

## **A Mobile Deformable Barrier Test for the Front Crash Assessment of Future Urban Microcars**

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### **ABSTRACT**

A rising share of electric microcars (with mass well below 800kg) is predicted for the future urban vehicle fleet. Therefore the relevance of safety hazards due to mass incompatibility in case of front crashes will increase significantly. The front crash test according to ECE regulation no.94 initially defined for M class vehicles does not allow to reproduce the predicted real-world crash severity for light vehicles. This paper describes an alternative test for front crash assessment of microcars using a mobile progressive deformable barrier (MPDB) with adjusted mass properties. Since the long term development of the vehicle fleet is unclear, a test set-up with parameterized barrier mass properties having the potential to reproduce variable car-to-car front crash constellations is proposed.

The relevant test parameters for a microcar front crash test are chosen based on predicted future trends from literature, expert surveys and car-to-car crash sensitivity tests. Based on that, a finite element (FE) model of a parametric MPDB is proposed, reproducing the mass properties of various possible front crash opponents. To quantify the use potential of the test, a comparison of MPDB test outputs for three types of possible microcar concepts with car-to-car crash outputs using FE Generic Car Models from the FIMCAR project as opponents is carried out. The main focus of this comparison is on structural crash performance and occupant injury. In order to bridge these two, an adequate crash restraint system triggering based on the acceleration sensing system is proposed.

As conclusion general use recommendations for the parametric MPDB test configuration are formulated.

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### **INTRODUCTION**

The small cars segments (A/B) are predicted to show highest global growth rates in a mid-term perspective (*Kalmbach et al., 2011*). In an urban environment cars showing special features globally attributed to the term microcar – such as reduced overall dimensions, low fuel consumption due to reduced engine capacity, limited seating and storage space and in case of electric powering also local emission free usage – can become especially attractive.

Until now cars showing these properties can either be classified as M class vehicles (*Directive 2007/46/EC*) or as heavy quadricycles belonging to the category L7e-CP (*Regulation (EU) No 168/2013*) on the European market. The main distinction between these classifications with respect to passive safety is the lack of crash test assessment, that a L7e-CP vehicle has to fulfil for homologation, while M class vehicles are required to pass several crash tests. In addition, there is an upper speed limit of 90 km/h and an upper weight limit of 450 kg (without battery system) set to vehicles attributed to the L7e-CP class. M class listing is not related to a lower weight limit. Nevertheless current M class vehicles weight generally more than approximately 800 kg, due to the weight-increasing fulfilment of comfort and functionality requirements, partly not relevant in an urban use environment. The present study is focussing on future urban microcars defined as being placed in the weight gap between L7e-CP class and the virtual lower limit of 800 kg for current M class vehicles.

The main front crash passive safety hazard identified for light vehicles is the potential crash against heavier opponent vehicles (*O'Brien, 2010*) due to the high significance of mass incompatibility. This results in higher velocity change for the lighter crash partner and therefore in higher crash severity. Current European front crash testing procedures, either related to M class according to *UN-ECE Regulation No. 94* or related to L7e-C vehicles as seen in Euro NCAP's most recent test series for heavy quadricycles (*Euro NCAP, 2014*), are not addressing the issues of mass incompatibility by testing against fixed crash barriers. These test conditions do not reproduce the energy balance of a vehicle-to-vehicle crash and the possible influence of the mass ratio on crash severity for the assessed vehicle. Higher reproduction potential is attributed to mobile deformable barrier (MDB) tests according to different studies (e.g. *O'Brien, 2010* or *Uittenbogaard and Versmissen, 2013*), due to the more realistic energy balance.

The use profile of these future urban microcars is not yet clear on midterm forecasting level: Will their use be restricted to urban areas? With what kind of possible crash opponents will they share the traffic environment and what developments will influence closing speed and impact direction in case of front crash? Resulting from that, precise parameters of the relevant real world safety hazard related to vehicle-to-vehicle front crash cannot yet be defined. Fixed testing conditions with a static logic behind the crash severity definition do not have the flexibility to respond to changes in the target crash scenario.

### **USE POTENTIAL OF THE MOBILE PROGRESSIVE DEFORMABLE BARRIER (MPDB)**

Previous studies have identified the high use potential of MDBs for the front crash assessment of light vehicles. MDB tests show good reproduction potential of the real world crash kinematic. In addition, the structural interaction between crash partners is also suitably reproduced, when a deformable barrier element is chosen with stiffness properties that are comparable to those of a crash opponent's vehicle front.

The MPDB, introduced by *Bosch-Rekvelde et al., 2006* and further developed during the 'Frontal Impact and Compatibility Assessment Research (FIMCAR)' project is the most recent European development in the field of MDBs for front crash assessment. The weight is adjusted to represent the European fleet average with inertia properties according to US vehicle fleet mass properties. The progressive deformable barrier (PDB) as energy absorption element has stiffness properties that are comparable the those of recent vehicles tested in EuroNCAP's offset front crash configuration (*Uittenbogaard and Versmissen, 2013*). First analysis of the influence of the barrier weight on crash severity was already executed by *Bosch-Rekvelde et al., 2006*, identifying a mayor influence on crash pulse and energy dissipation level of the tested vehicle. The test set-up investigated during the FIMCAR project for the 1,500 kg MPDB has the following parameters: 50 % overlap, 50 km/h-50 km/h impact speed, 0 ° impact angle.

Test configurations using a mobile test barrier offer the highest number of crash configuration parameters, therefore being most suitable for a flexible adjustment of the test in case of target scenario shift. In this way the current MPDB test set-up can easily be adapted to a configuration relevant for microcar assessment.

### **DEFINITION OF A PARAMETRIC MOBILE PROGRESSIVE DEFORMABLE BARRIER (P-MPDB)**

Concerning the future real-world vehicle-to-vehicle crash target scenario for microcars, only general trends can be discussed:

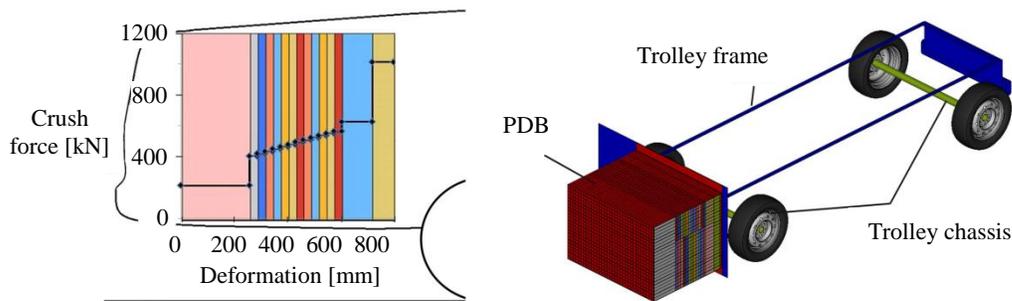
- Relevant crash opponent mass: The arguments related to fuel saving and emission reductions specially in urban traffic environment lead to significant lightweighting efforts in vehicle development, possibly leading to lower average vehicle weight (*Luttenberger et al., 2013*). *Wismans et al. 2013* identify 1,150 kg curb weight as average front crash opponent weight for possible future urban microcars.
- Impact speed: It is unclear, how far the use profile of future urban microcars will be restricted to urban traffic environment, resulting in lower relevant crash speeds. In the same form the future penetration of advanced driver assistance systems related to collision mitigation into the vehicle fleet might have an impact speed reducing effect.
- Impact angle: with a possible use concentration of microcars to urban areas, the relevance of accidents with oblique impact direction in turning and crossing traffic is supposed to grow in relation to conventional head-on collisions (*Wismans et al., 2013*).

The current MDPB test configuration requires a parametric adaptation to fit more to the possible traffic scenario developments and the resulting real world vehicle-to-vehicle front crashes involving microcars.

For a better understanding of the relevance of different vehicle-to-vehicle crash parameters (opponent vehicle mass properties and configuration parameters like impact speed and angle) on the resulting crash severity for the lighter crash partner, vehicle-to-vehicle crash sensitivity tests are executed on a virtual level. To eliminate the influence of specific structural properties of exemplary vehicle models on crash severity output parameters, vehicles with idealized form and force compatibility properties are used for these tests. For this purpose vehicle models with homogeneous energy absorbing honeycomb structures filling the front vehicle are defined (c.f. *Figure 1, left*). These idealized front vehicles show progressive stiffness comparable to the lower load path within the PDB. The only remaining incompatibility property within the sensitivity test set is related to mass, representing different vehicle-to-vehicle crashes with mass ratio between 1:1 and 1:2.8.

The executed sensitivity testing allows the formulation of approximately linear dependencies between crash configuration parameters and the crash severity output. Based on this assessment, the implementation of the following parameters into a parametric model of the MPDB FE model is decided (c.f. *Figure 1, right*):

- Centre-of gravity in x-direction (driving direction),
- Total barrier mass and
- Inertia properties of barrier (defined as dependent on total barrier mass).



**Figure 1** Idealized vehicle front model (left) and its correspondence to the P-MPDB FE model (right)

The barrier model's main property is to represent real front crash opponent vehicles of different possible total mass. To model the mass-dependent inertia properties of a broad range of vehicles, the inertia values expressed as function of mass are implemented into the FE model of the barrier, based on fleet measurements as discussed by *Bosch-Rekvelde et al., 2006* (c.f. Equations 1-3).

$$I_{XY} = 0.0497 \cdot m^{1.4879} \quad (1.)$$

$$I_{XZ} = 0.0289 \cdot m^{1.5572} \quad (2.)$$

$$I_{YZ} = 0.0256 \cdot m^{1.3644} \quad (3.)$$

with  $m$  [kg];  $I_{ij}$  [ $\text{kg}\cdot\text{m}^2$ ]

Besides this adjustability of the barrier itself, also the influence of change of crash configuration parameters is to be analyzed. Therefore a range of impact speeds and angles are to be considered to represent different possible front crash scenarios. The barrier overlap is fixed to 50 % of the vehicle width, to allow a meaningful assessment of microcars structural performance in case of one sided loading of its energy absorbing structures.

## DEMONSTRATION OF P-MPDB USE POTENTIAL - STRUCTURAL CRASH BEHAVIOUR

In a next step, the use potential of the P-MPDB test configuration is to be quantified. The focus of this analysis is double:

- Show the advantages of this test set-up for microcar assessment in comparison to conventional offset crash test procedures.
- Identify the capacities and limitations of the test set-up to reproduce different crash severity aspects of vehicle-to-vehicle crash in different possible crash configurations.

For this assessment, three reference electric vehicle examples, being potential representatives of future urban microcars, are analysed in FE modelling environment concerning relevant structural crash severity output parameters in front crash situations:

Reference electric vehicle model 1 (REVM1) represents a light weight vehicle (curb weight = 685 kg), designed according to M class vehicle standards and therefore dimensioned to fulfil M class front crash regulation targets (Puppini *et al.*, 2013).

Reference electric vehicle model 2 subversion 8 (REVM2\_V8) is representative for vehicles situated at the borderline of the L7e-CP vehicle category (curb weight = 513 kg, including battery system weight), using conventional design tools and materials not considering any structural passive safety requirement. This design strategy results in a behaviour comparable to the ones of current heavy quadricycles (*c.f. Euro NCAP, 2014*), showing weak structures resulting in high crash deformations but soft deceleration pulses. Reference electric vehicle model 2 subversion 9 (REVM2\_V9) shows the same structure and weight properties as REVM2\_V8, but applies high performance materials, therefore showing stiff structural design resulting in low crash deformations but hard deceleration pulses. (Hinc, 2015)

Possible M class crash opponent vehicles to simulate real world vehicle-to-vehicle front crash are taken from the FE vehicle model pool of generic car models (GCM) (Stein *et al.*, 2012).

### P-MPDB use benefit in baseline crash configuration

The first step of the use potential assessment of the P-MPDB consists of a comparison between a chosen baseline vehicle-to-vehicle front crash, different standard barrier front crash tests and front crash against P-MPDB in a mass property version adjusted to the chosen crash opponent vehicle. This assessment step allows to proof whether the defined test set-up shows a higher potential to reproduce the baseline real-world front crash than known standard laboratory tests. For this purpose the baseline vehicle-to-vehicle front crash configuration is chosen to be the same as the reference for the definition of the 56 km/h ODB front crash according to ECE regulation No. 94 (Lowne, 1994):

- 50 % horizontal overlap
- 50 km/h impact speed (100 km/h closing speed)
- 0 deg impact (in-line impacting)

The generic car model 2A (GCM2A) is selected as reference opponent (curb weight: 1,186 kg), at is has a weight comparable to the average front crash opponent weight for future urban microcars identified above. Standard front crash tests (ODB front crash test, according to *UN-ECE Regulation No. 94* and the PDB front crash test as described in *Regulation No. 94 – Proposal for draft amendments*) and the MPDB test are compared to the P-MPDB test (*c.f. Table 1*). For every assessed microcar in each barrier crash configuration the percentile variation of the structural crash severity parameters is calculated in comparison to the vehicle-to-vehicle reference crash output according to Equation 4.

$$Variation = \frac{(parameter_{veh-to-barrier} - parameter_{veh-to-veh})}{parameter_{veh-to-veh}} \cdot 100 \quad (4.)$$

To condense the percentile variation for the three used microcar types into one index value per crash severity parameter, the root mean square (RMS) of the percentile variation of each parameter is calculated (*c.f. Table 1*). The RMS was chosen because it penalizes big differences with few occurrences over small differences with many occurrences and prevents that positive and negative values may compensate each other leading into unrealistic interpretations. The test set-up with the smallest parameter variation with respect to the vehicle-to-vehicle crash reference is highlighted in blue.

**Table 1**  
**RMS of crash severity parameter deviation between baseline vehicle-to-vehicle crash (opponent: GCM2A) and examined vehicle-to-barrier tests**

<b>REVMx vs.</b>	<b>P-MPDB</b>	<b>MPDB</b>	<b>ODB</b>	<b>PDB</b>
Barrier properties	MDB- 1,336 kg	MDB - 1,500 kg	Fixed barrier	Fixed barrier
Test configuration parameters	50 - 50 km/h 50 % overlap	50 - 50 km/h 50 % overlap	0 - 56 km/h 40% overlap	0 - 60 km/h 50% overlap
<b>Passenger compartment intrusions</b>				
Max. intrusion	20 %	21 %	70 %	37 %
<b>Kinematic behavior</b>				
$a_{x,max}$	10 %	10 %	36 %	29 %
$\Delta v_x$	3 %	6 %	6 %	6 %
Average z-rotation speed	10 %	28 %	25 %	26 %
<b>Crash energy balance</b>				
Deformation energy	12 %	17 %	64 %	45 %
Energy Equivalent Speed (EES)	6 %	8 %	40 %	26 %

Both fixed barrier tests show high deviation from the reference vehicle-to-vehicle crash behaviour, while the MDB tests show a good reproduction capacity. These high deviations are clearly related to the incapacity to reproduce the crash mechanic behaviour of a moving crash opponent vehicle with a fixed barrier test. Meanwhile, the reduction of the moving barrier's total mass from the MPDB mass level (1,500 kg) to the mass of the reference crash opponent GCM2A explains the highest reproduction accuracy of the P-MPDB test.

The calculations leading to the impact speed of 56 km/h in the ODB test (c.f. *Lowne, 1994*) to reproduce a 100 km/h closing speed reference crash between two vehicles assume that the involved vehicles are identical. This is no longer valid when the reference crash shows a high mass ratio between the crash partners. To overcome the intrinsic deficit of fixed barrier crash, not being able to reproduce the kinetic behaviour of a moving crash opponent, the impact speed for light vehicles could be increased. In accordance with this argument additional fixed barrier tests at higher impact speeds are executed for REVM2\_V8 and REVM2\_V9, representing the lightest microcars in the assessment, therefore showing the highest mass ratio in a crash against the GCM2A.

With increasing impact speed the crash severity is increasing for different types of microcars, as REVM2\_v8 represents a weak SEV structure, while REVM2\_v9 represents stiff structural response. Nevertheless, the severity increase is not proportional, resulting in improved reproduction capacity for energetic output parameters but only weak change to the kinematic outputs. Therefore no clear speed value can be identified, that would allow to overcome the intrinsic deficits of fixed barriers, not being able to reproduce the kinematic behaviour of a moving crash opponent.

### **Reproduction limitations for alternative vehicle-to-vehicle crash configurations**

Having identified the use benefit of a P-MPDB test to reproduce vehicle-to-vehicle crashes in baseline configuration, the next step of the examination addresses the oblique crash configuration identified as representative for accident scenarios in turning and crossing traffic within an urban environment (c.f. *Wismans et al., 2013*). It is to quantify how far a P-MPDB based oblique test set-up can reproduce the crash severities occurring for different microcar structures in an oblique crash against the selected crash GCM2A. Table 2 shows the comparison of crash severity output parameters between the two oblique impact configurations for the three examined microcars.

The P-MPDB is capable of producing crash severities that are very well comparable (max. 15 % deviation) or higher than within the comparable vehicle-to-vehicle crash for different types of microcars also under oblique impact direction. Even though the barrier front shows better structural interaction possibilities for the assessed vehicles, the resulting severities in the field of intrusion and deceleration are higher than in the vehicle-to-vehicle crash. This is a result of the large size of the loaded surface of the barrier front under oblique impact angle in comparison to the interacting structures of a crash opponent's vehicle front. The difference between the interacting structures of a homogeneously deforming barrier and any given vehicle front geometry represents the intrinsic deficit of a MDB

test to reproduce a vehicle-to-vehicle crash. The relevance of this limitation is dependent on the impact angle, as the relative position of the interacting structures is influenced by the orientation of the crash partners.

**Table 2**  
**Comparison of crash severity indicators: vehicle-to-vehicle and vehicle-to-P-MPDB crash**

Assessed microcar	REVM1		REVM2_V8		REVM2_V9	
	GCM2A	P-MPDB	GCM2A	P-MPDB	GCM2A	P-MPDB
Crash opponent	1,336 kg					
Crash configuration parameters: Overlap 50 %, impact speed 35 – 35 km/h, opponent impact angle 30 deg						
Passenger compartment intrusions						
Max. intrusion [mm]	67.2	170	197	270	53.1	51.8
Kinematic behaviour						
$a_{x,max}$ [g]	28.7	30.7	25.9	30.8	34.0	42.0
$\Delta v_x$ [m/s]	11.5	13.2	10.97	11.75	10.72	10.92
$\Delta v_y$ [m/s]	6.25	5.5	5.7	5.15	5.82	5.02
Crash energy balance						
Deformation energy [kJ]	28.3	38.6	41.0	43.9	30.8	24.6
EES [m/s]	8.22	9.61	11.1	11.5	9.59	8.58
Legend: green = deviation from reference <15 %; red = severity is > 15 % higher than in vehicle-to-vehicle crash; yellow = severity is > 15 % lower than in vehicle-to-vehicle crash						

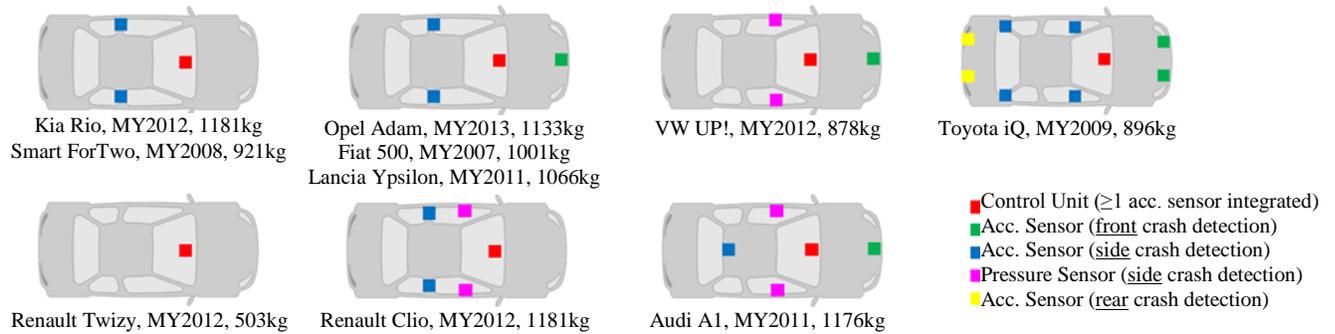
## CRASH RESTRAINT SYSTEM TRIGGERING

Overall goal of vehicle to barrier tests is the reproduction of a real world vehicle to vehicle crash situation. Besides the right deformation of the vehicle it is also important to predict or rather assess the passive safety sensors and the restraint system of the tested vehicle. Comparable to a state-of-the-art vehicle development process the virtual sensor evaluation for front crash safety represents one key part within the SafeEV project development of an advanced simulation methodology for consistent safety analysis of electric microcars.

First step within the virtual sensor evaluation process is to define the sensor layout for the microcar. Therefore sensors have to be positioned at suitable areas within the vehicle. The typical sensor layout for small state-of-the-art vehicles is shown in *Figure 2*.

For accurate detection of frontal crashes at least one acceleration sensor for detection and one for the plausibility verification are used. The external satellite sensors (green in *Figure 2*) can be damaged or switched off during crash after the restraint system has been triggered. The electronic control unit (ECU) must remain intact even after the crash event because of crash data recording. The acceleration sensor should be mounted on a stiff structure within the vehicle. Regular driving mode and misuse crashes like driving through a pothole should not cause a high excitation at the sensor position. In state-of-the-art vehicles the sensors are typically mounted at the vehicle tunnel or the pillars. If the vehicle structure of microcars changes strongly compared to these types of vehicles, a sensor on the left and right rocker sill can be placed instead of a central sensor at the tunnel.

The most important requirement for the virtual application of the sensor system is a good matching of acceleration crash signals between the real-world vehicle and the virtual model. Therefore the crash signals should be compared with state-of-the-art vehicles to check the plausibility of the virtual crash data. After defining the sensor position within the vehicle a crash set of different crash types must be generated including fire (e.g. ODB 40%, 64kph), no-fire (e.g. RCAR Bumper Test) and misuse (e.g. driving through a pothole) crashes. Via a simplified application procedure the trigger times for the restraint system are determined. The applied algorithm procedure consists of a standalone core part, which provides a capable base performance, and support functions, which consider the vehicle specific characteristics (c.f. *Kärner et al., 2008*).



**Figure 2** Sensor layout in small state-of-the-art vehicles according to A2Mac1 database

Since the used vehicle FE models in the SafeEV project are not suitable for the simulation of certain misuse cases only fire and nofire crash types are taken into account for the simplified application procedure. The advantage of the used algorithm application procedure is that the calibration of the use crashes is independent of the misuse crashes. Thus trigger times can be estimated by using the fire and no fire crash signals in the application procedure. However for the final determination of the trigger times the misuse crash signals are absolutely necessary. If misuse crash signals are included in the application procedure, a later triggering of restraint system may be obtained.

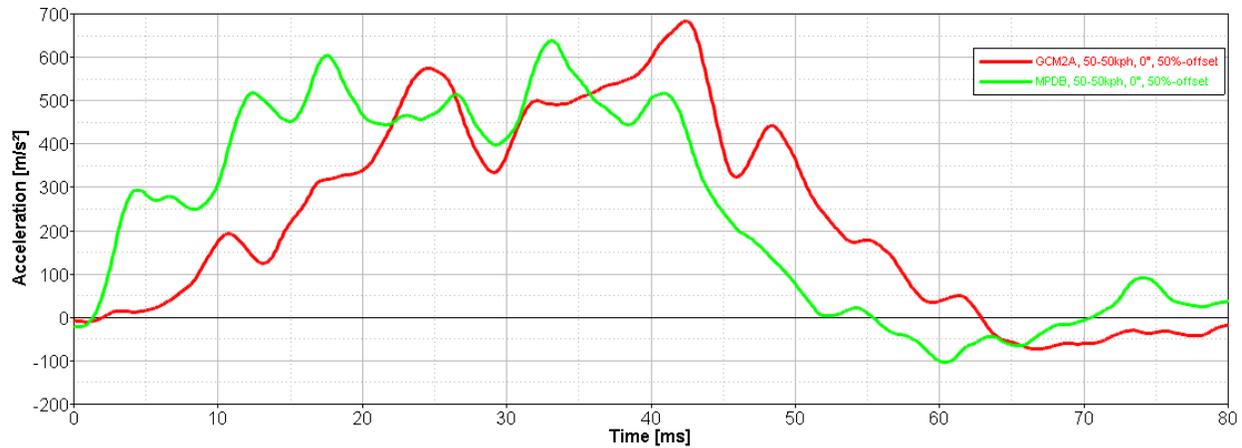
The application process in today's series algorithm calibration works contrary to the above described procedure. Generally the vehicle manufacturer first performs occupant simulations, defines the necessary triggering times for belt pretensioner and airbag for each crash and delivers the trigger times to the airbag control unit supplier. Afterwards the supplier adapts his algorithm to the customer needs. Through in-depth analysis of the vehicle crash pulses according to an extended and customer defined crash set the required trigger times are realized through an advanced version of the described application procedure.

The determined trigger times for the belt pretensioner and the first and second deployment stage of the airbag are shown in the Table 3 for REVM2\_V9 as a result of the simplified crash signal calibration. The determined trigger times are compared with publicly available trigger times from state-of-the-art small vehicles like the Smart Fortwo and Fiat 500 (IIHS database) and Renault Twizy (EuroNCAP database). The determined trigger times for SafeEV's microcars are lower than the trigger times of above small vehicles. The main reason for this effect is the combination of REVM2\_V9 low weight and high stiffness. High acceleration signals are measured earlier at the vehicle tunnel during the crash process resulting in an earlier triggering of the restraint systems. Nevertheless it should be verified if available in-crash sensors are capable to generate adequate crash signals in order to realize such an earlier triggering. Additional possible solutions would be more sensors in the vehicle front (upfront sensors) or environment sensing coupled with reversible or irreversible restraint systems, like electronic belt tensioner. Another alternative is to adapt the restraint systems, i.e. overall shorter deployment times.

**Table 3**  
Crash set for REVM2\_V9 for assessment of restraint system triggering time for front crashes

Vehicle	Crash Type (Opponent)	Impact Velocity [km/h]	Belt Pretensioner / Airbag 1 <sup>st</sup> Stage [ms]	Airbag 2 <sup>nd</sup> Stage [ms]
Smart ForTwo	ODB 40%	64	22	-
Fiat 500	ODB 40%	64	20	-
Renault Twizy	FWDB, 0°	50	24	-
REVM2_V9	ODB 40%	64	16.6 - 17.6	21.6 - 22.6
REVM2_V9	P-MPDB 50%, 0°	50 / 50	8.8 - 9.3	13.8 - 14.3
REVM2_V9	P-MPDB 50%, 30°	35 / 35	20.3 - 20.8	25.3 - 25.8
REVM2_V9	GCM2A 50%, 0°	50 / 50	23.2 - 24.1	28.2 - 29.1

The analysis of the use potential of the P-MPDB has shown that the reproduction of a vehicle-to-vehicle crash is generally possible. Although a good correlation in vehicle deformation between REVM2\_V9 vs. P-MPDB and REVM2\_V9 vs. GCM2A can be shown (see section “P-MPDB use benefit in baseline crash configuration”), the obtained trigger times for the P-MPDB crash (cf. Table 3) are much lower than for the vehicle-to-vehicle crash. This can be attributed to the higher crash signal of the P-MPDB crash in the early stage of the crash (see *Figure 3*).



**Figure 3** Comparison of acceleration signal from REVM2\_V9 vs. GCM2A / P-MPDB

The estimated occupant forward displacements at the calculated trigger times for both crash types can be shown to be almost in the same range. In case of the REVM2\_V9 vs. GCM2A crash the triggering of the restraint system occurs later but the occupant forward displacement is also slower than in the P-MPDB crash. Thus the same safety level for the occupant can be realized. The vehicle deformation and occupant safety of vehicle to vehicle crashes can be well reproduced by vehicle to P-MPDB barrier crash. However for the calibration of the restraint system triggering algorithm it makes a difference, since the signals must be processed differently.

### MICROCAR OCCUPANT INJURY PREDICTION IN OBLIQUE CRASH CONFIGURATION

For the assessment of the crash severity for the occupant a reduced sled model and the Human Body Model (HBM) “THUMSv4.0” was used. The results are then assessed with an injury prediction tool developed at the Vehicle Safety Institute in Graz. First a short summary of the models will be given. Secondly a review of energy, strain and stress based prediction for injuries is shown for the oblique crash configuration identified as representative for accident scenarios in turning and crossing traffic within an urban environment (c.f. *Wismans et al., 2013*).

The THUMSv4.0 was introduced in 2010 and is the latest version of Toyota’s HBM research activities in this field. The geometric data was obtained from computed tomography scans of a human male (173 cm, 77.3 kg) and scaled to a 50 percentile human. Due to the more detailed model and improved bio-fidelity injuries and injury criteria can be assessed. The validation of the model was done by running different loading situations on the human body regions (i.e. head or abdomen) and parts. For example, translational impacts, belt loading, 3-point bending, dynamic and quasi static tests, etc. were simulated (*Toyota Motor Company, 2011*). The sled model was derived from the microcar REVM2\_V9 and was reduced to the most important components for occupant safety analysis. As the original vehicle model has no interior parts the used parts were extracted from a Ford Taurus, available at the *NCAC download area*.

The used restraint system within the model was implemented by a project partner. This system was not well optimized for the oblique crash configuration itself, but delivers sufficient response quality on injury severity to assess the output sensitivity on crash configuration parameter change. The usual restraint system models within the solver are used and the values for the numerical simulation runs were set to:

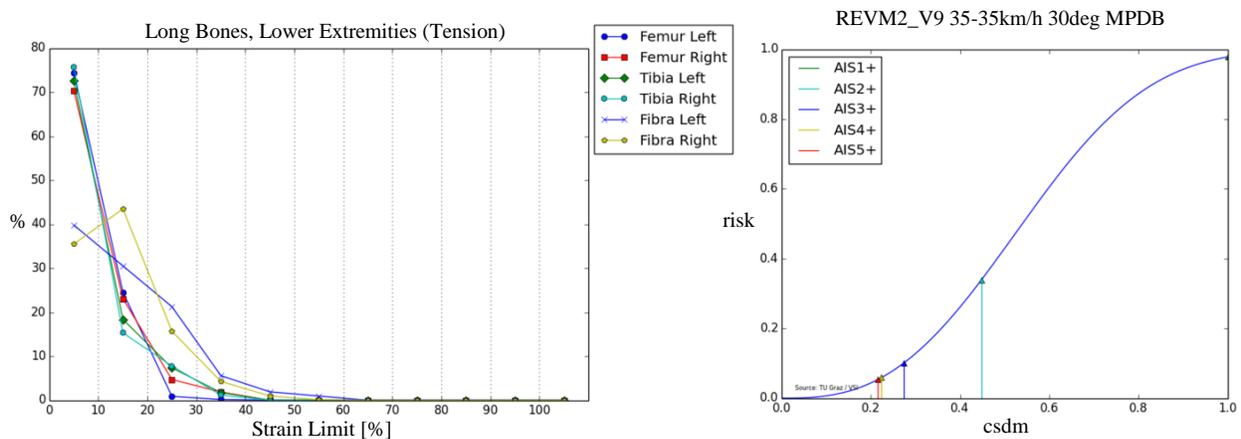
- Airbag Fire Time = 20.0 ms
- Pretensioner Fire Time = 20.0 ms
- Force Pretensioner = 1.5 kN
- Force Load Limiter = 4 kN

The assessment of the simulation results was performed with the injury tool. The development of the tool was necessary as already available post-processors are not capable of handling the amount of data caused by a detailed HBM and the evaluation procedure and injury criteria cannot be implemented easily. The injury tool includes following assessment groups in the latest version:

- Rib Fractures, Organ Damage, Bone Fractures, Head Injury, Ligament Elongation.

For the analyzed oblique front crash configuration the Strasbourg University Finite Elements Head Model (SUFEHM) criteria level is very low (probability of injury ~1 %). The Cumulative Strain Damage Measure (CSDM) criterion has an AIS3+ probability of 10 % for the load case. The probability for rib fracture was calculated with 83.6 % for 4 fractures and 16.4 % for 3 fractures. From the Abbreviated Injury Scale (AIS) codebook it is known that 4 fractured ribs would be classified as AIS3. The fractures occur in the shoulder area and next to the sternum. For the assessment of organ injuries the selected thresholds predict a probability of a possible damage varying from 38 % to  $\geq 100$  %.

In *Figure 4* the head and lower extremity assessment is shown. For the CSDM an injury risk curve is already available.



**Figure 4** Head and lower extremity assessment for REVM2\_V9

In case of the long bones and strain-stress based injury prediction no risk curve was found. For the bones only the cortical volume was used. 100 % of strain limit in the diagram is the predefined threshold for long bones. The ordinate shows the fraction of elements of the cortical parts reaching a certain value based on the threshold.

## GENERAL USE RECOMMENDATIONS FOR THE P-MPDB TEST CONFIGURATION

The proposed virtual test shows good ability to reproduce the hazards arising for microcars within a car-to-car front crash and exceeds the use potential of common tests using fixed deformable barriers as crash targets. The advantage of the defined set-up in comparison to conventional tests is growing with shrinking mass of the assessed microcar. All configuration parameters of a vehicle-to-vehicle crash can be implemented directly into the P-MPDB crash set-up.

The comparison between the P-MPDB test and vehicle-to-vehicle front crashes quantifies the capacities of barriers to reproduce vehicle crash opponents. Visible limitation appears due to the barrier's homogeneous energy absorption properties in planar direction in comparison to exemplary crash opponent front structures. The relevance of this limitation is dependent on the impact angle, as the relative position of the interacting structures is influenced by the orientation of the crash partners. This effect cannot be overcome as long as a neutral assessment of the vehicle

should be assured, inhibiting optimization related to single selected opponent structures. Furthermore the resulting higher structural crash severities in a P-MPDB test are supposed to be beneficial to the crashworthy development of future microcars.

Through a simplified algorithm procedure plausible trigger times for an adequate in-crash triggering of the restraint systems could be achieved for the proposed test set-up. In comparison to a vehicle-to-vehicle crash against M class opponents, a microcar's restraint system triggering has to occur earlier as the occupant's forward displacement is faster during a P-MPDB crash.

The deceleration based occupant injury predicted for the oblique impact crash appears to be well controlled with common restraint system functioning also for microcars showing stiff structural response. The lateral displacement and rotation effect of an oblique impact on the microcar nevertheless is challenging for the effective interaction between occupant and front airbag.

## REFERENCES

A2Mac1 database <https://www.a2mac1.com>

Bosch-Rekvelde, M.; Versmissen, T.; van der Zweep, C.; Mooi, H.; McEvoy, S., 2006. "The Development of a Load Sensing Trolley for Frontal Offset Testing". Conference ICrash 2006. Athens / Greece

Directive 2007/46/EC of the European Parliament and of the Council of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles

EURO NCAP, 2014. Euro NCAP tests on Heavy Quadricycles, [www.euroncap.com](http://www.euroncap.com)

Hinc, K., 2015. „SafeEV Deliverable No. 3.7 – Report on final test configuration and evaluation criteria”. Graz/Austria

Kalmbach, R.; Bernhart, W.; Grosse Kleinmann, P.; Hoffmann, M., 2011. „Automotive landscape 2025 – Opportunities and challenges ahead”. Roland Berger Strategy Consultants, 03/2011

Kärner, C.; Körner, O.; Kolatschek, J., 2008. „Usage of FEA methods in order to ensure integration and application in the restraint system control in early development phase”. 9<sup>th</sup> International Symposium and Exhibition on Sophisticated Car Occupant Safety Systems. Karlsruhe/Germany

Lowne, R., 1994. "EEVC Working Group 11 report on the development of a frontal impact test procedure". 14th international technical conference on Enhanced Safety of Vehicles. Munich/Germany

Luttenberger, P.; Tomasch, E.; Willinger, R.; Bourdet, N.; Mayer, C.; Ewald, C., 2013. "SafeEV Deliverable No.1.1 – Methodical analysis on future accident scenarios involving SEVs". Graz/Austria

NCAC download area - <http://www.ncac.gwu.edu/>

O'Brien, S., 2010. "Measurement and Assessment of Passenger Vehicle Compatibility in Front and Side Collisions". Faculty of Engineering, RMIT University, Melbourne / Australia

Puppini, R.; Puleo, G.; Hinc, K. M., 2013. "SafeEV Deliverable No.3.1 – Reference Electric Vehicle Models". Graz/Austria

Regulation (EU) No 168/2013 of 15 January 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles

Regulation No. 94 – Proposal for draft amendments, 2007. Proposal submitted by France. Working Party on Passive Safety of GRSP, 42. Session. Geneva/Switzerland.

Safe Small Electric Vehicles through Advanced Simulation Methodologies – [www.project-safeev.eu](http://www.project-safeev.eu)

Stein, M.; Johannsen, H.; Puppini, R., 2012. „FIMCAR Models for the Assessment of Frontal Impact Compatibility” iCrash Conference 2012. Milan/Italy

Toyota Motor Company, Toyota Central R&D Labs, Inc. 2011. Documentation – AM50 Occupant Model: Academic Version 4.0

Uittenbogaard, J.; Versmissen, T., 2013. “FIMCAR-Frontal Impact and Compatibility Assessment Research, Part IX - MDB Test Procedure: Initial Test Protocol”. Technische Universität Berlin, Institut für Land- und Seeverkehr, Universitätsverlag der TU Berlin

UN-ECE Regulation No. 94, Revision 1, Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision

Wismans, J.; Davidsson, J.; Carlsson, A.; Mayer, C.; Luttenberger, P.; D’Addetta, G. A.; Hinc, K. M.; Dux, E.; Nuss, F.; Willinger, R., 2013. “SafeEV Deliverable No.2 - Report on test conditions and evaluation criteria for occupant and vulnerable road user protection of small electric vehicles”. Graz/Austria