
	MPDB	57,2	86	50,7	62	57	15

Figure 6.4: Repeatability / delta-v of vehicle and trolley.

6.3 Reproducibility

The reproducibility tests were carried out as part of the FIMCAR project by TTAI/TNO and IDIADA, the test set up of both labs is presented in Figure 6.5. It is clearly visible that both laboratories use a different trolley to carry out the tests.

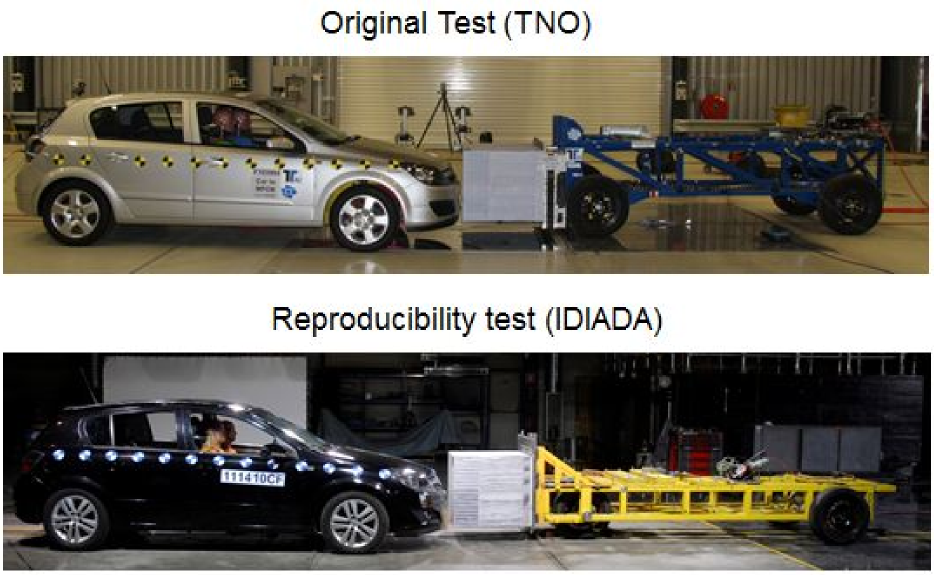


Figure 6.5: Reproducibility / test set up

The main results of the comparison of the reproducibility tests are presented in Figure 6.6 and Figure 6.7. The deformation of both vehicles is again similar as can be seen in Figure 6.8, the deformation of both PDB barriers is presented in Figure 6.9. The related DDY results are:

- TNO test : 2.96
- IDIADA test : 2.46

average : 2.71 ± 10%

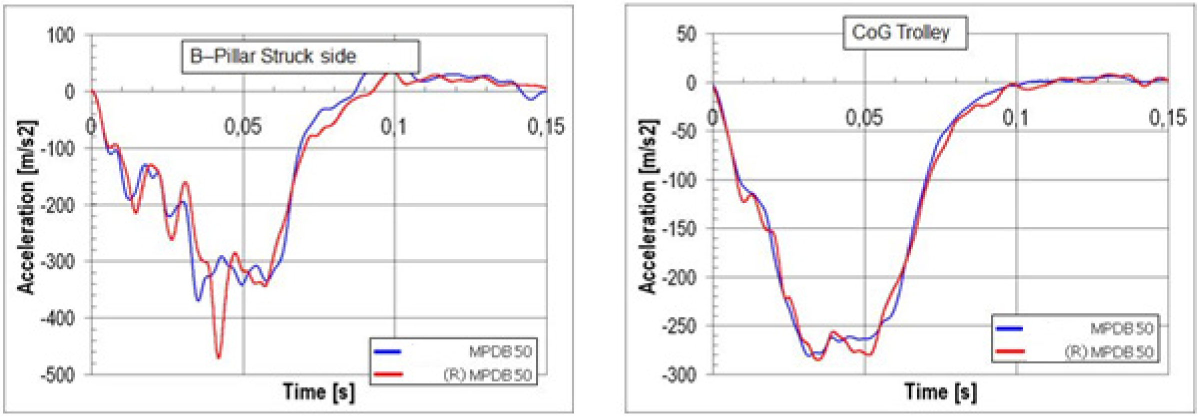
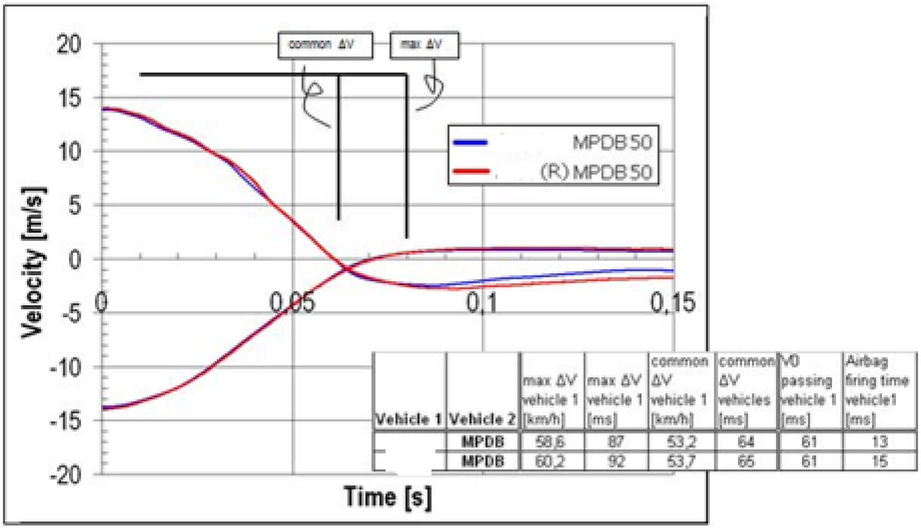


Figure 6.6: Reproducibility / B-pillar and trolley accelerations.



Vehicle 1	Vehicle 2	max ΔV vehicle 1 [km/h]	max ΔV vehicle 1 [ms]	common ΔV vehicle 1 [km/h]	common ΔV vehicles [ms]	V0 passing vehicle 1 [ms]	Airbag firing time vehicle1 [ms]
	MPDB	58,6	87	53,2	64	61	13
	MPDB	60,2	92	53,7	65	61	15

Figure 6.7: Reproducibility / delta-v of vehicle and trolley.

Figure 6.8: Reproducibility / vehicle deformations

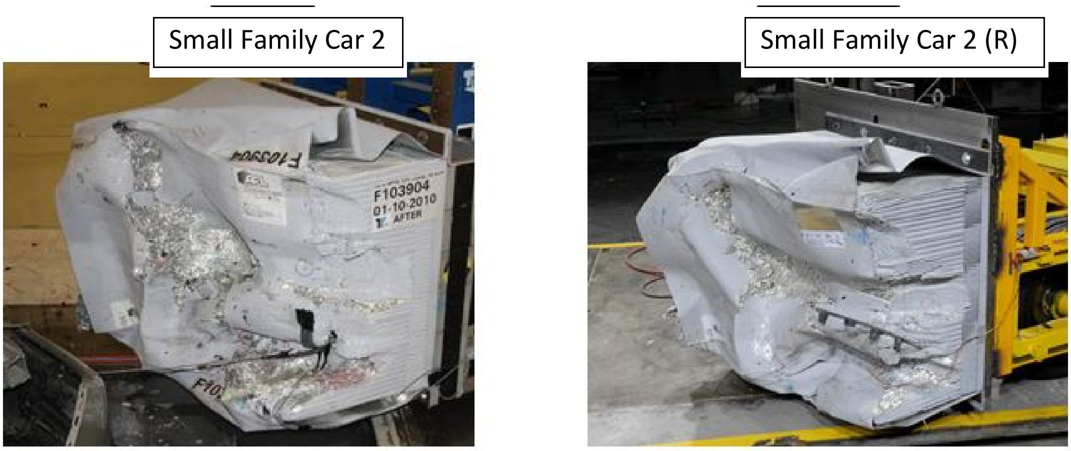


Figure 6.9: Reproducibility / PDB barrier deformation

For the reproducibility tests, the dummy results and vehicle deformation recordings were compared. An overview of the dummy results, presented in Euro NCAP layout, is shown in Figure 6.10. The A-pillar and B-pillar deformation of the tested vehicles, as recorded according to the Euro NCAP ODB protocol are presented in Figure 6.11. The Small Family Car 2 tested at IDIADA shows twice the A-pillar deformation, however this deformation is still far below the maximum level of 50 mm and may therefore be neglected.

It can be seen that the colour coding of the dummies is slightly different for both tests. This can be explained by the obtained injury values themselves. For body regions where the colouring is different, the injury reading is usually borderline with respect to the given colour. Therefore, slight changes in the actual value cause a shift in colouring. The overall score calculated per dummy is for both tests very similar.

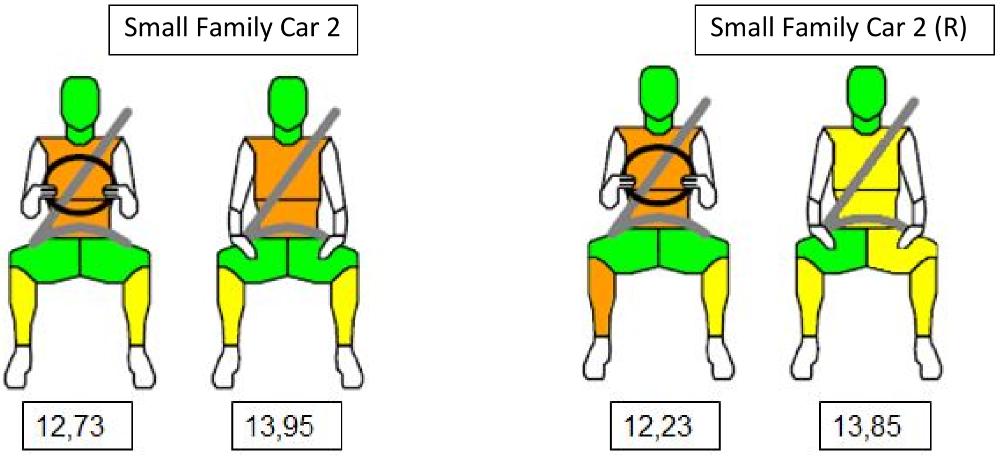


Figure 6.10: Reproducibility / dummy results (Euro NCAP layout)

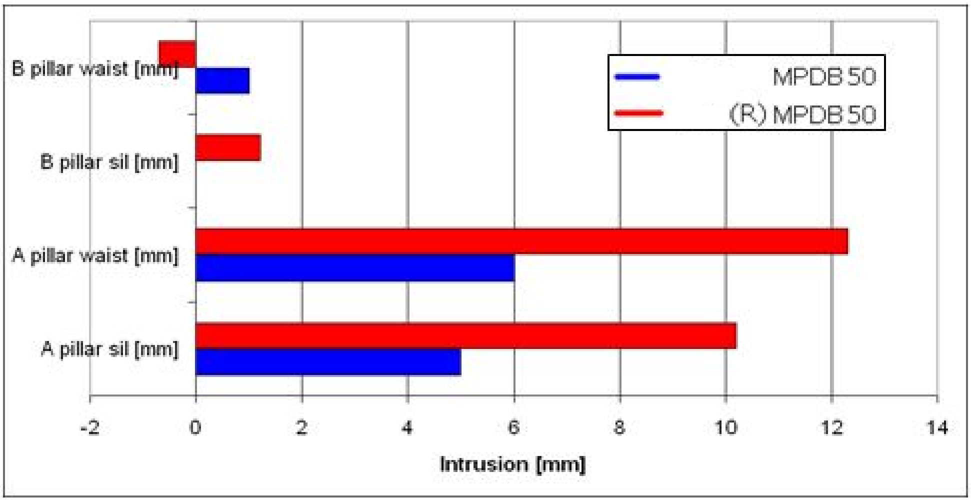


Figure 6.11: Reproducibility / vehicle deformations

7 DISCUSSION

7.1 Feasibility and Test Severity

As a mobile deformable barrier test (MDB test) procedure for compatibility testing is seen as the best method to evaluate car-to-car frontal crash behaviour by relevant groups in Europe [Uittenbogaard 2013 / Section IX] and the US [Hollowell 1999], a test protocol for such a test was developed within the FIMCAR project. It is believed, that this MDB test procedure provides a good base for harmonisation with efforts made by initiatives from other continents in the future.

As the development of a new deformable barrier was out of the scope of the FIMCAR project, the PDB barrier as used in WP2 “Offset test” was used for the MDB tests, which results in a so called MPDB test. Prior to conducting this test program a draft test protocol was defined in FIMCAR Deliverable D4.1 [Uittenbogaard 2013 / Section IX].

For the FIMCAR project 15 MPDB tests were carried out in five laboratories using four different trollies. From these 15 tests, 12 tests were carried out within the tight specifications of the draft protocol. For all the three tests outside the specifications an incorrect overlap/offset before impact was recognised as the only issue. One incorrect offset was due to an incorrect positioning of the vehicle and trolley prior test. The other two wrong offsets resulted most probably from an incorrect wheel alignment of test vehicle and/or trolley. In the future, extra attention is needed to check wheel alignment prior to the test. Also a change in the offset tolerance from ± 25 mm (for a static offset test) to ± 50 mm for a dynamic offset test (two moving objects) could be considered in the future.

Within the vehicle mass range used in the FIMCAR project, the kerb mass ranges from about 1000 kg to 2200 kg, the test severity of an MPDB tests with a trolley mass of 1500 kg and impact speed of 50 km/h is proposed. Based on B-pillar acceleration, delta-v, vehicle deformations and dummy values discussed in Chapter 3, the test is found comparable to the current R94 and Euro NCAP tests for heavy vehicles’, but more severe for average mass and light vehicles. However during the MPDB tests with the tested light vehicles most of the dummy results still fulfil most of the ECE R94 requirements. The severity of this proposal for heavy vehicles is also confirmed by the SUV 4 simulations carried out by VCC.

For vehicles outside the FIMCAR mass range, the test severity might be inappropriate: less severe (resulting in insufficient self-protection) for very heavy vehicles and too severe for very light vehicles, as for example new light weight electric urban vehicles. For these situations an adjustment of the test severity by means of changing the trolley mass and/or test speed could be necessary. Further investigation on this subject is needed from further future studies. Also the suggestion to test vehicles with a certain mass with a static PDB test instead of a MPDB test should be investigated further.

7.2 Compatibility Metrics

A metric based on the slope, or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate for a compatibility metric for MPDB tests. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

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

While structural alignment and occupant compartment stability issues can be addressed with current ODB and proposed FWDB barrier recommendations in FIMCAR, there is no test procedure available that reliably assesses horizontal load spreading. The proposed DDY metric for the MPDB test allows the front structure for vehicles to be assessed and to be updated to also assess vertical load spreading

7.3 Repeatability and Reproducibility

Due to the limited FIMCAR test program a detailed investigation of repeatability and reproducibility was not possible. Only two repeated tests at one laboratory and 1 set of similar tests in 2 laboratories were conducted. From this brief investigation it was found, that both, repeatability as well as reproducibility were good, with test result variations less than 10%. In order to make a more well-grounded statement, further investigations (e.g. round robin tests) are needed.

8 CONCLUSION AND RECOMMENDATIONS

A draft test protocol for MPDB test was set up in the FIMCAR project. Using this protocol 15 tests were carried out. The results of these tests show that the test configuration is feasible in various laboratories. For this type of test, special attention is needed for the wheel alignment of trolley and test vehicles.

For the used mass range, kerb weight of 1000 kg to 2200 kg, a trolley mass of 1500 kg and test speed of 50 kg/h is proposed to define the required test severity. For vehicles outside this range, for example light electrical vehicles or heavy SUV's, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out. These series of tests both showed good results, giving an indication for good R&R, however, more tests are needed to make this statement statistically relevant

The metric for horizontal load spreading based on the deformation of the PDB barrier, as defined for the offset test of FIMCAR WP2, is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

Discussion is needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in a shorter term, as it has some advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

Investigations are needed if the proposed metric for horizontal load spreading can be extended to a metric for vertical load spreading.

9 REFERENCES

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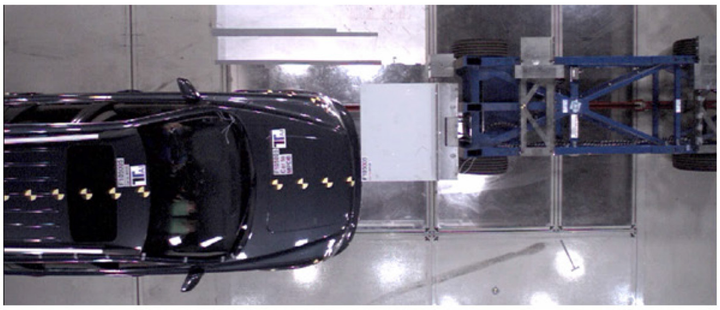
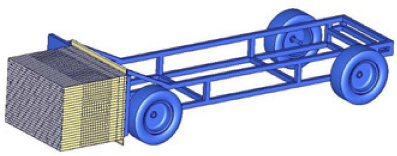
APPENDIX A: SUV 4 SIMULATION RESULTS

FIMCAR
WP4 SUV 4 activities

Car-to-MPDB simulations
Linus Wågström, Volvo Cars Safety Centre
2012-09-18





Barrier model:
PDB_June20_2011_version2.key

Trolley model:
VCC modified side impact trolley
see Appendix for more information

Part 1

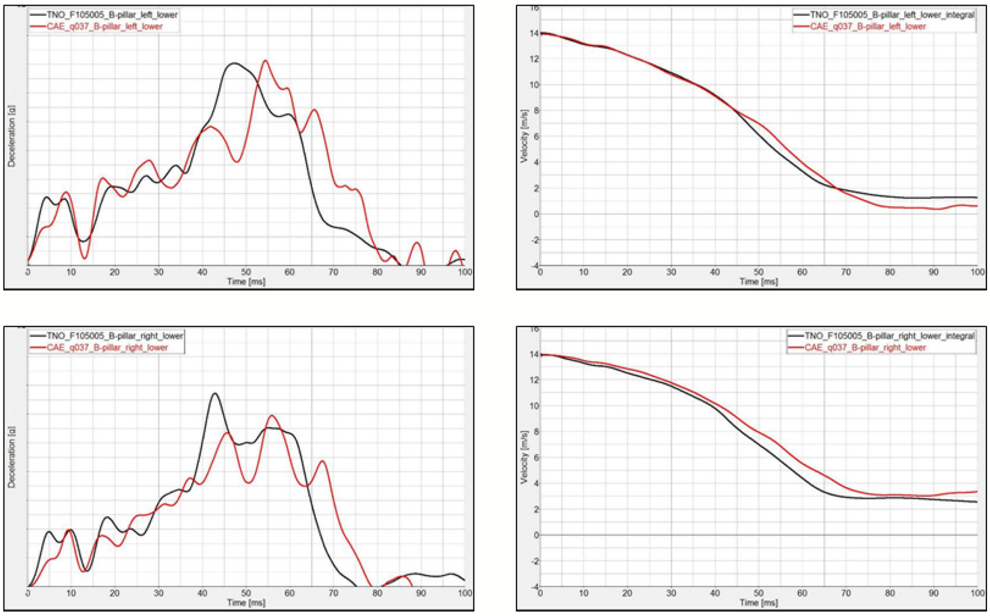
Baseline model validation
Trolley 1500 kg / closing speed 100 km/h
CAE model q037 vs. TNO test 105005

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study **FXX-11-300**

SUV 4 crash pulses and velocity profiles

LHS sill
Struck

RHS sill
Non-struck



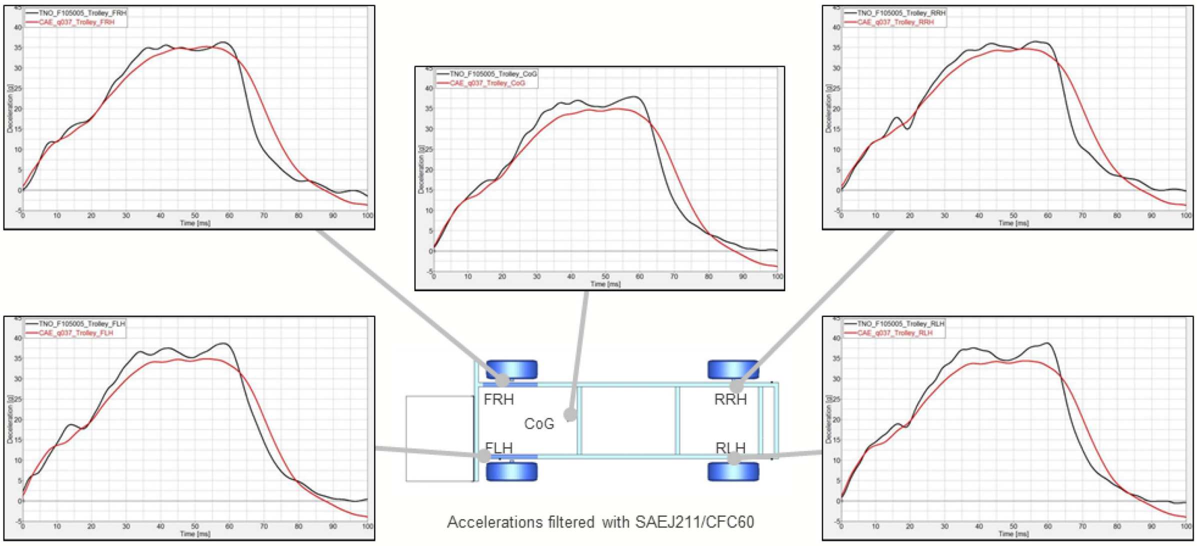
Accelerations filtered with SAEJ211/CFC60

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
Volvo Cars Safety Centre, Linus Wågström
Date: 2012-09-18
Page 3

FIMCAR frontal impact and compatibility assessment research
VOLVO

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study **FXX-11-300**

Trolley crash pulses



Accelerations filtered with SAEJ211/CFC60

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
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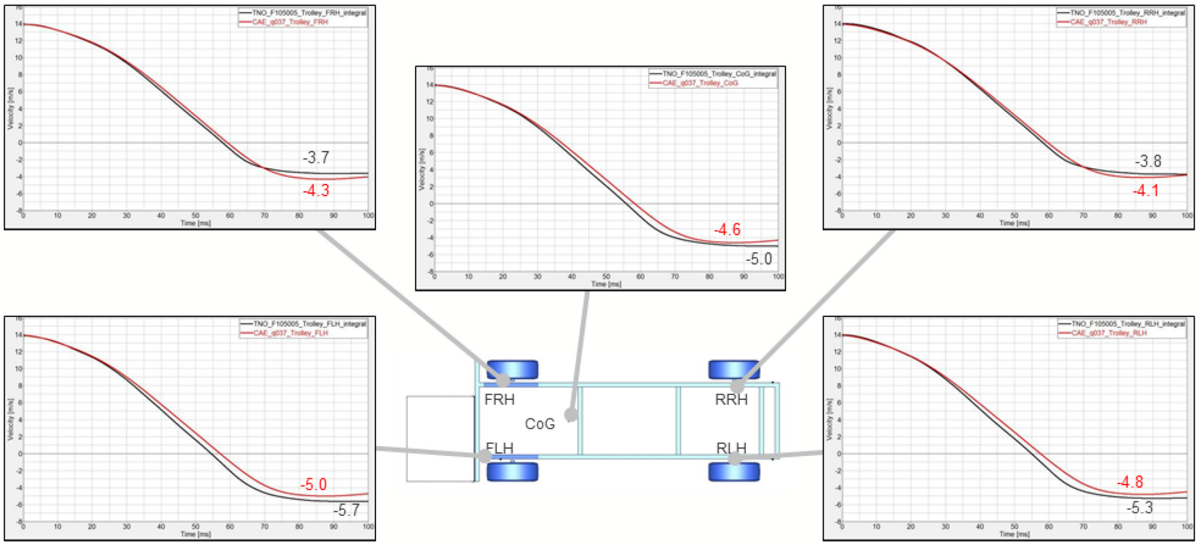
Trolley velocity profiles



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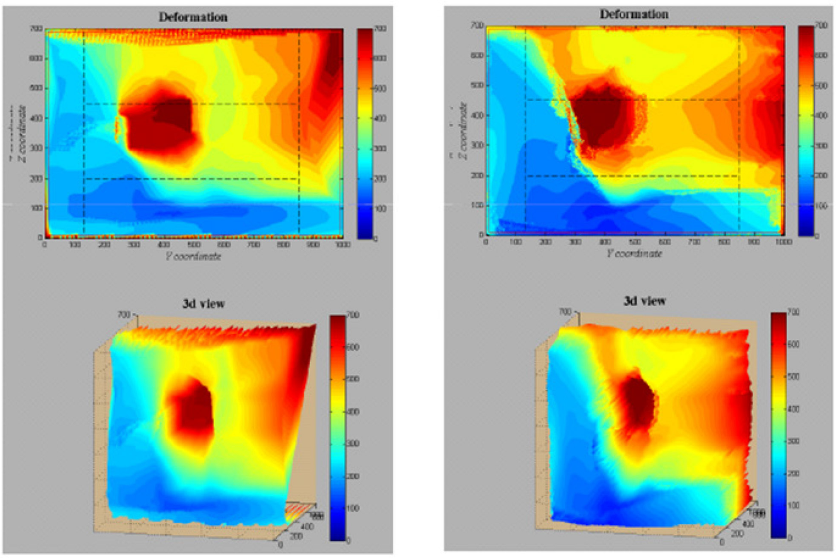
Barrier deformation

Simulation

CAE
q037



Crash test

TNO test
105005

Picture from TU Berlin evaluation

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Conclusions - Part 1:

- CAE model captures car crash pulses and velocity profiles. Some timing differences when comparing CAE and test.
- CAE model captures trolley crash pulses and velocity profiles. Test generally shows slightly higher acceleration.
- Barrier deformation very similar in simulation compared to test. Acceleration curves suggest that PDB CAE model should be stiffened slightly.

Overall, the results indicate sufficient model quality to proceed with the parameter study in Part 2.

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Part 2

Parameter study

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Simulation matrix

	Simulation	Barrier	Car velocity [kph]	Barrier velocity [kph]	Relative velocity [kph]	Barrier mass [kg]	Car mass [kg]	Initial kinetic energy [kJ]
Baseline	⇨SUV 4_fimcar_q037	MPDB	50	50	100	1500		376
	SUV 4_fimcar_q038	MPDB	50	50	100	1300		357
	SUV 4_fimcar_q039	MPDB	50	50	100	2200		444
	SUV 4_fimcar_q040	MPDB	56	56	112	1500	2400	472
Euro-NCAP	⇨SUV 4_fimcar_o041	ODB	64		64			379
R94	⇨SUV 4_fimcar_n041	ODB	56		56			290
Fixed PDB	⇨SUV 4_fimcar_q042	PDB	60		60			333

Project: FIMCAR
Load cases: q - MPDB LHD, o - ODB LHD
Code version: LS DYNA mpp 971 sR4.2.1.

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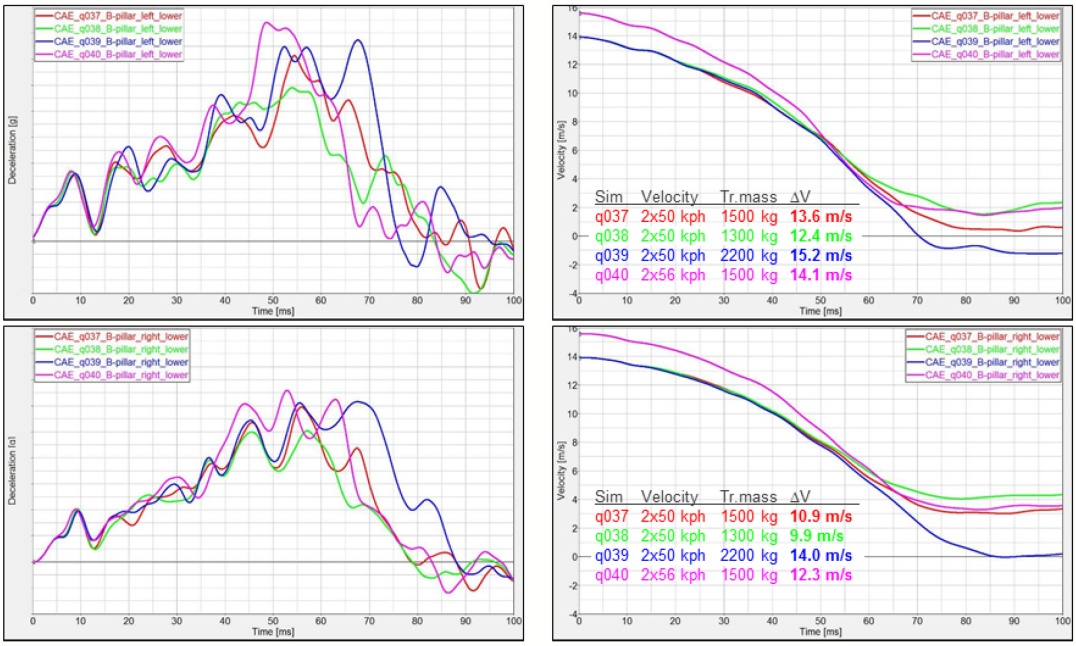
SUV 4 crash pulses and velocity profiles

LHS sill
Struck

RHS sill
Non-struck



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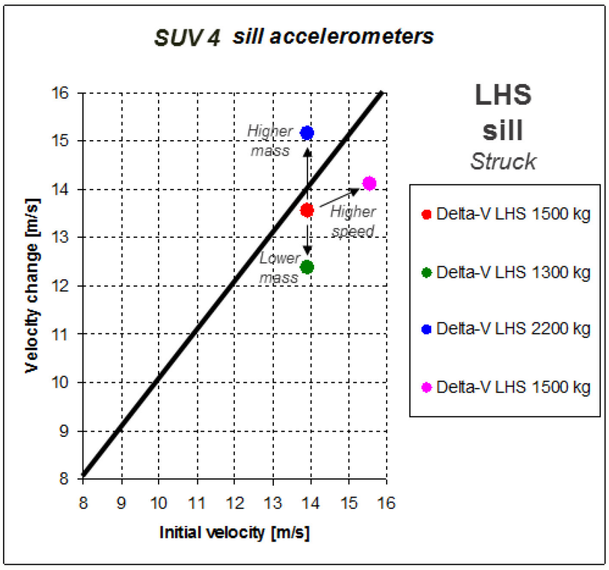
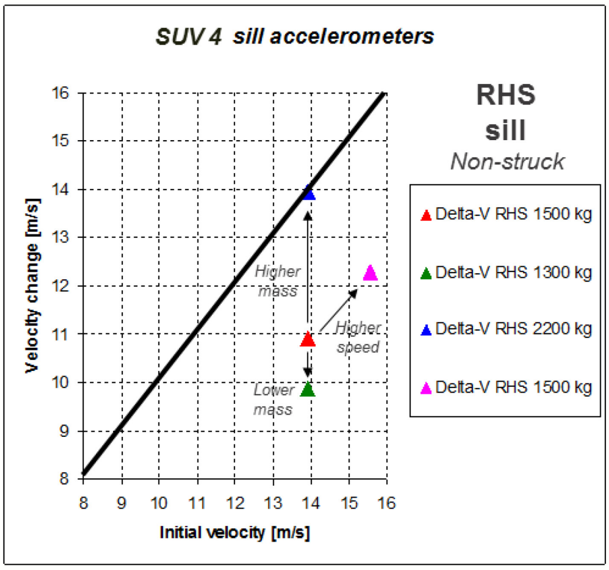
SUV 4 overview of velocity change vs. initial velocity





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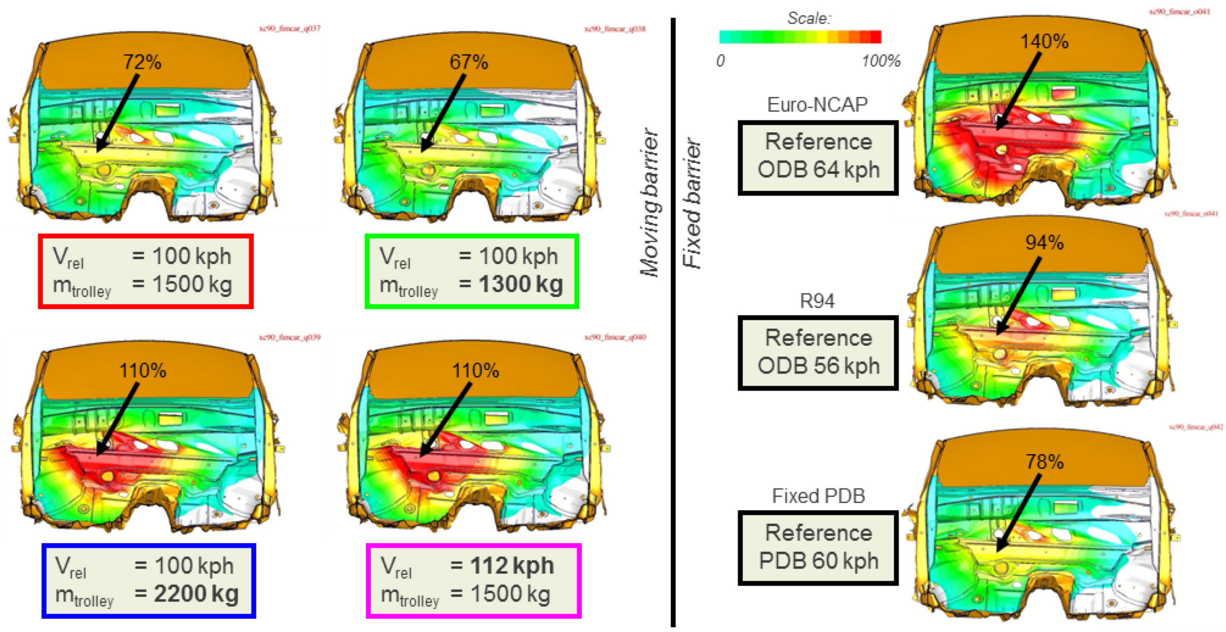
SUV 4 passenger compartment max dynamic intrusion (normalised)



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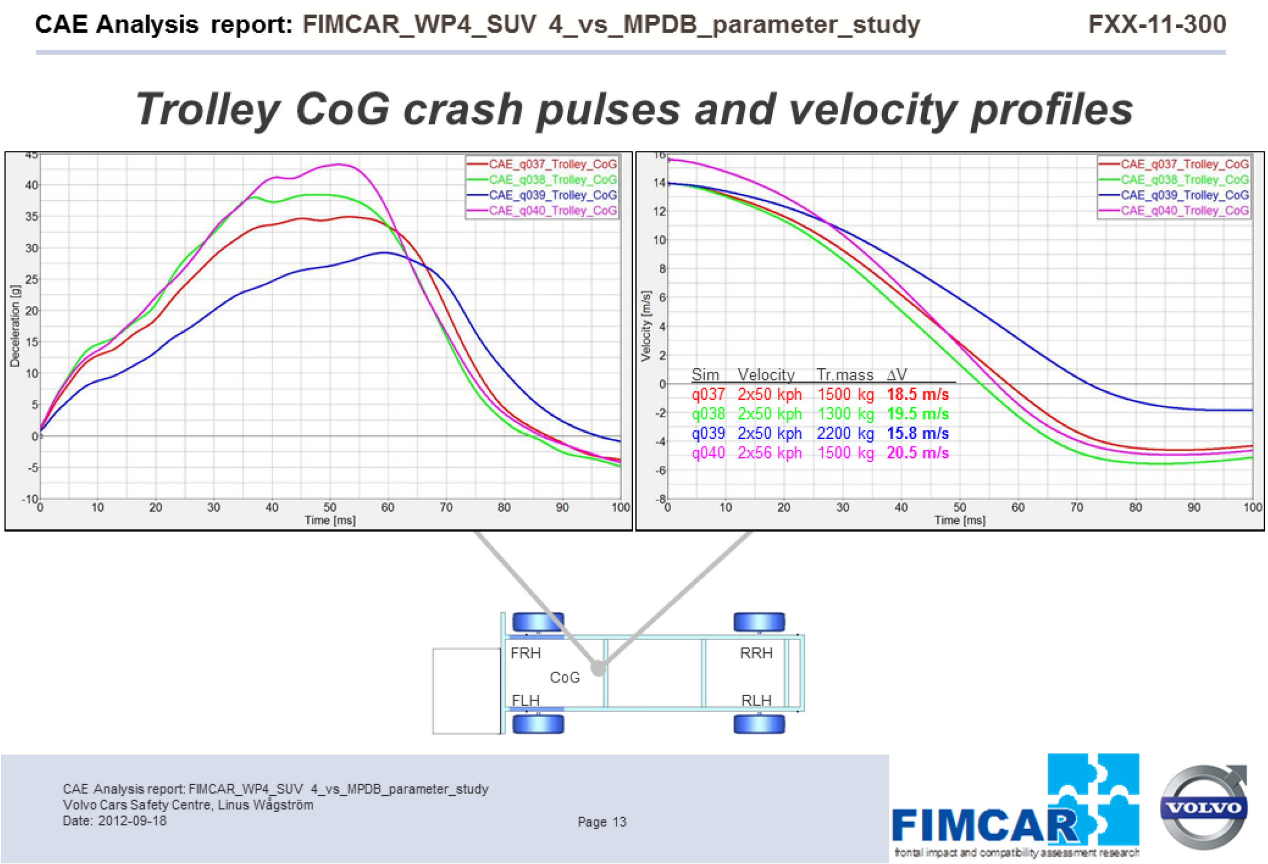
CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
FXX-11-300
Trolley CoG crash pulses and velocity profiles
CAE_q037_Trolley_CoG
CAE_q038_Trolley_CoG
CAE_q039_Trolley_CoG
CAE_q040_Trolley_CoG
Deceleration [g]
Time [ms]
Velocity [m/s]
Sim Velocity Tr.mass ΔV
q037 2x50 kph 1500 kg 18.5 m/s
q038 2x50 kph 1300 kg 19.5 m/s
q039 2x50 kph 2200 kg 15.8 m/s
q040 2x56 kph 1500 kg 20.5 m/s
FRH
RRH
CoG
FLH
RLH
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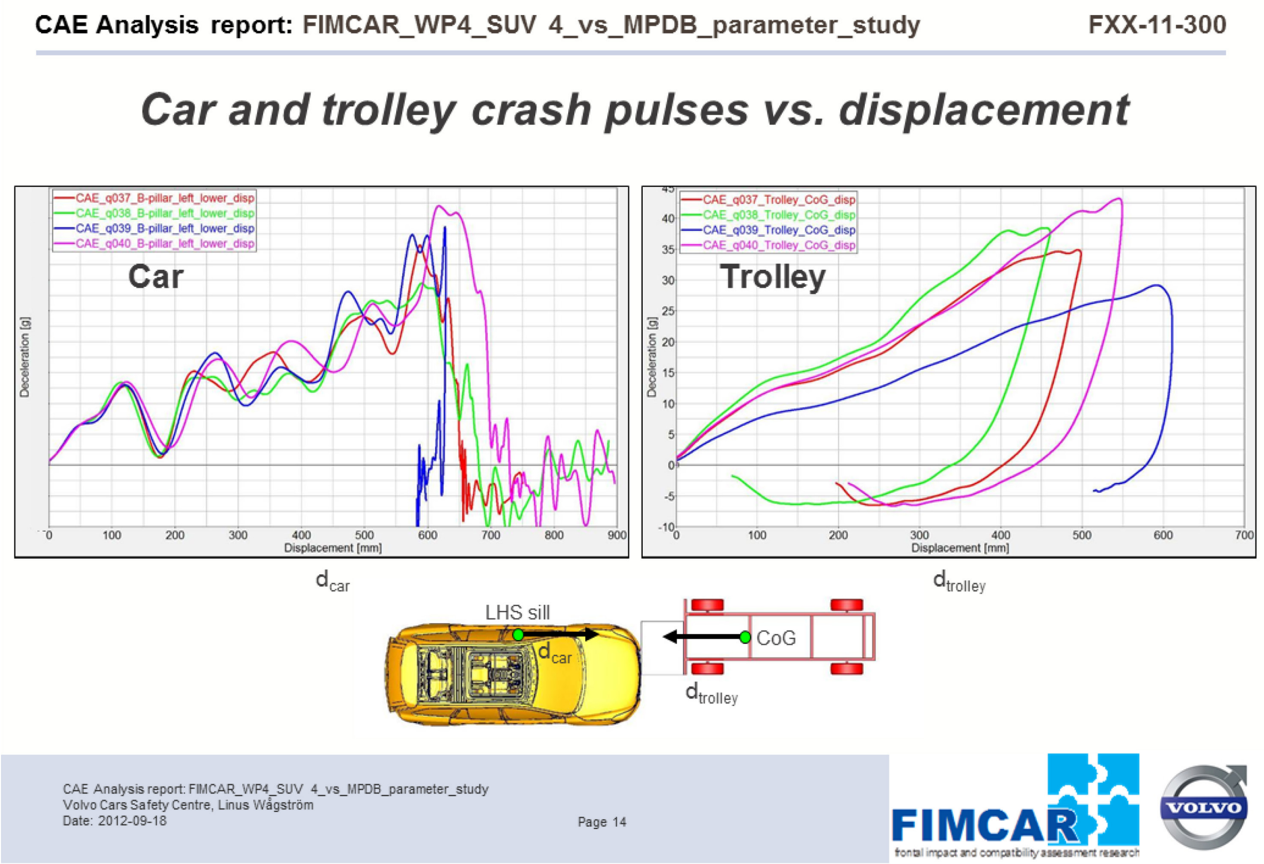
CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
FXX-11-300
Car and trolley crash pulses vs. displacement
CAE_q037_B-pillar_left_lower_disp
CAE_q038_B-pillar_left_lower_disp
CAE_q039_B-pillar_left_lower_disp
CAE_q040_B-pillar_left_lower_disp
Car
Deceleration [g]
Displacement [mm]
CAE_q037_Trolley_CoG_disp
CAE_q038_Trolley_CoG_disp
CAE_q039_Trolley_CoG_disp
CAE_q040_Trolley_CoG_disp
Trolley
d car
d trolley
LHS sill
CoG
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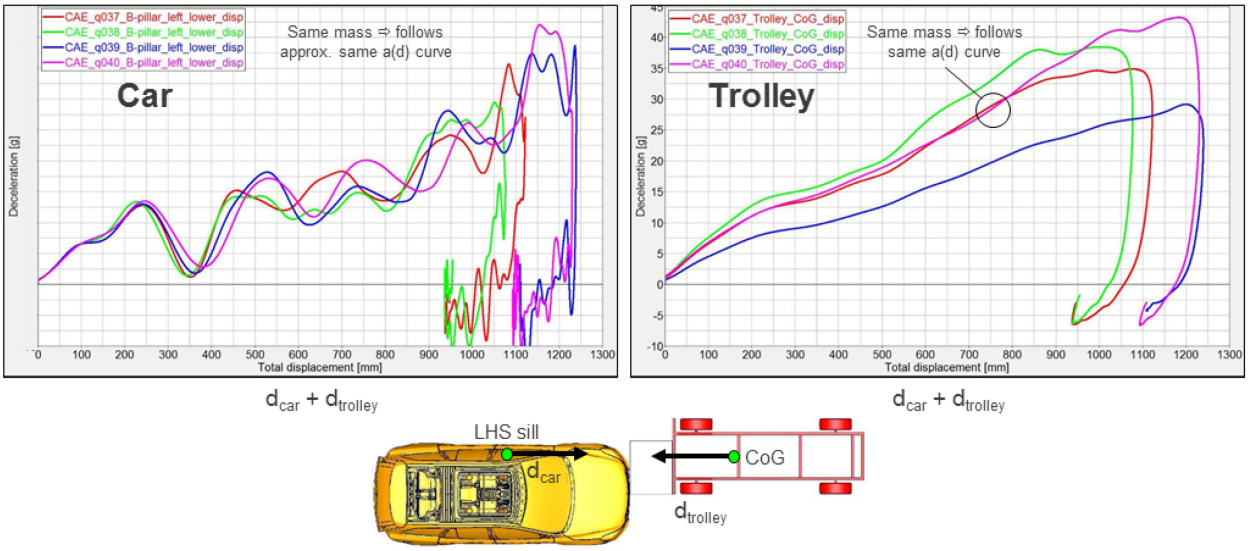
Car and trolley crash pulses vs. displacement



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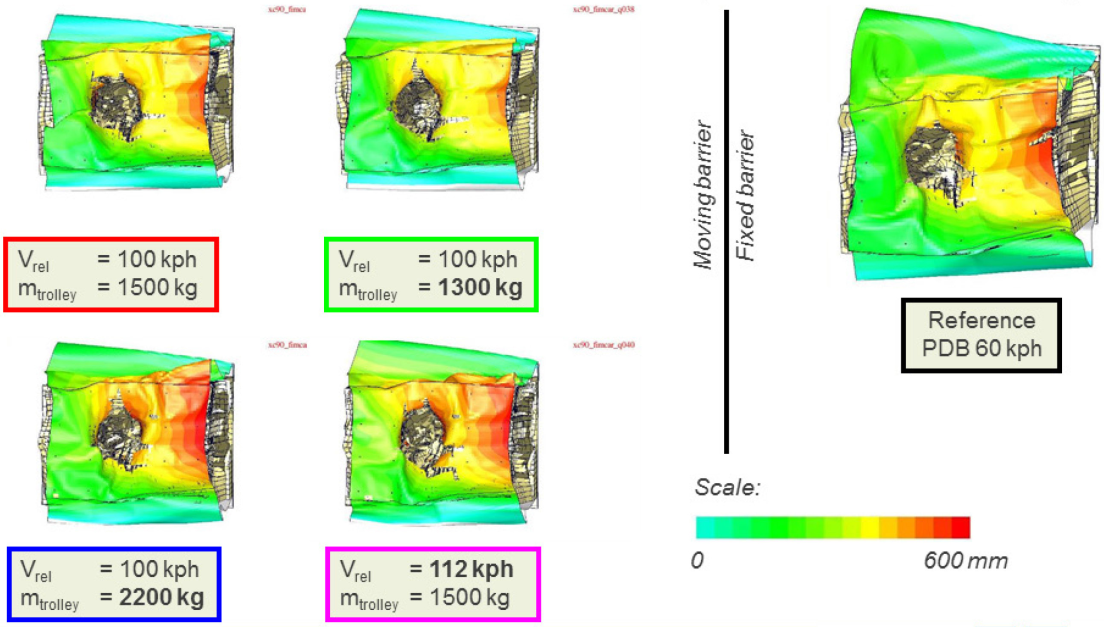
Barrier deformation at 150 ms (i.e. with rebound)



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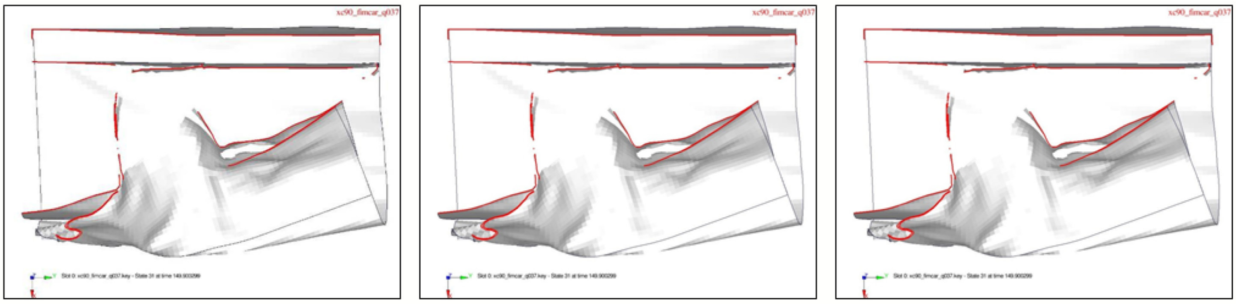
Barrier deformation at 150 ms (i.e. with rebound)



V_{rel} = 100 kph $m_{trolley}$ = 1500 kg	V_{rel} = 100 kph $m_{trolley}$ = 1500 kg	V_{rel} = 100 kph $m_{trolley}$ = 1500 kg

Cross section at z = 770 mm
Flip between pages to see difference

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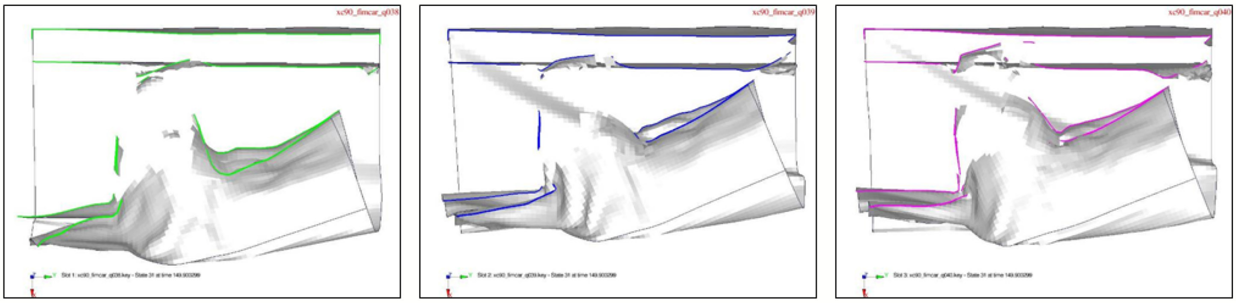
Barrier deformation at 150 ms (i.e. with rebound)



V_{rel} = 100 kph $m_{trolley}$ = **1300 kg**	V_{rel} = 100 kph $m_{trolley}$ = **2200 kg**	V_{rel} = **112 kph** $m_{trolley}$ = 1500 kg

Cross section at z = 770 mm
Flip between pages to see difference

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PDB energy dissipation and EES

	Sim #	Relative velocity [km/h]	Trolley mass [kg]	Total kinetic energy [kJ]	Total dissipated energy [kJ]	PDB dissipated energy [kJ]	PDB share of dissipated energy	EES [km/h]
Moving barrier	q037	100	1500	376	345	186	54%	42.9
Moving barrier	q038	100	1300	357	317	177	56%	40.1
Moving barrier	q039	100	2200	444	426	213	50%	49.9
Moving barrier	q040	112	1500	472	433	220	51%	49.4
Fixed barrier	q042	60	N/A	333	308	171	55%	41.9

Formulas used for EES

$$E_{to\_absorb} = \frac{1}{2} \cdot \frac{m_{car} \cdot m_{trolley}}{m_{car} + m_{trolley}} \cdot v_{rel}^2$$

This energy is the initial kinetic energy when normalised for equal momentum

$$E_{abs} = E_{to\_absorb} - E_{barrier}$$

$$EES(km/h) = 3.6 \times \sqrt{\frac{2 \times Eabs}{M}} \quad (1a).$$

Eabs = energy absorbed by the vehicle (J)
Eabs = Kinetic energy – Energy in the barrier
M = mass of the vehicle (kg) Here: 2400 kg

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Conclusions - Part 2 (see also next slides):

In terms of SUV 4 passenger compartment intrusions and EES:

- Small differences between 1500 kg and 1300 kg trolley, both give lower intrusion than ODB at 56 kph.
- Similar results using 2200 kg trolley at 100 kph closing velocity compared to 1500 kg at 112 kph.
- Out of the tested variants, the baseline car-to-MPDB (1500 kg trolley at 100 kph closing velocity) is most similar to fixed PDB
- All car-to-MPDB show lower intrusion than Euro-NCAP test

In terms of SUV 4 velocity change:

- Higher velocity change using 2200 kg trolley at 100 kph closing velocity compared to 1500 kg at 112 kph.

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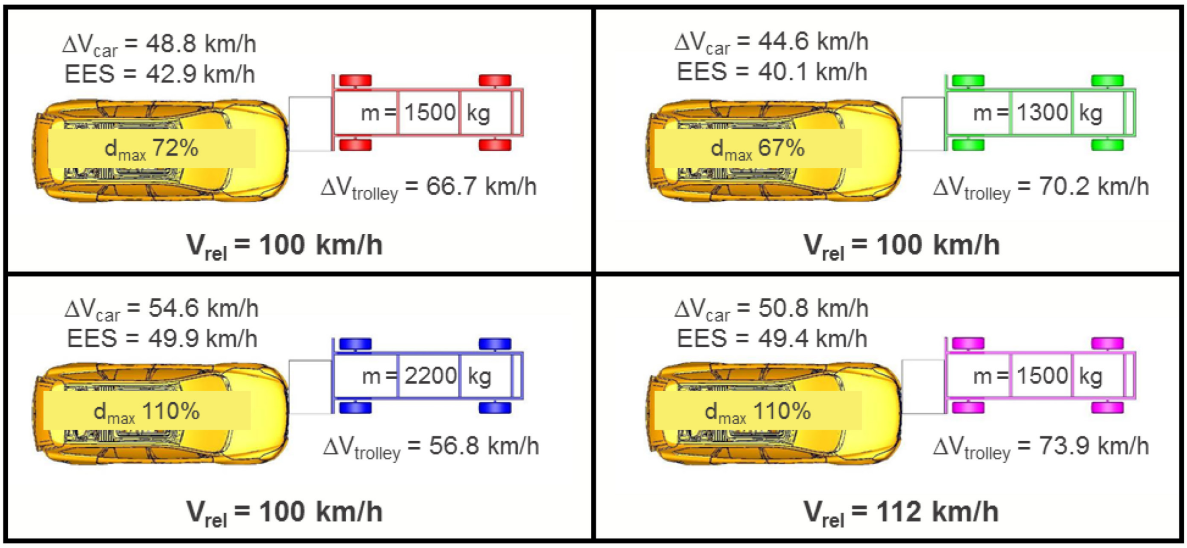
Overview of results

SUV 4 struck side and trolley CoG – Normalised intrusions



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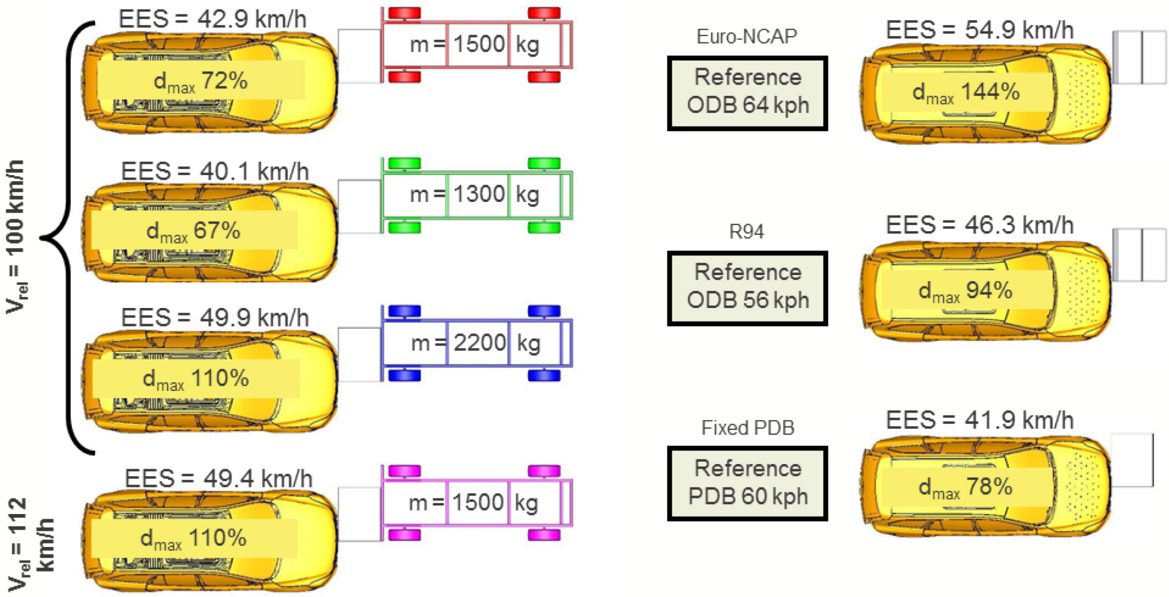
Overview of results – Normalised intrusions / EES



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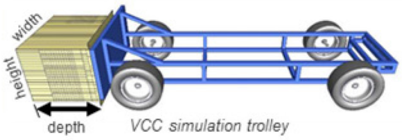
Appendix:
Trolley comparison

Test trolley



VCC simulation trolley

Physical data from TNO
2011-02-23

Description	Unit	TNO Physical values	VCC CAE model	Δ
Mass	[kg]	1500	1501	0%
Mass front axle	[kg]	1100	1116	1%
Mass rear axle	[kg]	400	385	-4%
Barrier height	[m]	0.70	0.70	0%
Barrier width	[m]	1.00	1.00	0%
Barrier depth, extended	[m]	0.8	0.78	-3%
Barrier ground clearance	[mm]	150	150	0%
Overall Length	[m]	4.35	4.37	0%
Axle height	[m]	0.28	0.3	7%
Wheel base	[m]	2.60	2.60	0%
Track width, centerline of wheels	[m]	1.20	1.20	0%
CoG x-dir from front (extended)	[mm]	2000	1917	-4%
CoG x-dir from frontal axle	[mm]	700	676	-3%
CoG y-dir from trolley centerline	[mm]	0	5	
CoG z-dir from ground	[mm]	600	602	0%
Iyz Roll	[kg·m²]	550	560	2%
Ixz Pitch	[kg·m²]	2550	2520	-1%
Ixy Yaw	[kg·m²]	2650	2650	0%
Tyre pressure	[bar]	2.5	2.5	0%
Tyres		205/55		
Barrier face location		Left outlined with outside of wheels		

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