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FIMCAR
VII –Full Width Test Procedure: Review and Metric Development

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CONTENT

EXECUTIVE SUMMARY

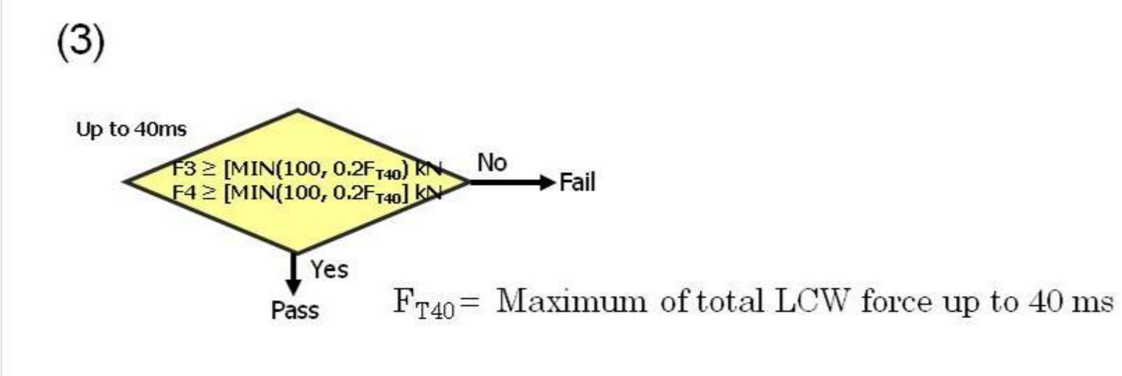
For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. Taking into account the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) and the FP5 VC-COMPAT project activities, two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

The overall objective of the FIMCAR project is to complete the development of the candidate test procedures and propose a set of test procedures suitable for regulatory application to assess and control a vehicle's frontal impact and compatibility crash safety. In addition an associated cost benefit analysis should be performed.

The objectives of the work reported in this deliverable were to review existing full-width test procedures and their discussed compatibility metrics, to report recent activities and findings with respect to full-width assessment procedures and to assess test procedures and metrics.

Starting with a review of previous work, candidate metrics and associated performance limits to assess a vehicle's structural interaction potential, in particular its structural alignment, have been developed for both the Full Width Deformable Barrier (FWDB) and Full Width Rigid Barrier (FWRB) tests. Initial work was performed to develop a concept to assess a vehicle's frontal force matching. However, based on the accident analyses performed within FIMCAR frontal force matching was not evaluated as a first priority and thus in line with FIMCAR strategy the focus was put on the development of metrics for the assessment of structural interaction which was evaluated as a first priority.

The FWDB and FWRB tests both have advantages and disadvantages. The metrics developed for these tests also have advantages and disadvantages. FIMCAR WP3 members have discussed these advantages and disadvantages and recommend that priority is given to the further development of the FWDB test and FWDB metric (3) as shown below.



The reasons for selecting the FWDB as 1st priority are:

- The FWDB test has the edge technically over the FWRB test because there is no need for a supplementary test. Also the structural interaction assessment is made later in the impact than for the FWRB test which, because the vehicle's crash structures are more fully loaded, allows a more meaningful assessment of them.

- The FWDB metric (3) is recommended because its correlation with a geometric assessment of the vehicle is as good as the other FWDB metric candidates, it is a single stage metric which follows the spirit of keeping the metric as simple as possible and effectively it allows the mass of the vehicle to be taken into account in the performance requirements.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. From the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) [Faerber 2007] and the FP5 VC-COMPAT project activities [Edwards 2007], two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

Within the FIMCAR project off-set, full overlap and MDB test and assessment procedures will be developed further with the ultimate aim to propose a compatibility assessment approach. This should 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 FIMCAR consortium and to disseminate the project results early, taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (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 car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objectives of this Deliverable

The objectives of the work reported in this deliverable were to review existing full-width test procedures and their discussed compatibility metrics, to report recent activities and findings with respect to full-width assessment procedures, to assess test procedures and metrics and to start the development of FIMCAR metrics.

2 BACKGROUND

The overall aim of FIMCAR is to develop a suite of test procedures which address self and partner protection in order to decrease the injury risks in single and multiple vehicle frontal impact accidents. It is expected that compatible vehicles will deform in a stable manner allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved. In Europe, at present, one Offset Deformable Barrier (ODB) test procedure is used for regulatory and consumer testing. Essentially, this test procedure addresses a vehicle’s self protection but not its partner protection.

From a review of previous research, such as the EEVC WG15 [Faerber 2007], VC-COMPAT project [Edwards 2007], and IHRA [O'Reilly 2003], and additional accident analysis [Thompson 2013], FIMCAR members have set priorities for the development of the test procedures. The top priorities with respect to this report are that the test procedures should address structural interaction, high overlap collision types and the risk of injuries arising from acceleration loading.

The main structural interaction problems identified in FIMCAR Deliverable D1.1 [Thompson 2013] were under/overriding, low overlap and the fork effect. In order to address the under/overriding aspect of structural interaction, structural alignment was considered a necessary but not totally sufficient first step. To address structural alignment, it was decided to use the approach that all vehicles should have crash structures in alignment with a common interaction zone. The US voluntary commitment for a common vertical interaction zone [Barbat 2005] was considered as a good starting point. A further step to address under/overriding is load spreading in the vertical direction. This can be achieved with vehicles that have multi-level load paths and strong connections between them. Load spreading in the horizontal direction is also an important factor for prevention of the fork effect and addressing accidents with small overlaps. Strong cross beams can help provide good interaction in accidents with narrow objects and cross beams extending outboard from longitudinal members can improve structural interactions in cases with small overlap at the corners.

As regards the assessment of structural interaction, the approach proposed in FIMCAR is that structural alignment in the vertical direction is assessed with a full width test using a load Cell Wall (LCW). At the same time a small step towards the assessment of vertical load spreading can be achieved. It is proposed that this will be achieved using the ‘common interaction zone’ concept.

The purpose of the work reported in this document was to investigate further the use of a Full Width Rigid Barrier (FWRB) or Full Width Deformable Barrier (FWDB) test as a candidate for assessing structural alignment for vehicles. The test severity of the selected full width test should also promote further development of occupant restraint systems for additional protection in crashes with high acceleration levels such as high overlap cases. The possibility of introducing force matching metrics in a full width test has been investigated as it is desirable that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy. However this last item has not been judged as a first priority, because compartment strength of lighter cars was not identified as a specific issue in accident data analyses.

For both full width tests, Load Cell Wall (LCW) data is being investigated as a method to assess the structural interaction characteristics of a vehicle by measuring the vehicle’s force distribution. The current defacto standard for a LCW is one that consists **of 125 mm square elements** with the bottom row mounted with an **80 mm ground clearance** (Figure 2.1).

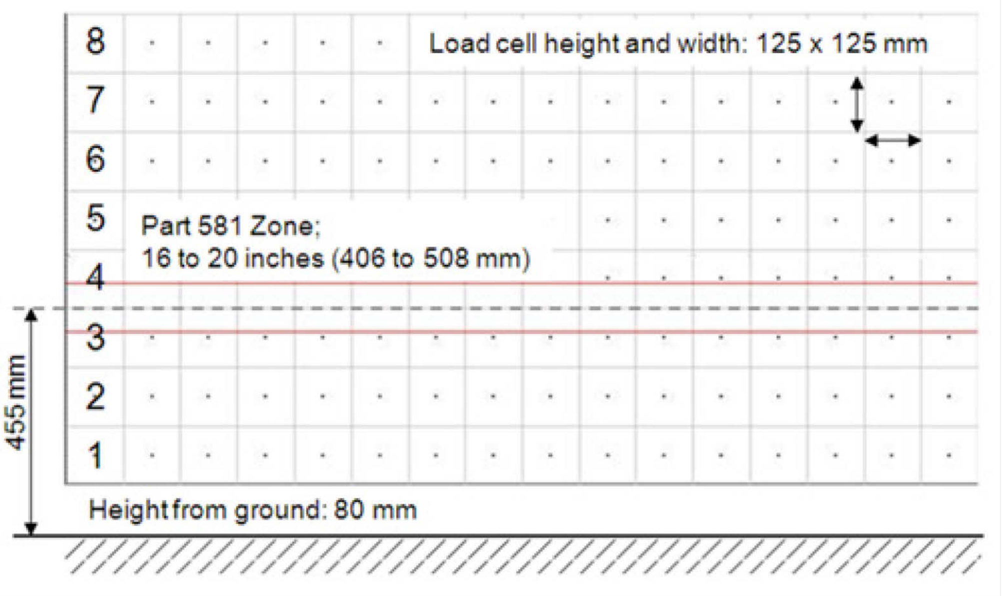


Figure 2.1: Overview of the specifications of the LCW (rows, columns, height of ground, Part 581 zone).

The FWRB test is conducted in many countries (USA, Canada, Japan etc.) for both regulation and consumer testing programs. Test speeds range from 50 km/h to 56 km/h. Instrumented Hybrid III dummies are typically used to measure occupant response.

The FWDB test has a 300 mm deep deformable element as shown in Figure 2.2 [Edwards 2003].

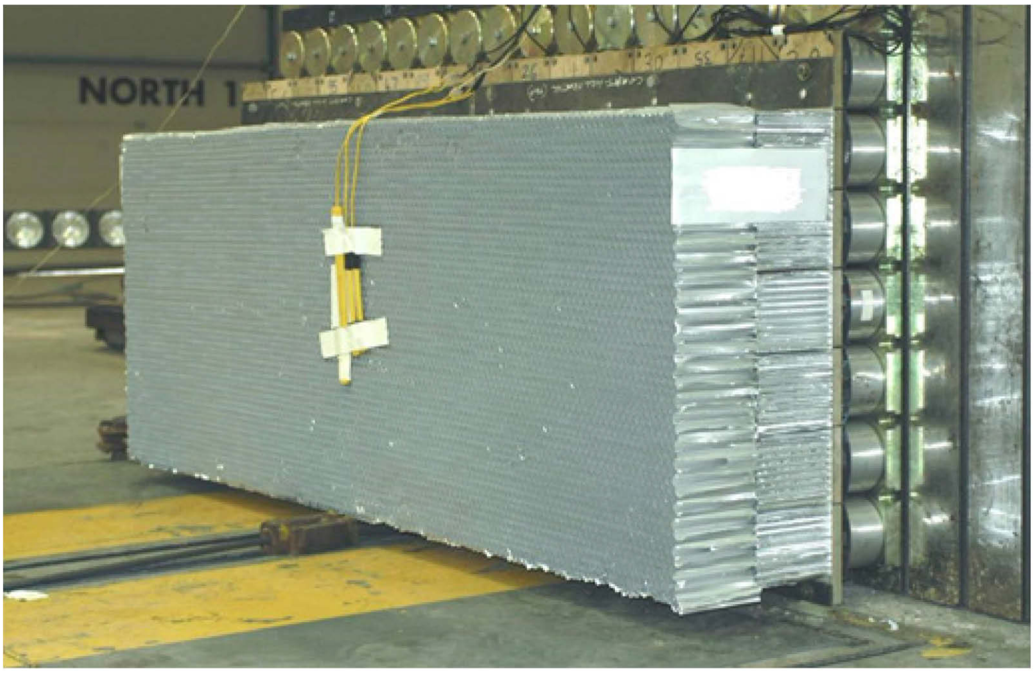


Figure 2.2: Full Width Deformable Barrier.

The FWDB is currently only used in research applications and is not part of a regulation or consumer test procedure. As with the FWRB, tests are conducted with Hybrid III dummies to assess occupant response. Although essentially the same test configuration as the FWRB, the additional honeycomb is included to help make the test more representative of real world accidents, especially in the initial stage of the impact. This is important for sensing of the crash for restraint system triggering. The barrier consists of two layers, each 150 mm deep. The first layer consists of 0.34 MPa axial crush strength honeycomb and the second layer 1.71 MPa crush strength honeycomb. The second layer is segmented into 125 mm x 125 mm blocks which align with the individual cells of the LCW to prevent the deformable face spreading loads applied in one area over a wider area on the LCW. The general hypothesis is that vehicles with better structural interaction potential should produce a more even load distribution in the FWDB test. The main purpose of the front layer is to attenuate engine dump loads and make them more similar to those seen in a car-to-car impact. The main purpose of the rear layer is to prevent localised stiff structures on the car, such as protruding bolts and towing eyes which would have little / no influence in a car-to-car impact, forming preferential load paths to the wall and hence altering the LCW force distribution in an unrepresentative manner by reducing the loading from adjacent structures [Edwards 2003]. Furthermore, the deformable face can help detect Secondary Energy Absorbing Structures (SEAS) and hence assess them because the deformable face ‘reaches’ into the vehicle and allows these structures to load the wall even though they may not be in direct contact with it. On the other hand, the possible risk of load spreading due to the deformable element can be counted as a disadvantage compared to the rigid barrier.

3 ASSESSMENT CRITERIA DEVELOPMENT

This section is divided into three parts. The first part describes a review of current and previous criteria. This determines a starting point for the development of a new / revised metric and helps to give an understanding of how to develop a metric. The second part describes the advantages and disadvantages of the Full Width Deformable Barrier (FWDB) and Full Width Rigid Barrier (FWRB) tests and the third part the development of the metrics. New metrics were developed for both the FWDB and FWRB tests including the development of proposals for performance limits.

3.1 Review of Current and Previous Assessment Criteria

Over the last ten years a number of assessment criteria have been developed for the Full Width Rigid Barrier (FWRB) and Full Width Deformable Barrier (FWDB) tests. The aim of these criteria was to assess and control a vehicle's compatibility, in particular its structural interaction potential and in some cases its stiffness. To date none of these criteria have been deemed suitable for consumer and / or regulatory testing. The sections below describe the main criteria developed for the FWDB and FWRB tests and the issues with them.

3.1.1 Full Width Deformable Barrier (FWDB)

Three main metrics have been developed for the FWDB test:

- Homogeneity Criterion
- Structural Interaction (SI) Criterion
- Force in a common interaction zone type metric

The development of the deformable face is reported by Edwards *et al.* [Edwards 2003]. The aim of the first two metrics, the homogeneity and structural interaction criteria, was to assess a vehicle's structural interaction potential. These metrics were based on an assessment of the force distribution on a high resolution LCW placed behind the barrier face following the hypothesis that vehicles with better structural interaction potential should give a more even load distribution on the LCW. It should be noted that the structural interaction criterion was developed to resolve issues with the homogeneity criterion. The aim of the third metric, force in a common interaction zone, was to assess a vehicle's structural alignment. This metric was based on the concept that vehicles with a strong structure in alignment with the common interaction zone should apply a high proportion of their load to the rows on the LCW in alignment with the zone.

These metrics and the issues associated with them are described in greater detail in the sections below.

3.1.1.1 Homogeneity Criterion

As mentioned above, the concept which this metric was based on was that vehicles with a better structural interaction potential should give a more even load distribution on the LCW. The homogeneity criterion assessed the LCW force distribution over a footprint [Figure 3.1]. The size of the footprint was defined individually for each vehicle and depended on the size and geometry of the vehicle.

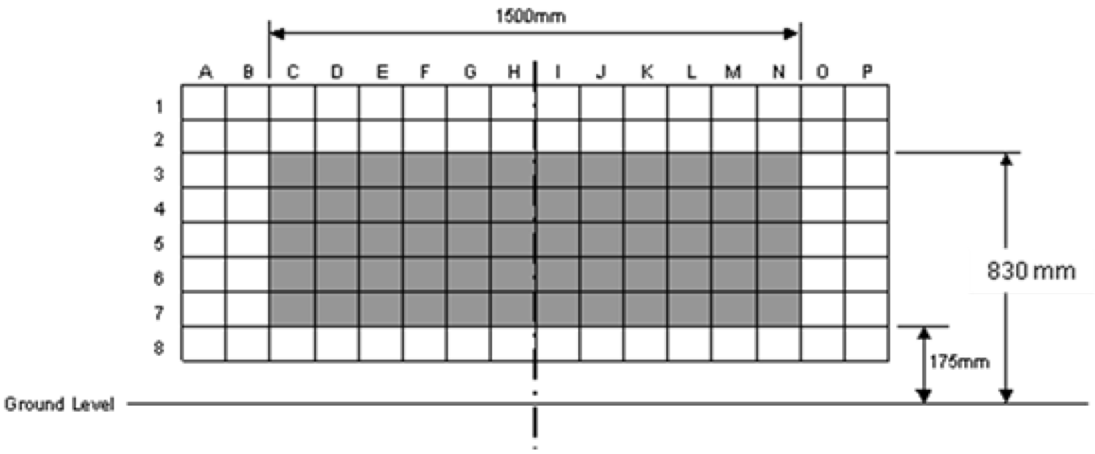


Figure 3.1: Typical dimensions of footprint for calculation of homogeneity criterion for mid-size car. Note in this case the LCW ground clearance was 50 mm. For later work this was increased to 80 mm.

Initially the LCW data was smoothed to reduce sensitivity of the metric to the alignment of the vehicle with the LCW. Following this, the metric was calculated by summing the difference squared between peak load (f) and an average load (L) for individual cells (H_{cl}), rows and columns within the vehicle footprint. The cells, rows and columns contributions were then weighted (if deemed necessary) and added together.

$$H_{cl} = \frac{\sum_{i=1}^{{}_s n} (L - {}_s f_i)^2}{{}_s n}$$

where ${}_s$n is the total number of cells within the vehicle footprint after smoothing

Further details of how to calculate this metric can be found in [Edwards 2003].

Later, this metric was developed further to take into account the mass of the vehicle being tested. Specifically, it was normalised using the average load as shown in the formula below and renamed the ‘relative homogeneity criterion’.

$$RH_{cl} = \frac{H_{cl}}{L^2}$$

The following issues were found with the homogeneity criterion:

- Repeatability
  - The sensitivity of the metric to impact alignment was found to be too high to allow acceptable test to test repeatability. This was despite the fact that the LCW data were smoothed to attempt to reduce this.
- Effect of data smoothing
  - Effectively, this caused a reduction in the resolution of the metric and an inability to distinguish adequately between some vehicles.
- Definition of assessment area

  - An objective methodology to determine the footprint (assessment area) for each individual vehicle could not be derived.
- Bottoming out of the barrier face
  - In tests some vehicles bottomed out the barrier face and directly contacted the LCW whereas others did not. There appeared to be a discontinuity in the homogeneity assessment values for these two sets of vehicles which was not dependent on the vehicle's structural interaction potential.

To try and resolve these issues the structural interaction criterion was developed.

3.1.1.2 Structural Interaction (SI) Criterion

The Structural Interaction (SI) criterion was developed to resolve issues with the Homogeneity Criterion. Its development was based on the following requirements:

- An ability to be applied in a stepwise manner to allow manufacturers to gradually adapt vehicle designs
- To encourage better horizontal force distribution (crossbeams).
- To encourage better vertical force distribution (multi-level load paths).
- To encourage a common interaction area with minimum load requirement.

Compared to using peak cell loads recorded throughout the duration of the impact (as with the previous homogeneity criterion), the SI criterion was calculated from the peak cell loads recorded in the first 40 ms of the impact. This has the advantage of assessing structural interaction at the beginning of the impact when it can be more effective and minimising the loading applied by structures further back into the vehicle such as the engine. The 40 ms time interval corresponds to a B-pillar displacement (including barrier crush) of approximately 550 mm for most cars [Figure 3.2].

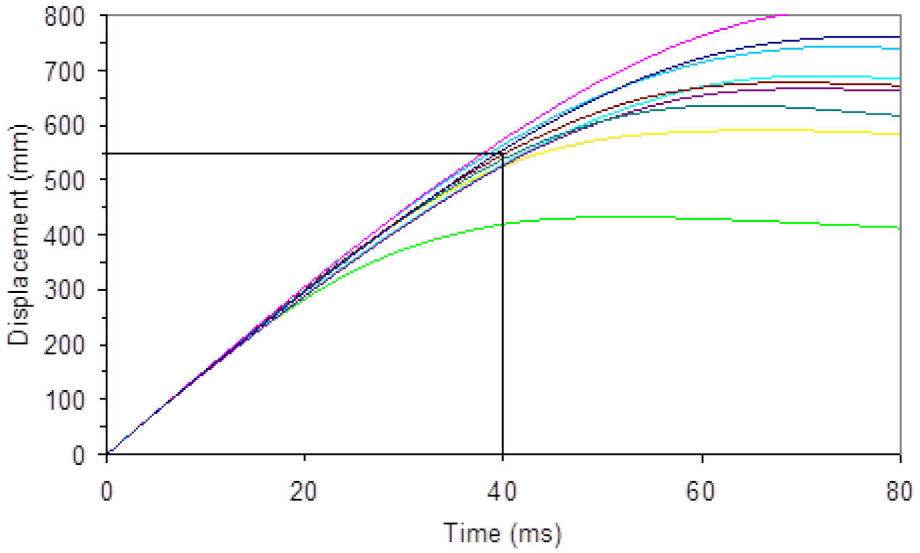


Figure 3.2: B-pillar displacement vs. time plots for FWDB tests. The outlier is a supermini car with unique short stiff frontal structure which restricts its deformation.

Based on the assumption that structures which only crush the 150 mm softer front layer of the barrier will not apply sufficient load to the LCW to be adequately detected, this criteria should allow the detection of structures up to 400 mm (550 mm -150 mm) from the front of the vehicle. This is adequate for detection of most Secondary Energy Absorbing Structures (SEAS), such as subframes, that interact with the partner vehicle in a crash.

To allow manufacturers to gradually adapt vehicle designs to become more compatible, the SI criterion consisted of two parts which could be adopted in a stepwise manner. The first part assessed the forces on the LCW over a common interaction area, an area from 330 mm to 580 mm above ground level, LCW Rows 3 and 4 (Area 1), (Figure 3.3). The intention of this part of the assessment was to ensure that all vehicles had adequate structure in alignment with the common interaction area to ensure good interaction. The second part assessed the forces over a larger area, from 205 mm to 705 mm above ground level, LCW Rows 2, 3, 4 and 5, (Area 2). The intention of this part of the assessment was to encourage cars to distribute their load more homogeneously over a larger area to reduce the likelihood of over/under-ride and the fork effect.

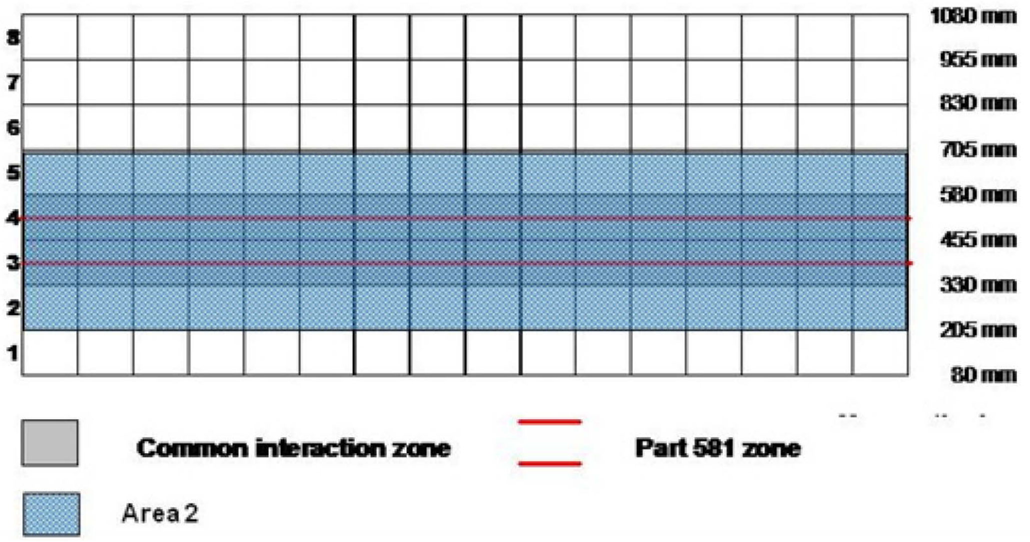


Figure 3.3: Assessment areas for Structural Interaction metric.

Each part of the SI assessment consisted of two components, a vertical component (VSI) and a horizontal component (HSI). The aims of the various parts of the metric are summarised below:

- Vertical component (VSI)
    - Area 1 – common interaction area (Rows 3 & 4)
    - To encourage structural alignment using a requirement of a minimum load of 100 kN in Rows 3 & 4
    - Area 2 (Rows 2, 3, 4 & 5)
    - To encourage vehicles to distribute their loads better vertically using a combination of minimum load and even distribution of load requirements.
- Horizontal component (HSI)
    - Area 1 and 2
    - To encourage vehicles to have strong crossbeam connections which are matched to the strength of the rail.

Further details of how to calculate this metric can be found in [Edwards 2007].

The following issues were found with the structural interaction criterion:

- Repeatability
    - Poor repeatability was observed with the horizontal component of the metric in tests performed in the APROSYS EC 6th framework project [Edwards 2008].
- Differentiation
    - For the SI criterion for Area 2, generally SUVs gave much higher values than cars. Hence, it was not possible to set performance limits that were appropriate to encourage both cars and SUVs to improve their structural interaction potential.
- Complexity
    - In general, the SI criterion was quite complex and difficult to understand.

3.1.1.3 Force in a common interaction zone metric

This metric was developed to enhance the US voluntary commitment for the improvement of the geometric frontal impact compatibility of Light Trucks and Vans (LTVs) [Barbat 2005] and resolve the issues with the Structural Interaction metric described above.

The aim of the US voluntary commitment is to ensure that LTVs have structure in alignment with a common interaction zone from 16 to 20 inches (406 – 508 mm), further named as "Part 581 zone") measured vertically from the ground (Figure 3.4) to enable better interaction with cars. The US voluntary commitment states that all LTVs sold by participating manufacturers in the US should fulfil one of the options below:

OPTION 1

The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone (Option 1a)

AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2

If a light truck does not meet the criteria of Option 1, there must be a secondary energy absorbing structure (SEAS), connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone.

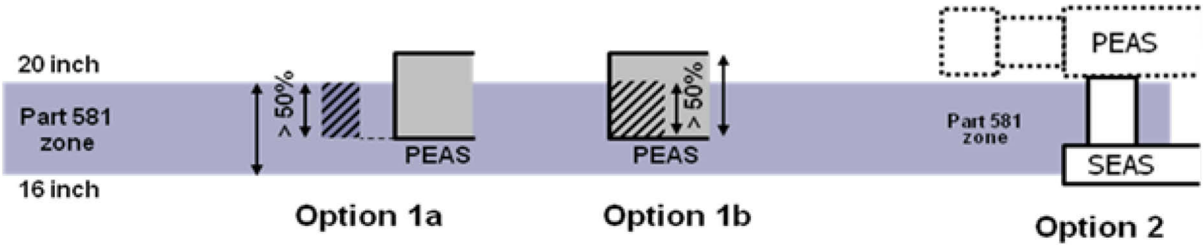


Figure 3.5. US voluntary commitment for improved compatibility of LTVs.

It should be noted that the US voluntary commitment was not felt to be appropriate for regulatory application because ideally regulations should be 'performance based' and the voluntary commitment is 'design based'. A design based requirement is generally more restrictive for the layout of a vehicle than a performance based one and hence is less desirable for regulatory application. However, sometimes design based regulations are the only option.

Using accident data analysis, the IIHS have shown that the introduction of the US voluntary commitment has helped to reduce casualties in LTV to car crashes [Teoh 2011].

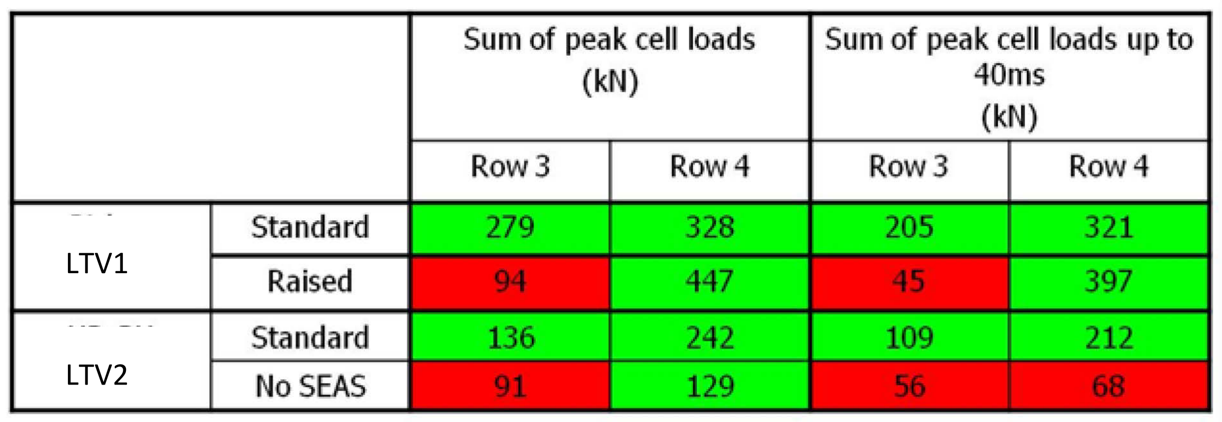
The US Enhanced Vehicle Compatibility (EVC) Working Group investigated the potential of the FWDB test to assess and control Light Truck or Van (LTV) compatibility [Barbat 2005] based on the concept of controlling the force measured on the LCW in alignment with a common interaction zone. They found that metrics to control the load applied to Rows 3 and 4 such as:

‘Sum of peak cell loads up to end of impact ≥ 100 kN

‘Sum of peak cell loads before 40 ms ≥ 100 kN

could distinguish between:

- An LTV with its main Primary Energy Absorbing Structures (PEAS) in alignment with the Part 581 zone and the same LTV raised 100 mm so that its PEAS were not in alignment with the Part 581 zone.
- An LTV with and without Secondary Energy Absorbing Structures (SEAS)



		Sum of peak cell loads (kN)		Sum of peak cell loads up to 40ms (kN)	
		Row 3	Row 4	Row 3	Row 4
LTV1	Standard	279	328	205	321
	Raised	94	447	45	397
LTV2	Standard	136	242	109	212
	No SEAS	91	129	56	68

Figure 3.6: Metric values for LTV tests showing that the metric can distinguish between vehicles with and without structure in alignment with Part 581 zone. Note: the ‘Sum of peak cell loads before 40 ms’ metric is identical to the vertical component of Structural Interaction criterion for the ‘Area 1’ assessment [Verma 2007].

It should be noted that this work was focused on LTVs and later research with cars found that some lighter cars could not meet the performance limit of 100 kN proposed for LTVs even if they had their main structure in alignment with the common interaction zone.

3.1.2 Full Width Rigid Barrier (FWRB)

Three main metrics have been previously developed for the FWRB test:

- Average height of Force 400 (AHOF400)
- Stiffness matching or frontal force control (KW 400)
- Force in a common interaction zone type metric

The first two metrics were developed by the US National Highway and Traffic Safety Administration (NHTSA) and the third by Nagoya University on behalf of the Japanese government. The metrics are described further in the sections below.

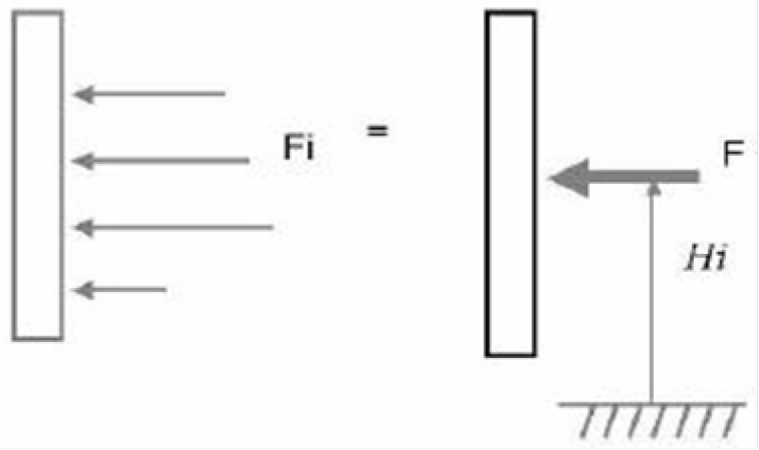
One major issue with the rigid barrier test regarding the assessment of a vehicles structural interaction potential is that, in general, it is only suitable for the assessment of vehicle’s which have their Primary Energy Absorbing Structure in alignment with the common interaction zone and it is not suitable for vehicle’s which have Secondary Energy Absorbing Structure (SEAS) in alignment with the common interaction zone. This is because the rigid barrier test is not particularly representative of a vehicle-to-vehicle impact as regards loading of SEAS, especially for SEAS that are attached directly to the PEAS. This is because, in general, the front of a vehicle's SEAS is positioned behind the front of a vehicle's PEAS. Hence in a rigid barrier test the PEAS are always loaded fully when the SEAS are loaded, whereas in a vehicle-to-vehicle impact the PEAS may not be loaded fully when the SEAS are loaded. For example, a vehicle's PEAS may over-ride the structure of its impact partner. In the case where a vehicle's SEAS are directly connected to its PEAS, deformation of the PEAS behind the position where the SEAS are connected can occur in a rigid barrier test. This can cause the SEAS to move rearwards without actually been loaded directly by the wall. This results in LCW forces which are not representative of the loading that the SEAS would experience in a vehicle-to-vehicle impact and hence an incorrect assessment of the vehicle.

To resolve this issue NHTSA proposed a supplementary Over-Ride Barrier (ORB) test to assess the structural interaction potential of vehicles which have their SEAS in alignment with the common interaction zone. Generally these vehicles are 'high' vehicles such as Light Trucks and Vans (LTVs) or vehicles such as SUVs designed to have off-road capability. The ORB test and its associated metrics are described further below.

3.1.2.1 AHOF400

The Average Height of Force 400 (AHOF400) is the average height of force that the vehicle applies to the LCW during its first 400 mm of crush [Patel 2007]. The aim of the AHOF400 metric is to control the vertical positioning of a vehicle's structures to ensure that the vehicle has structure in alignment with the common interaction zone. Precise performance limits have not been proposed for this metric although they would likely be in the region of the Part 581 zone. It is calculated as shown in Figure 3.7. First, the Height of Force (HOF) is estimated by multiplying the individual cell force by the height of the middle of that cell above ground, summing this for all cells and dividing this summation by the total wall force. Next the AHOF400 is calculated by averaging the weighted HOF for the period in which the vehicle crushes from 25 mm to 400 mm. This crush range was used to eliminate the noise in the data in the first 25 mm of crush when the relatively soft bumper engages the wall and is limited to a maximum crush of 400 mm to include the forces exerted on the wall by the rails buckling, but stop before the engine contact exerts significant forces. The vehicle crush is calculated from a double integration of an accelerometer trace mounted in the vehicle's compartment.

Issues regarding AHOF400 include that it is only suitable for the assessment of vehicles which have their PEAS in alignment with the common interaction zone. As mentioned above, a supplementary test (e.g. the ORB test) is also needed to assess vehicles which have their SEAS in alignment with the common interaction zone. Other issues include that further work is needed to prove that AHOF400 metric is appropriate and to derive performance limits.



$$HOF(d) = \frac{\sum_{i=1}^{i=n} Fi(d) * Hi}{\sum_{i=1}^{i=n} Fi(d)} \qquad AHOF400 = \frac{\sum_{d=25mm}^{d=400mm} HOF(d) * F(d)}{\sum_{d=25mm}^{d=400mm} F(d)}$$

Figure 3.7: Calculation of AHOF400.

3.1.2.2 Stiffness Matching and KW 400

One objective for compatibility that has been investigated previously has been to control the frontal interactions between vehicles to avoid overcrushing of energy absorbing structures of smaller vehicles. As shown in Figure 3.8, the compartment strength of vehicles is generally related to the mass of the vehicle. The frontal force levels are lower than the compartment forces for a given vehicle to ensure that the compartment is intact while the front deforms and absorbs energy. The problem with frontal force mismatch between vehicles is highlighted in Figure 3.8 where the heavier vehicle's force levels exceed the compartment strength of the small car. This force mismatch is caused by some extent to the current regulations and the tendency for manufacturers to minimise the vehicle's deformation zone for more effective packaging. The current regulations effectively enforce that in a crash test a vehicle has to be able to absorb its kinetic energy in its frontal crash structure. Hence, a heavier vehicle's frontal structure has to be able to absorb more energy than a lighter vehicle's because it has more kinetic energy. Therefore, if a heavy vehicle's deformation zone is a similar length to that of a lighter vehicle the heavier vehicle will have to have higher force levels in its frontal structure than a lighter vehicle to absorb the additional kinetic energy. Hence the force/mass relationship shown in the figure is common for modern vehicles [Faerber 2007, Edwards 2007].

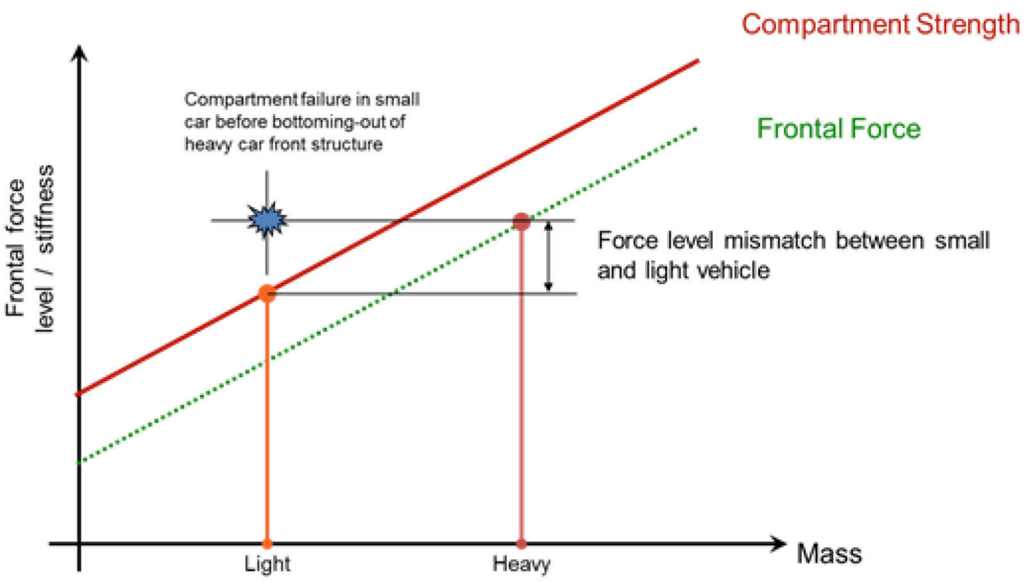


Figure 3.8: Basic concepts for front unit and compartment strengths.

There is a desire to promote better structural interaction between vehicles but there are still concerns that the stiffness levels between vehicles should not be allowed to develop unrestricted so that a very stiff vehicle can cause deformations of a partner vehicle's compartment due to incompatible force levels. There are constraints on this issue as it is not feasible to extend this requirement over the full range of vehicle sizes (0.8 to 3.5 t) due to likelihood of collisions and side effects for vehicle design (extended lengths and increased mass). Previous work recommends force matching over a mass ratio of 1:1.6 [Faerber 2007, Edwards 2007] for smaller vehicles (around 1 t) based on accident analyses.

Although the concept of force/stiffness matching may be encountered in literature, few concrete examples of evaluation metrics have been derived. Van der Zweep [van der Zweep 2006] evaluated the minimum force levels for smaller cars in the VC-Compat project. The use of 350-400 kN as a minimum compartment strength showed promise as a reference occupant survival in 1,200 kg vehicles colliding with vehicles 1.6-1.7 times heavier. This value has not been connected to a force requirement other than the proposal by TRL in VC-Compat to use the ODB test to ensure a minimum vehicle strength. VC-Compat did not develop any further force matching criteria.

The most discussed force matching criterion was developed at NHTSA and is called the KW 400 [Patel 2007]. The metric, expressed in the following equation, measures the work dissipated in the deformation of the vehicle between 25 and 400 mm of crush in a full width frontal impact with a rigid barrier and estimates the initial slope of the force/deflection curve for the vehicle in a car-barrier impact. Figure 3.9 shows the energy and slope calculated in KW 400.

There have been different issues raised in conjunction with the KW 400. An initial issue is the calculation of the displacement information as this currently is found by the double integration from a vehicle accelerometer signal and must be synchronized with the load cell data. Thus the calculation is not carried out with parameters (displacement) directly measured in the test.

$$K_w 400 = \frac{2\int_{25mm}^{400mm} F(x)dx}{(400mm)^2 - (25mm)^2}$$

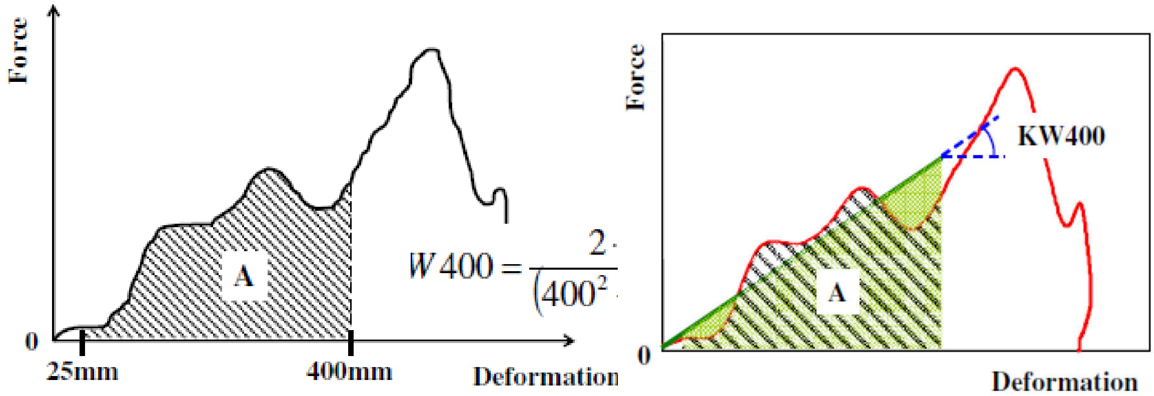


Figure 3.9: Energy calculation and KW 400 slope.

A fundamental issue with KW 400 is that the concept of this type of metric is that it should evaluate the amount of energy that the vehicle can absorb under a given force level, i.e. the passenger compartment strength of an impact partner. If the force deflection characteristic of the vehicle is assumed to be linear, then this is the case. This is because the energy absorbed by one vehicle under a given force level is inversely proportional to the KW 400 of the collision partner. Hence the ratio of the energy absorbed for two vehicles having a KW 400 of A and B is:

$E_A/E_B = KW\,400_B\,/\,KW\,400_A$

This means that in a vehicle-to-vehicle impact an impact partner (struck) vehicle will have to absorb more energy when the striking vehicle has a higher KW 400 as illustrated in Figure 3.10.

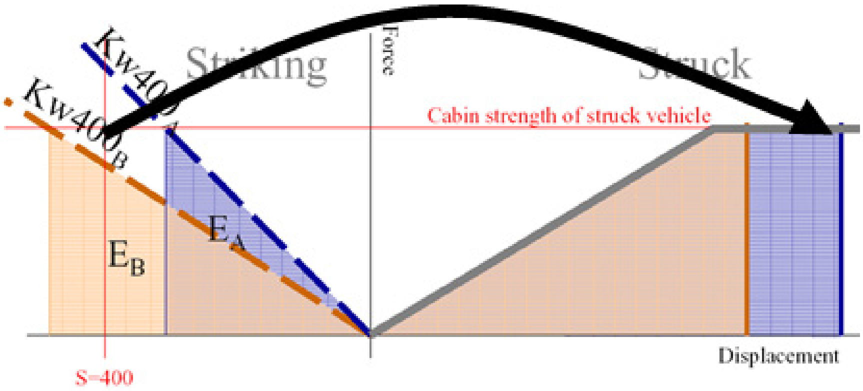


Figure 3.10: Force deflection plot showing that energy absorbed in vehicle-to-vehicle impact by struck vehicle is higher (blue area on right) when striking vehicle has higher KW 400 if it is assumed that vehicle has a linear force deflection relationship. Note: energy in striking vehicle A with high KW 400 above 'cabin strength of struck vehicle' is absorbed by struck vehicle (blue area on right).

However, in general, the force deflection characteristic of a vehicle is not linear and hence controlling the KW 400 does not necessarily control the energy absorbed under a given force level, i.e.

E_A/E_B (is not necessarily equal to) KW 400_B / KW 400_A

This means that a vehicle may have to absorb more impact energy (and hence be crushed more) when struck by a vehicle having a lower KW 400 as illustrated in Figure 3.11. This shows a fundamental issue with KW 400 and that, in principle, it is not suitable for its intended purpose.

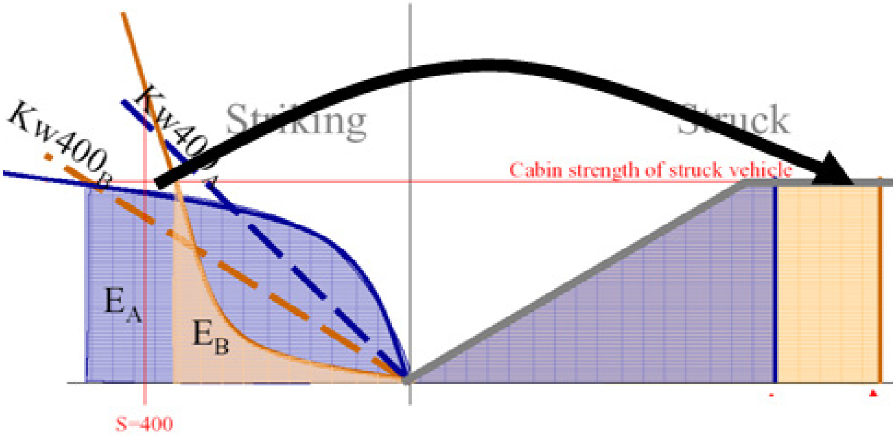


Figure 3.11: Force deflection plot showing that if a vehicle does not have a linear force deflection relationship then it is possible that energy absorbed in vehicle-to-vehicle impact by struck vehicle is higher (brown area on right) when striking vehicle has lower KW 400. Note: energy in striking vehicle B with low KW 400 above 'cabin strength of struck vehicle' is absorbed by struck vehicle (brown area on right).

Another issue with KW 400 was reported by Nissan [Hirayama 2007]. Their main point was that reducing the KW 400 of a vehicle will reduce its self protection if the vehicle deformation zone is not increased. This is because it would likely introduce a more "back loaded" crash pulse which is undesirable for the design of restraint systems and hence protection of occupants.

Other issues regarding KW 400 include that, as for the AHOF400 metric, this metric may not be suitable for the assessment of vehicles which have their SEAS in alignment with the common interaction zone. When a vehicle, such as an LTV, which has its SEAS in alignment with the common interaction zone, impacts a car, the LTV's PEAS will be loaded less than in a rigid barrier test because it will override the car's structure. As result, the effective stiffness of the LTV vehicle in the impact with the car will be substantially less than that measured in the rigid barrier test.

3.1.2.3 Force in a common interaction zone

Japan (Nagoya University) has proposed a metric to evaluate the height of a vehicle's PEAS based on the concept of force in a common interaction zone. The LCW 3rd (F3) and 4th (F4) row forces are measured when the total LCW force is 200 kN and the following performance limits applied to ensure that the PEAS align with the common interaction zone:

- $F3+F4 \geq 80$ kN
- $F4/(F3+F4) \geq 0.2$

- F4/(F3+F4) ≤ 0.8

The row forces are measured when the total LCW load is 200 kN so that the measurement is taken before the engine loads the wall. This ensures that the metric gives a measure of the height of the vehicle's crashworthy structures, i.e. its PEAS, and not its engine.

Issues with this metric include that, as for the AHOF400 metric, this metric may not be suitable for the assessment of vehicles which have their SEAS in alignment with the common interaction zone. Also, the metric is based on LCW row forces when the total LCW force is 200 kN. For some vehicles this is very early in the impact and hence the forces at this time may not be representative of the position of the vehicle's load carrying crash structures, i.e. PEAS. However, it should be noted that this metric has the advantage that it is very simple and easy to calculate.

3.1.2.4 Over-Ride Barrier (ORB) test

As mentioned above, in general, the Full Width Rigid Barrier (FWRB) test is not suitable for the assessment of a vehicle's structural interaction capability for vehicle's which have their SEAS in alignment with the common interaction zone. For this reason NHTSA proposed the use of a supplementary Over-Ride Barrier (ORB) test [Patel 2007, Patel 2009]. The idea was that vehicles with SEAS in alignment with the common interaction zone, which failed to meet the FWRB metric requirements, would be able to undergo an ORB test to properly assess their SEAS.

The Over-Ride Barrier consists of load cells which are mounted 500 mm from the instrumented back wall (Figure 3.12). The top of the ORB was infinitely adjustable to 16"–20" height (Part 581 zone) and was adjusted to be below the PEAS of the vehicle being tested. The vehicle is propelled into the barrier at a speed of 40 km/h and the force on the ORB measured. An initial proposal that a minimum force of 100 kN should be recorded before the vehicle has displaced 400 mm over the front of the barrier was made.

Figure 3.12: Over Ride Barrier (ORB).

NHTSA performed some ORB and vehicle-to-vehicle tests / simulations to verify the ORB test and proposed metric [Patel 2009]. The results for the Chevrolet Silverado were not encouraging. The Silverado has a bracket type SEAS (i.e. it consists of two brackets attached to each PEAS without a cross-member structure between them) which does not have a cross-member as shown in Figure 3.13.

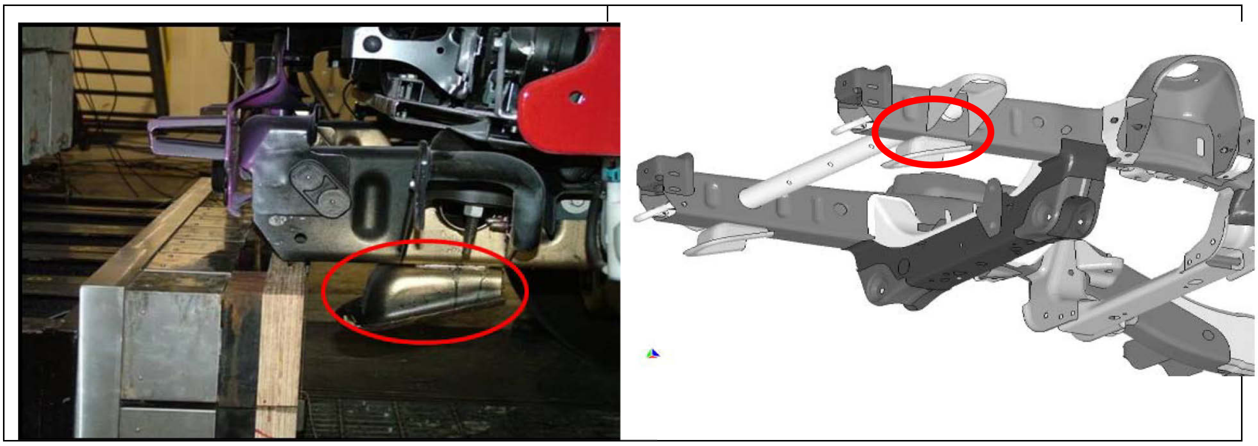


Figure 3.13: Chevrolet Silverado bracket type SEAS.

It was found that even though the SEAS met the 100 kN load requirement in the ORB test, simulations of 100 % overlap impacts between a Silverado and a Chrysler Neon with and without SEAS showed negligible effect on the overall crush kinematics of the Neon frontal structures. In contrast, a similar set of tests and simulations with the Ford F250, which had a SEAS with a cross-member structure, and a Chrysler Neon showed an improvement in the structural interaction with the SEAS present.

The results discussed above illustrate a possible problem with the ORB test, in that it may not detect crossbeam structures adequately. Further work is required to identify an appropriate ORB test procedure and performance limits. It may be the case that a deformable element in front of the ORB is required to detect SEAS crossbeam structures adequately. Also, additional criteria such as the energy absorbed may be required to ensure that the stiffness of the SEAS is controlled and they are not designed to be so strong that the collision partner is forced to absorb most of the impact energy.

3.2 Advantages / Disadvantages of FWDB and FWRB Tests

The advantages (disadvantages) of the FWDB and FWRB tests are as follows:

FWDB

- More representative of real world accident especially in initial stage of impact.
- More representative for initial deceleration of vehicle and loading of main rails which is important for sensing of crash for restraint system triggering.
- Engine dump loading attenuated, so can make assessment of vehicle structures that are relevant to crash that are loaded later in the impact, i.e. an assessment can be made of the vehicle’s main rails as opposed to its crush cans.
- Can assess SEAS structures, so no need for supplementary test, e.g. ORB.
- Possibly can assess horizontal structures (bumper beams).

FWRB

- Effectively already de-facto worldwide standard test so hence would be easier to introduce from harmonisation point of view.
- LCW measures vehicle forces directly, i.e. not filtered by deformable element.
- No problems with stability of deformable face or possibility of load spreading by deformable face.
- More test data available for development of metric

Note: Disadvantages of FWDB test are effectively advantages of FWRB test and vice versa for disadvantages of FWRB test.

In summary, the FWDB and FWRB tests both have advantages and disadvantages, but the FWDB has the edge technically because there is no need for a supplementary test and the assessment can be made later in the impact when it is more relevant. However, the FWRB is already a defacto worldwide standard test and hence has a large advantage from the harmonisation point of view.

3.3 Development of New / Revised Metrics

As described in Section 2 'Background', from a review of previous research, additional accident analysis and consultation with the GRSP Informal Group on Frontal Impact (GRSP IG FI), FIMCAR members have derived a strategy for the development of a set of test procedures to assess a vehicle's crash performance in frontal impacts. The first part of this strategy is that the set of test procedures should contain a full width test and an offset test. A full width test is required to provide a hard deceleration pulse to assess the restraint system. An offset test is required to assess the integrity of the occupant compartment and to provide a softer deceleration pulse to ensure that the restraint system performance is assessed for a variety of pulses.

As a first priority the tests should address structural interaction by improving the structural alignment of a vehicle's main crash structures and promoting good load spreading by vehicles having multiple load paths with strong connections between them. Based on previous research it was decided that the best way forward was to use the full width test with a LCW to assess a vehicle's structural alignment and the PDB offset test to assess a vehicle's load spreading capability. This approach was chosen because it was believed that it offered the best likelihood of success.

As a second priority, the tests should introduce force matching to ensure that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy using a full width and/or an offset test.

Hence, in summary for the full width test as a first priority it should be used to:

- Control structural alignment of a vehicle's main crash structures by using a LCW to detect that appropriate structures are in alignment with a common interaction zone.
- Provide a high passenger compartment deceleration pulse to provide a more severe test of the occupant restraint system. Note: It is intended that the offset test will provide a softer passenger compartment deceleration pulse, so that the restraint system is tested for a variety of pulses.

As a possible further step the full width test could be used to introduce force matching to ensure that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy

At this stage of the work, the advantages and disadvantages of both full width test procedures showed promising results (see also Section 3.2). Hence it was decided that metrics should be developed for both the FWDB and FWRB tests.

Based on the strategy and the review of the assessment criteria above the following objectives were formulated for the development of new / revised metrics for the FWDB and FWRB tests:

- Structural alignment (First priority)
  Metrics should be developed based on the 'force in a common interaction zone' concept. The 'common interaction zone' should align with the Part 581 zone used in the US voluntary commitment. The reason for this approach is to ensure that the metric developed aligns with assessments that are already used to aid harmonisation and to build on the most viable aspects of metrics previously developed.
  For the FWDB test, metric development should build on the 'force in a common interaction zone' metric described above. The reason for this is that this metric appears to offer a good chance of success based on the review above. It is expected that metric development will investigate issues such as, 'Up to what time in the impact the assessment should be performed?'.
  For the FWRB test, metric development should build on the 'force in a common interaction zone' metric proposed by Japan (Nagoya University). The reason for this is that, compared to the AHOF400 metric, this metric follows the concept of 'force in a common interaction zone' more closely and makes an assessment early in the impact (before engine dump loading) and hence should give a better assessment of the position of the vehicle's structures. It should be noted that for the FWRB test it may be necessary to develop further the ORB test, or an equivalent test, for the assessment of vehicles which have SEAS in alignment with the common interaction zone.
- Force matching (Second priority)
  The review above shows that the KW 400 metric has a fundamental issue and that, in principle, it is not suitable for the control of force matching. Hence, development of new metrics should be investigated which are better linked to the vehicle's force levels. It is proposed that initial effort is concentrated on the FWRB test because this barrier face does not have the added complications of a deformable element which modifies force levels and absorbs energy.

Metrics developed should be kept as simple as possible so that their purpose and how they work can be understood easily. This should make them easier to accept.

The remainder of this section is divided into four parts. The first describes the test data available for development of the metrics. The second part describes the development of metrics to control a vehicle's structural alignment and the third development of metric concepts to control a vehicle's force matching. The final part is the discussion and conclusions.

3.3.1 Test Data

For the development of a new / revised metric, crash test data for a range of vehicles which should and should not meet the metric requirements was needed. This is mainly to be able to try different solutions and determine the best one. Test data from previous European projects and tests performed in other countries were collected. These data were then arranged into the appropriate format and imported into the FIMCAR test data base.

FWDB test data were obtained mainly from previous European projects such as VC-Compat and APROSYS, as this type of test is a research test. However, the Japanese government also provided some data for FIMCAR to use. FIMCAR gratefully acknowledges the provision of these data by Japan which were provided through a project collaboration. Table 1 shows an overview of the test data collected. It should be noted that the ground clearance of the bottom of the LCW was not the same for all tests. The current standard for ground clearance is 80 mm. To be able to use the results from tests which did not have a ground clearance of 80 mm, it was assumed that they were equivalent to a test with the same vehicle but with a changed ride height to account for the difference in ground clearance. For example, a test performed with a vehicle with a barrier ground clearance of 50 mm was assumed to be the same as a test performed with a barrier clearance of 80 mm with the vehicle's ride height increased by 30 mm.

Table 2: Overview of test data for the development of FWDB metric.

Vehicle	Vehicle size	Source	LCW ground clearance (mm)
Wagon R	Japanese mini-car	Japan	125
Smart	Supermini	VC-Compat	50
Fiesta	Supermini	APROSYS	80
Panda	Supermini	VC-Compat	80
Micra	Supermini	APROSYS	80
Golf IV	Small Family	BASt	50
Golf V	Small Family	VC-Compat	80
Astra MY2004 (x2)	Small Family	VC-Compat / DfT	80
Bravo (x2)	Small Family	APROSYS	80
Focus	Small Family	DfT	50
Rover 75 (x3)*	Large family	ACEA	50
Laguna II	Large family	VC-Compat	50
E-Class	Executive	VC-Compat	50
CR-V	Small SUV	VC-Compat	50
Touareg	Large SUV	VC-Compat	80
XC90	Large SUV	VC-Compat	50

*Bumper crossbeam strength was changed between tests (weak, standard, strong)

FWRB test data were obtained from a variety of sources as this test is performed more widely than the FWDB test because a rigid barrier test is a mandatory test procedure in many parts of the world. In many consumer and regulatory rigid barrier tests LCW data is collected for research purposes. The FWRB collected included many crash tests which were performed within the Japanese NCAP test programme. In total 82 crash tests with the rigid barrier and the load cell wall measures were supplied by Japan (n = 19 from 2005; n = 18 from 2006; n = 15 from 2007; n = 18 from 2008; n = 12 from 2009). Additionally test data from NHTSA (n = 15) were available which helped to complement the crash test data in regard to another world wide market. FWRB data sets for three further vehicles were available from previous European projects.

3.3.2 Structural Alignment

As mentioned above the overall objective of the work was to develop new / revised metrics for the FWDB and FWRB tests to control structural alignment of a vehicle's main crash structure by using an LCW to detect that appropriate structures are in alignment with a common interaction zone.

The common interaction zone should be based on the Part 581 zone to ensure harmonisation with the US voluntary commitment Section 3.1.1 'Full Width Deformable Barrier (FWDB)', 'Force in a common interaction zone metric'. The common interaction zone was chosen to be LCW Rows 3 and 4 which is centred on the centre of the Part 581 zone and encompasses it (Figure 3.14). This means that a minimum load requirement in Rows 3 and 4 ensures that the vehicle has loaded the wall in a manner which spans the Part 581 zone, i.e. a load requirement for Row 3 ensures that load is applied to the bottom half of the Part 581 zone or just below it and similarly a load requirement for Row 4 ensures that load is applied to the top half of the Part 581 zone or just above it.

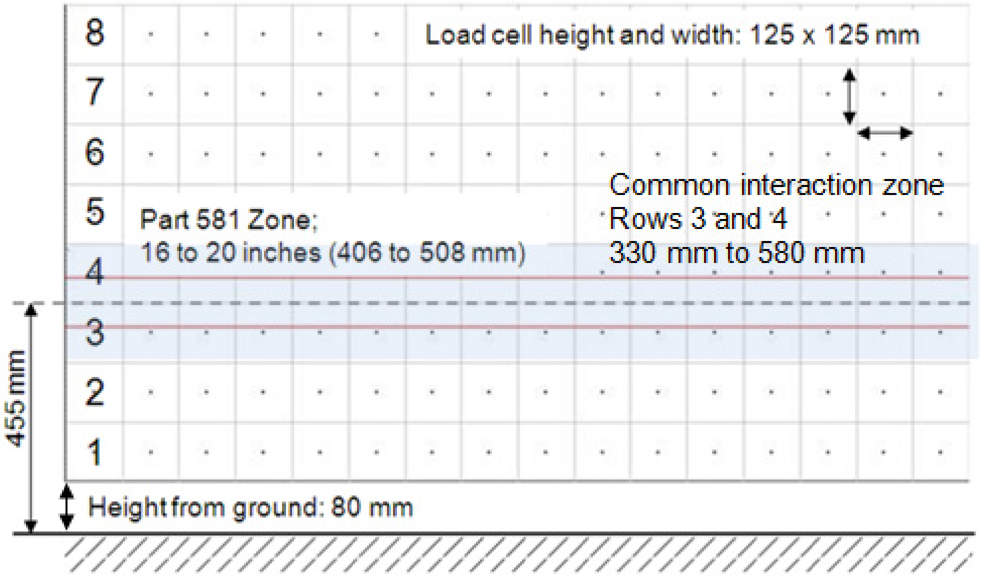


Figure 3.14: Alignment of Part 581 zone and 'common interaction zone' with LCW.

Another objective for development of the metric for structural alignment is that it should not discourage the design of vehicles that spread their load better by using multiple load paths, e.g. an engine subframe load path, and if possible encourage this type of design. The reason for this is to ensure that there are no conflicts between the requirements for structural alignment and those for load spreading, both of which are needed for good structural interaction.

The methodology followed to develop the metrics was to investigate how modifications to the metrics affected the assessment of the vehicle using the metric compared to a geometric assessment of the vehicle based on the US voluntary commitment. The aim was to achieve a 100 % correlation between the metric assessment and the geometric assessment unless a suitable explanation could be found of why they should not correlate.

The US voluntary commitment states that all LTVs sold by participating manufacturers in the US should fulfil one of the options below:

OPTION 1

The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone (Option 1a)

AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2

If a light truck does not meet the criteria of Option 1, there must be a secondary energy absorbing structure (SEAS), connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone.

Based on this a geometric assessment of the vehicles was made with minor modifications compared to the US voluntary agreement for the options below as shown in Figure 3.5:

- Option 1a	a/b ≥ 50%
- Option 1b	a/c ≥ 50%
- Option 2	For vehicles which do not meet Option1a or b, are there SEAS in Part 581 zone?

It should be noted that for all the work performed the LCW data was filtered using a CFC60 filter for the output of each cell.

3.3.2.1 Development of metrics for FWDB

Starting from the ‘Force in a common interaction zone’ metric described in the ‘Review of current and previous assessment criteria’, Section 3.1.1.3, three candidate metrics were developed which are summarised in Figure 3.15.

Many metric variations were investigated and the most promising chosen based on the correlation of the metric assessment of the test vehicles with the geometrical assessment based on the US voluntary commitment as described above. Also stakeholders, such as the GRSP Informal Group on Frontal Impact were consulted to help determine which metrics were the best. In addition, feedback received from other stakeholders attended the first FIMCAR workshop to discuss the different options was considered.

The development process involved consideration of issues such as:

- Up to what stage of the impact should the assessment be made? Good structural interaction is important throughout the whole of the impact. To achieve this, ideally the structures should be in alignment from the beginning to the end of the impact. However, the offset test with the PDB can only assess the structural interaction potential of a vehicle at the end of the impact because the assessment is based on a barrier deformation measure. Hence, it was decided that the FWDB test should make an assessment earlier in the impact so that the procedures proposed by FIMCAR assess structural interaction at two points in time; towards the beginning of the impact and at the end of the impact.
- Should the metric consist of one or two stages and if it has two stages should it have an eligibility assessment to determine whether or not the vehicle should be allowed to undergo the second stage? It should be noted that feedback from the GRSP IG FI said that, if possible, they would prefer not to have an eligibility assessment and if one was required then it should not be based on vehicle category type.

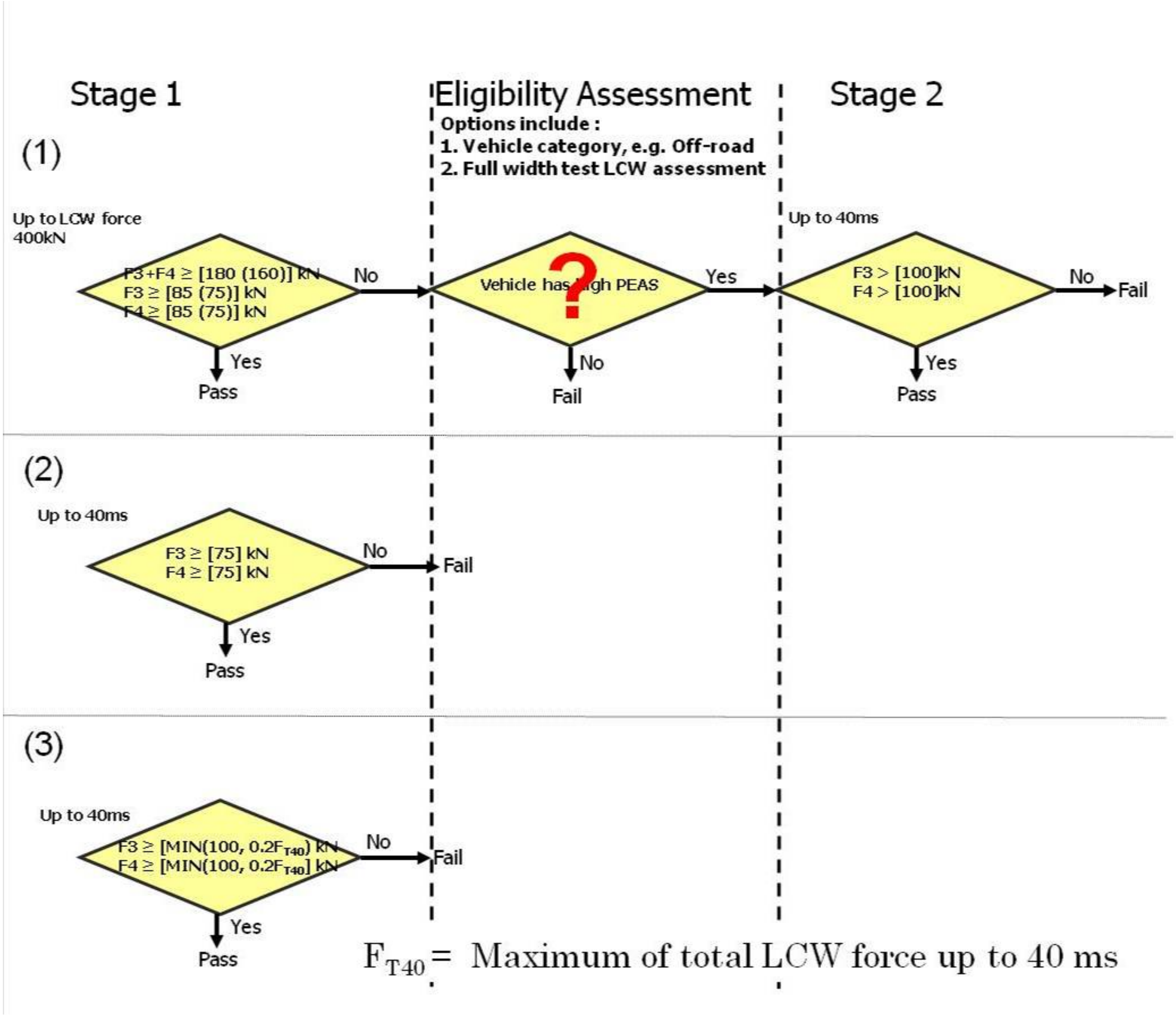


Figure 3.15: Proposed metric candidates for FWDB test.

FWDB metric (1)

This metric candidate consists of two stages with a possible eligibility assessment. The idea is that the first stage should assess whether the vehicle's PEAS align with the common interaction zone. If they do not, then the second stage should assess whether the vehicle has an adequate SEAS in alignment with the common interaction zone. A possible eligibility assessment could be used to ensure that only certain vehicles, for example those which require a high PEAS, such as offroad vehicles to achieve a high approach angle, would be allowed the concession of the second stage.

For the first stage an assessment up to the point in the impact when the LCW total force first reaches 400 kN is made. The value of 400 kN was chosen because:

- At this point in the impact the vehicle's crash structures are loaded fully and hence their characteristics can be assessed properly.
- The metric assessment correlated better with the geometric assessment compared with an assessment made earlier in the impact, e.g. 200 kN or 300 kN.

Performance requirements proposed are:

$$F3+F4 \geq [180]\ \text{kN}$$

F3 ≥ [85] kN

F4 ≥ [85] kN

where F3 and F4 are the maximum of the load on Row 3 and Row 4 up to the time in the impact when the LCW total force first reaches 400 kN.

For vehicles for which the LCW total force does not reach 400 kN (which is possible for light cars) a concession is made; the performance requirements are reduced as below:

F3+F4 ≥ [160] kN compared with 180 kN

F3 ≥ [75] kN compared with 85 kN

F4 ≥ [75] kN compared with 85 kN

where F3 and F4 are the maximum of the load on Row 3 and Row 4 up to the time in the impact when the LCW total force reaches its maximum. At present this concession is implemented in a step wise fashion. At a later date, if this candidate metric is adopted, it may be necessary to change this to a sliding scale based on the difference between the maximum LCW total force and 400 kN.

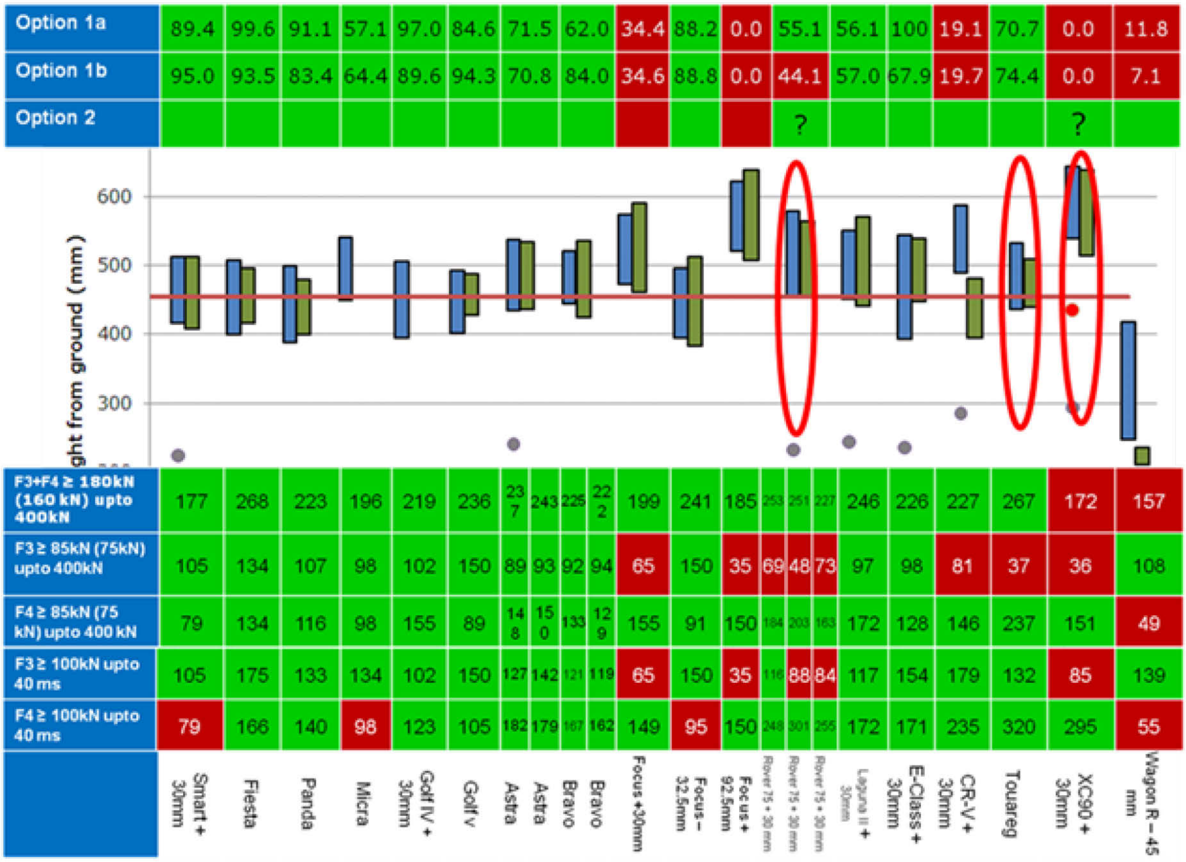
The possibility of including an eligibility assessment for stage 2 is included. The concept is to only allow certain types of vehicles (i.e. those with a high PEAS) to be able to proceed to stage 2. Stage 2 assesses if the vehicle has an adequate SEAS in alignment with the common interaction zone (Part 581 zone). An eligibility assessment could be based either on the vehicle category, e.g. Off-road vehicle (Category G as defined in the framework Directive), or an LCW assessment. An LCW assessment has been developed which is based on a minimum requirement for the loads in the early part of the impact (up to time when LCW total force equals 200 kN) on the upper part of the LCW (rows 4 and 5). The concept is that this should detect vehicles which have high PEAS in alignment with Rows 4 and 5. The proposed performance requirement is that the total of the loads on Rows 4 and 5 should be greater than 100 kN. However, it should be noted that during consultation the GRSP Informal Group on Frontal Impact informed FIMCAR that an eligibility assessment was undesirable and that it should be avoided if possible. They said that ideally all vehicles should be subjected to the same test and performance requirements. The majority of the FIMCAR consortium came to the same conclusion.

For the second stage an assessment is made up to 40 ms into the impact. This time was chosen because it should be sufficient to allow the detection of SEAS positioned up to 400 mm rearwards of the front of the vehicle. This has been explained previously in Section 3.1.1 ‘Review of Structural Interaction Criterion’. Performance requirements proposed are:

F3 ≥ [100] kN

F4 ≥ [100] kN

The correlation of this metric with a geometrical assessment of vehicle’s structures based on the US voluntary commitment is shown below (Figure 3.16). The top part of the figure shows the geometric assessment of the vehicle’s structures as described in Figure 3.5. The bottom part of the figure shows the assessment of the vehicle using the metric. It should be noted that some vehicles are labelled with a measurement attached, e.g. SMART +30 mm. This is to indicate that the ride heights of these vehicles have been adjusted to account for the fact that the test was performed with a different LCW ground clearance to the standard of 80 mm. For example, the SMART test was performed with a LCW ground clearance of 50 mm which is equivalent to performing a test with the SMART with a ride height increase of 30 mm and a LCW with a ground clearance of 80 mm, i.e. both the car and the wall have been raised by 30 mm. It is seen that there is good agreement between the geometric assessment and the metric for all vehicles expect those circled in red, namely Rover 75 (ride height raised), VW Touareg, and Volvo XC90 (ride height raised). For the Rover 75, the subframe structure was not assessed consistently by the metric for all the vehicles tested (Note: the three vehicles had different bumper beam structures). However, it is debatable whether this was an adequate subframe structure because of its small frontal area and hence whether it should be assessed as adequate or not. For the VW Touareg the PEAS was not detected by the metric 1st stage even though it aligned with Row 3 and Row 4. This could have been caused by movement of the rails during the crash, the design of the front of the rails and bumper beam preventing the full height of the rail interacting with the wall or errors in the measurements of the heights of the vehicle's structures. For the Volvo XC90 with a ride height increase of 30 mm the SEAS was not judged adequate by the metric. However, it is not known whether or not the XC90 SEAS in this configuration is adequate or not and hence it is not known definitely whether or not the metric assessment is correct or not. In short it is probably a borderline case.



	Smart + 30mm	Fiesta	Panda	Micra	Golf IV + 30mm	Golf V	Astra	Astra	Bravo	Bravo	Focus +30mm	Focus – 32.5mm	Focus + 92.5mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Laguna II + 30mm	E-Class + 30mm	CR-V + 30mm	Touareg	XC90 + 30mm	Wagon R – 45 mm
Option 1a	89.4	99.6	91.1	57.1	97.0	84.6	71.5		62.0		34.4	88.2	0.0	55.1			56.1	100	19.1	70.7	0.0	11.8
Option 1b	95.0	93.5	83.4	64.4	89.6	94.3	70.8		84.0		34.6	88.8	0.0	44.1			57.0	67.9	19.7	74.4	0.0	7.1
Option 2	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟥	🟩	🟥	?			🟩	🟩	🟩	🟩	?	🟩
F3+F4 ≥ 180kN (160 kN) upto 400kN	177	268	223	196	219	236	237	243	225	222	199	241	185	253	251	227	246	226	227	267	172	157
F3 ≥ 85kN (75kN) upto 400kN	105	134	107	98	102	150	89	93	92	94	65	150	35	69	48	73	97	98	81	37	36	108
F4 ≥ 85kN (75 kN) upto 400 kN	79	134	116	98	155	89	148	150	133	129	155	91	150	184	203	163	172	128	146	237	151	49
F3 ≥ 100kN upto 40 ms	105	175	133	134	102	150	127	142	121	119	65	150	35	116	88	84	117	154	179	132	85	139
F4 ≥ 100kN upto 40 ms	79	166	140	98	123	105	182	179	167	162	149	95	150	248	301	255	172	171	235	320	295	55

Figure 3.16: Correlation of FWDB (1) metric with geometrical assessment of vehicle's structures based on the US voluntary commitment showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail

overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.

2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB (1) metric consists of two stages. The values of the metric for stage 1 for (F3+F4), F4, and F3 are noted in the top three rows of the metric assessment and the values of the metric for stage 2 for F4 and F3 are noted in the bottom two rows. Whether or not the performance limit is met is indicated in green (met) and red (not met). Please note that if stage 1 of the metric is met stage 2 does not have to be met as well. Hence, the 'Focus – 35 mm' meets the metric requirements because it passes stage 1 even though it does not pass stage 2.

FWDB metric (2)

This metric candidate consists of one stage which assesses all of the vehicle's structures, i.e. PEAS and SEAS. The assessment is made up to 40 ms into the impact to enable the detection of structures up to 400 mm rearward of the front of the vehicle, as with stage 2 of the FWDB (1) metric. Performance requirements proposed are:

F3 ≥ [75] kN

F4 ≥ [75] kN

The correlation of this metric with a geometrical assessment of vehicle's structures is shown below (Figure 3.17). The agreement is very good; all vehicles which pass the geometric assessment meet the metric requirements and all those which do not pass the geometric requirements do not. For the Rover 75 (increased ride height) and XC90 (increased ride height) the metric requirement is met even though it is debatable whether or not they should meet the requirements.

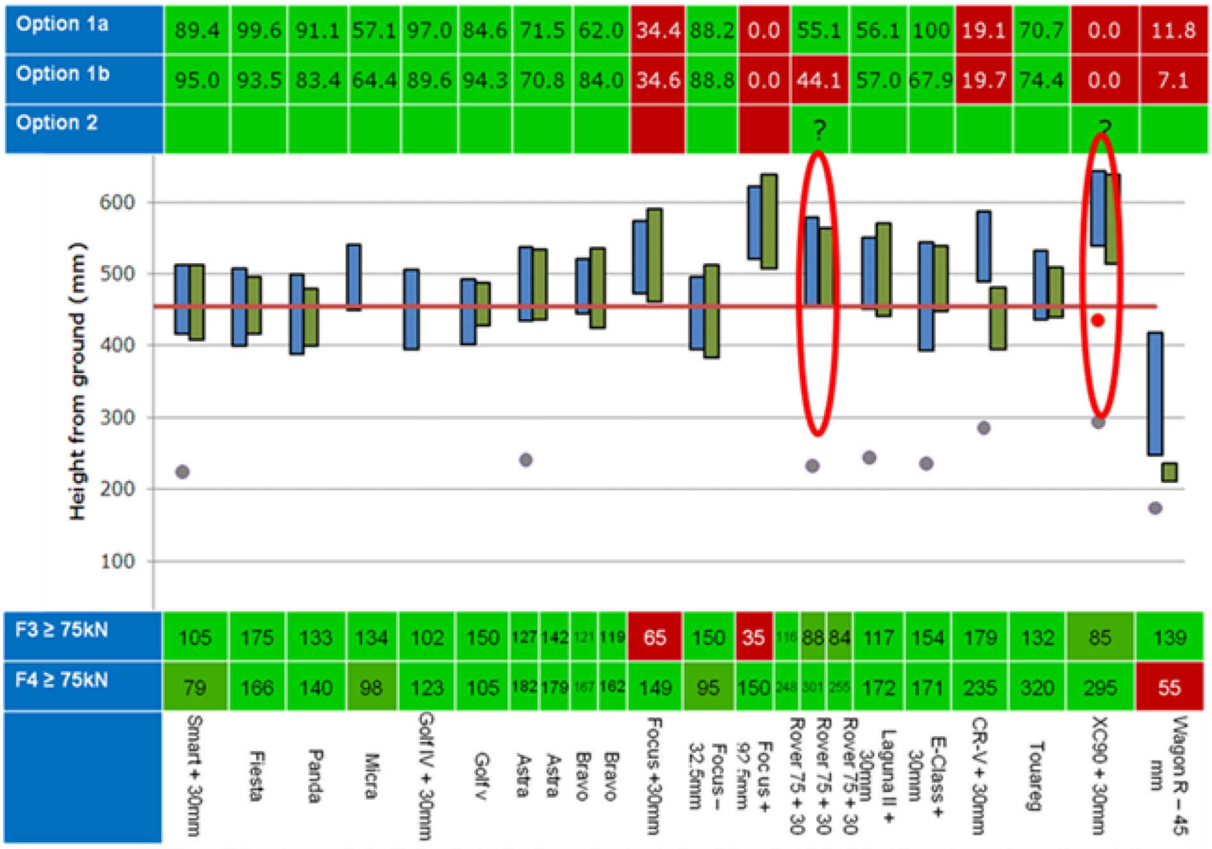


Figure 3.17: Correlation of FWDB (2) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.
2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB (2) metric consists of one stage. The values of the metric for stage 1 for F4, and F3 are noted in the two rows of the metric assessment. Whether or not the performance limit is met is indicated in green (met) and red (not met).

It should be noted that the main reason the requirement was set at 75 kN was to ensure that the SMART car could meet the requirement because the geometric assessment showed that it should. However, it is debatable that a requirement of 75 kN is high enough to ensure an adequate SEAS on larger vehicles for whom 75 kN is a much lower proportion of the total load on the wall (total LCW force max up to 40 ms SMART 370 kN, XC90 = 800 kN). For this reason the FWDB (3) metric was developed.

FWDB (3)

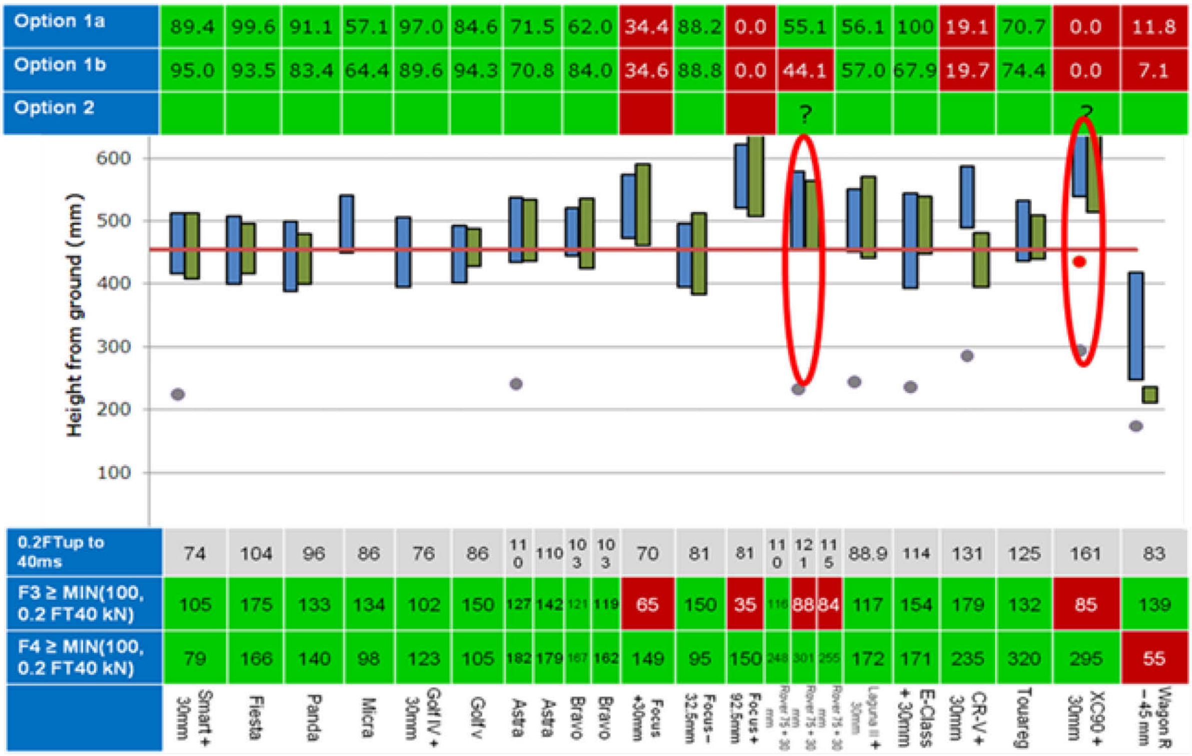
As for FWDB metric 2, this metric candidate consists of one stage which assesses all of the vehicle's structures and the assessment is made up to 40 ms into the impact to enable the detection of structures up to 400 mm rearward of the front of the vehicle. The concept of the metric is to ensure realistic load requirements for both heavy and light vehicles. This is achieved by using a row load requirement of 100 kN for heavy vehicles and a requirement of a proportion of the total LCW force for light vehicles. The performance requirements are:

$$F3 \geq [\mathrm{MIN}(100, 0.2F_{T40}) \text{ kN}$$

$$F4 \geq [\mathrm{MIN}(100, 0.2F_{T40}] \text{ kN}$$

where F_{T40} = Maximum of total LCW force up to time of 40 msec

The correlation of this metric with a geometrical assessment of vehicle's structures is shown below (Figure 3.18). Agreement is good, but now the Rover 75 (increased ride height) and XC90 (increased ride height) fail to meet the requirements, the opposite result to the FWDB metric (2) assessment.



Option 1a	89.4	99.6	91.1	57.1	97.0	84.6	71.5	62.0	34.4	88.2	0.0	55.1	56.1	100	19.1	70.7	0.0	11.8
Option 1b	95.0	93.5	83.4	64.4	89.6	94.3	70.8	84.0	34.6	88.8	0.0	44.1	57.0	67.9	19.7	74.4	0.0	7.1
Option 2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩 ?	🟩	🟩	🟩	🟩	🟩 ?	🟩

0.2FTup to 40ms	74	104	96	86	76	86	110	110	103	103	70	81	81	110	121	115	88.9	114	131	125	161	83
F3 ≥ MIN(100, 0.2 FT40 kN)	105	175	133	134	102	150	127	142	121	119	65	150	35	116	88	84	117	154	179	132	85	139
F4 ≥ MIN(100, 0.2 FT40 kN)	79	166	140	98	123	105	182	179	167	162	149	95	150	248	301	255	172	171	235	320	295	55
	Smart + 30mm	Fiesta	Panda	Micra	Golf IV + 30mm	Golf V	Astra	Astra	Bravo	Bravo	Focus +30mm	Focus – 32.5mm	Focus + 92.5mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Laguna III + 30mm	E-Class + 30mm	CR-V + 30mm	Touareg	XC90 + 30mm	Wagon R – 45 mm

Figure 3.18: Correlation of FWDB metric (2) with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.

2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB metric (3) consists of one stage. The values of the metric for stage 1 for F4, and F3 are noted in the bottom two rows of the metric assessment. Whether or not the performance limit is met is indicated in green (met) and red (not met).

Discussion and Conclusions

Three metrics have been developed for the FWDB test. One of these has two stages with a possible eligibility assessment for the second stage and the other two have one stage only. In the spirit of keeping the metric as simple as possible and because the correlation of the metrics with the geometric assessment is similar, it is believed that a single stage metric is the better way forward. Of the two single stage metrics it is believed that the FWDB (3) metric is the better candidate because effectively it allows the mass of the vehicle to be taken into account in the performance requirement.

3.3.2.2 Development of Metrics for FWRB

Starting from the 'Force in a common interaction zone' metric developed by Japan (Nagoya University) described in the 'Review of current and previous assessment criteria', Section 3.1.2.3, three candidate metrics were developed. These are summarised in Figure 3.19.

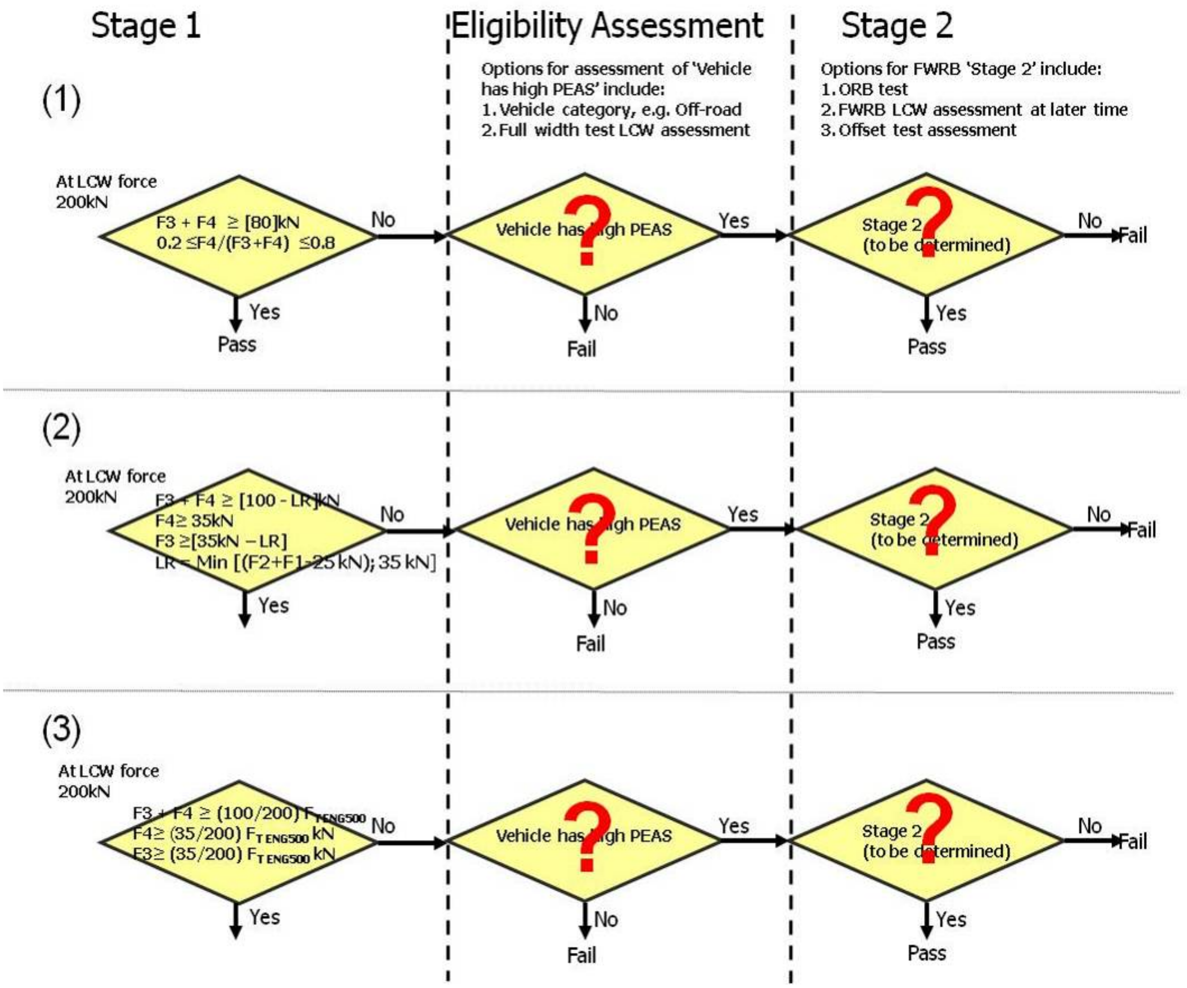


Figure 3.19: Proposed metric candidates for FWRB test.

As for the FWDB test, many metric variations were investigated and the most promising chosen based on the correlation of the metric assessment of the test vehicles with the geometrical assessment based on the US voluntary commitment as described above. Also stakeholders, such as the GRSP Informal Group on Frontal Impact and experts at the FIMCAR workshop were consulted to help determine which metrics were the best.

The development process involved consideration of the following issues:

- At what stage in the impact should the assessment be made up to?
  It was found that an assessment based on the 'force in a common interaction zone' concept could only be made before 'engine dump' loading occurred, i.e. the rapid deceleration of the engine caused by direct or indirect contact with the LCW. This was because in a rigid barrier test the loads applied by the engine to the LCW may not be representative of those applied in a car-to-car impact. In turn, this is because the loads applied by the engine in the rigid wall test can be very localised and high because of rigid features on the engine, such as the alternator, interacting with the rigid wall and causing the engine to come to an abrupt halt. In contrast in an impact with another vehicle the engine is less likely to come to such an abrupt halt because the other vehicle will be more compliant and not behave in such a rigid manner, e.g. the engine of a partner vehicle may move and rotate.
- Should the metric consist of one or two stages and if it has two stages should it have an eligibility assessment to determine whether or not the vehicle should be allowed to undergo the second stage?
- Should vehicles that have load paths positioned below the common interaction zone which improve their structural interaction potential be allowed concessions to ensure that they are not discouraged and possibly encouraged?

FWRB Metric (1)

This metric candidate is based on the proposal made by Japan (Nagoya University) described in Section 3.1.2.3 which in turn is based on the 'Force in a common interaction zone' concept. It should be noted that the development of this metric was supported by Japan (Nagoya University and JARI) and this is gratefully acknowledged. The metric consists of a Stage 1 and possibly a Stage 2 with a possible eligibility assessment. The Stage 1 of the metric is described below followed by a discussion of a possible Stage 2 and a possible eligibility assessment.

Stage 1 of the metric effectively assesses the height of the vehicle's PEAS. The LCW 3rd (F3) and 4th (F4) row forces maximums are measured at the time when the total LCW force is 200 kN. The following performance limits are applied to ensure that the PEAS align with the common interaction zone:

- $F3+F4 \geq 80$ kN
- $F4/(F3+F4) \geq 0.2$
- $F4/(F3+F4) \leq 0.8$

The reason why the row forces are measured at the time when the total LCW load is 200 kN is so that the measurement is taken before the engine loads the wall as shown in Figure 3.20. This ensures that the metric gives a measure of the height of the vehicle's structures, i.e. its PEAS, and not its engine. Also, because the row load forces are assessed when the total LCW force is a fixed magnitude (200 kN), it is effectively normalised. This helps to ensure that the metric is independent of the mass of the vehicle and assesses the vehicle's structural interaction potential only.

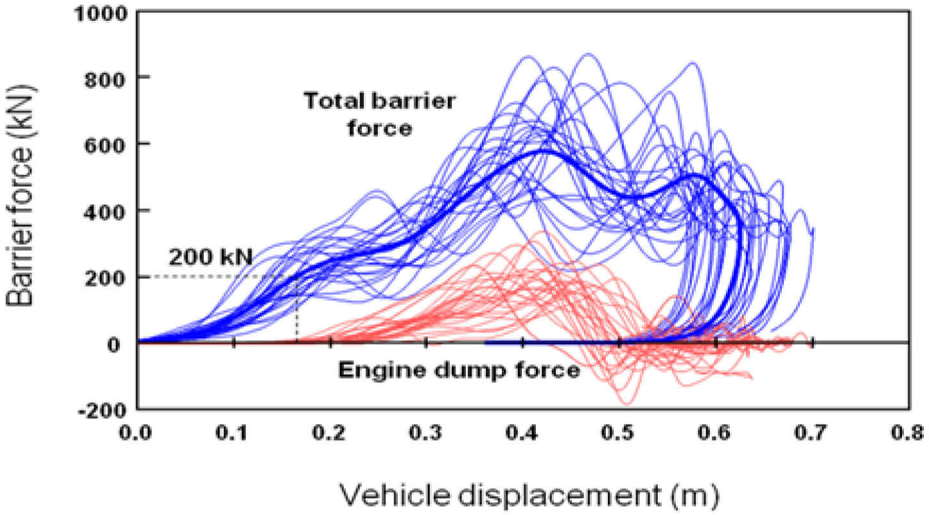


Figure 3.20: Total barrier force and engine dump force showing engine dump loading does not occur before total barrier force is greater than 200 kN. Data JNCAP 2007-2008 excluding Japanese minicars[1].

The correlation of this metric with a geometrical assessment of vehicle's structures based on the US voluntary commitment is shown below (Figure 3.21 and Figure 3.22). The top part of the table shows the result of a geometric assessment of the vehicle's structures as described in Figure 3.5, i.e. Option 1a the vehicle's PEAS overlap at least 50% of the Part 581 zone; Option1b at least 50% of the vehicle's PEAS overlap the Part 581 zone. The bottom part of the table shows the result of the metric assessment of the vehicle. It is seen that the geometric and metric assessments correlate for all vehicles except those circled in red. Reasons why the assessments do not correlate for these vehicles are discussed further below:

- Suzuki Cervo and Nissan Moco
  These vehicles do not fulfil Option 1b of the geometric assessment because their PEAS have a particularly tall cross-sectional height and hence 50% of their PEAS do not overlap the Part 581 zone. Whether or not these PEAS should be assessed as sufficient is a debatable point. It can be argued that the PEAS have a tall cross-sectional height which spreads the load and helps to offer good structural interaction, hence they should be assessed as sufficient. Alternatively, it can be argued that the PEAS do not put sufficient load into the top half of the Part 581 zone (Row 4 about 25 kN) and should be assessed as insufficient. This is because in an impact with a high SUV type vehicle which has structures mainly in alignment with the top half of the Part 581 zone (Row 4) it could be overridden. The authors concur with the latter point and believe that it is important that a specified minimum load is applied to Row 4 to ensure the vehicle has sufficient structure in alignment with the

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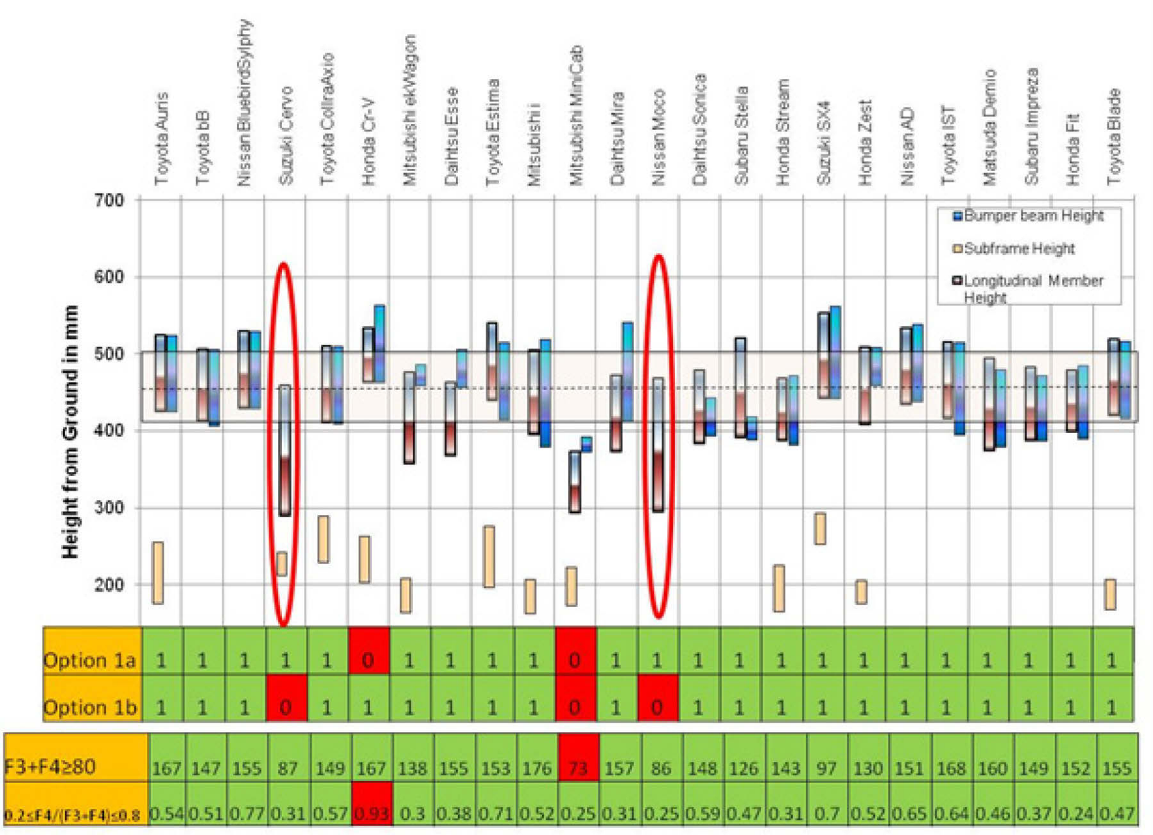
[1] Japanese minicars are restricted in external dimensions (i.e., l < 3.39 m; w < 1.475 m) and engine size < 660 cm³ and offer the advantage of lower tax. In ordert o fulfil the external dimension restrictions while offering a maximum internal space the front end design is considerably different to standard cars (i.e., often without crash box and cross member

top half of the Part 581 zone. This is one of the reasons for the development of FWRB metric (2) which is based on the specification of minimum row loads.

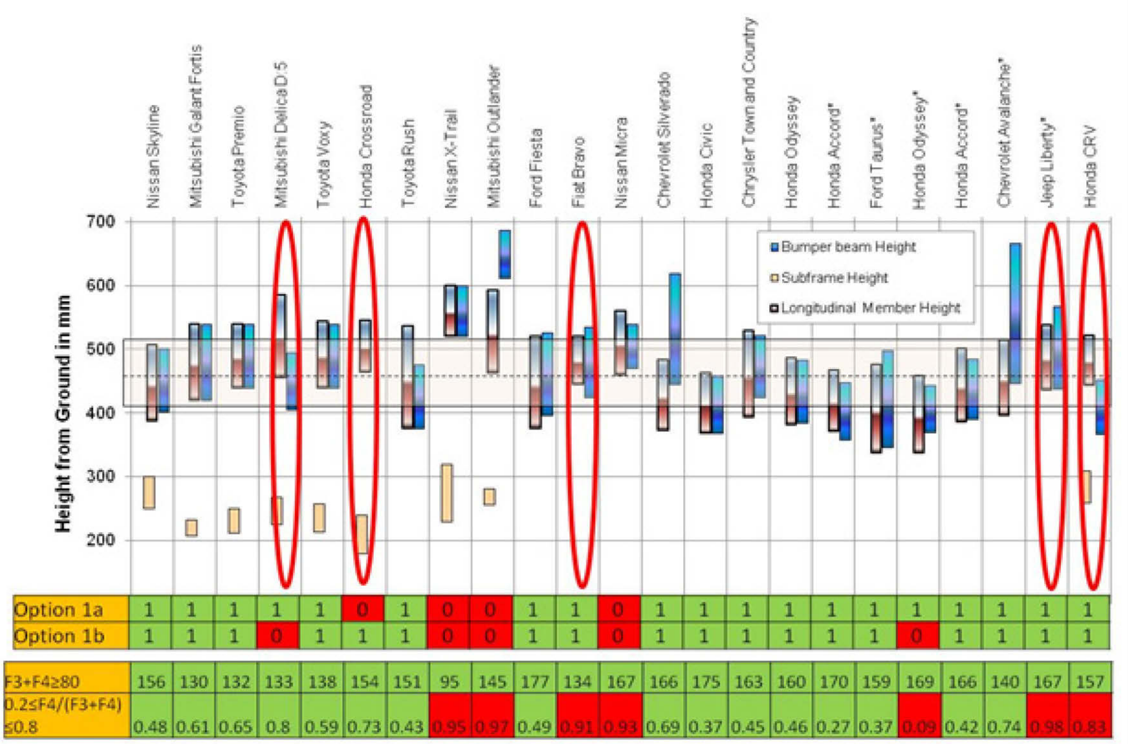
- Mitsubishi Delica
  This vehicle was assessed as borderline for both the geometric assessment and the metric assessment. Hence it is unclear whether this vehicle should be assessed as sufficient or not.
- Honda Crossroad
  Further examination of the test data found that the impact accuracy for this test was z = -11 mm. This is sufficient to explain why the vehicle failed the geometric assessment but passed the metric assessment. The vehicle was 11 mm lower in the test than for the geometric assessment and hence its PEAS (longitudinals) had a greater overlap of the Part 581 zone.
- Fiat Bravo
  This vehicle met the geometric assessment but failed to meet the metric assessment because it did not apply a large enough load to Row 3. A possible explanation for this discrepancy could be the impact accuracy in the test; the vehicle may have impacted high leading to lower loads on Row 3. Unfortunately impact accuracy was not recorded in the test.
- Jeep Liberty
  Again the explanation for this discrepancy may be impact accuracy. This is not known for this test.
- Honda CRV
  The most likely explanation for this discrepancy for this test is the position of the crush cans on the Honda CRV. They are positioned in alignment with Row 4 and hence would result in most of the load from the PEAS (longitudinals) being applied to Row 4 in the initial stages of the impact before the LCW total force reached 200 kN even though the longitudinals actually overlap Row 3.



Option 1a	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Option 1b	1	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1

F3+F4≥80	167	147	155	87	149	167	138	155	153	176	73	157	86	148	126	143	97	130	151	168	160	149	152	155
0.2≤F4/(F3+F4)≤0.8	0.54	0.51	0.77	0.31	0.57	0.93	0.3	0.38	0.71	0.52	0.25	0.31	0.25	0.59	0.47	0.31	0.7	0.52	0.65	0.64	0.46	0.37	0.24	0.47

Figure 3.21: Correlation of FWRB (1) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.



Option 1a	1	1	1	1	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
Option 1b	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1

F3+F4≥80	156	130	132	133	138	154	151	95	145	177	134	167	166	175	163	160	170	159	169	166	140	167	157
0.2≤F4/(F3+F4) ≤0.8	0.48	0.61	0.65	0.8	0.59	0.73	0.43	0.95	0.97	0.49	0.91	0.93	0.69	0.37	0.45	0.46	0.27	0.37	0.09	0.42	0.74	0.98	0.83

Figure 3.22: Correlation of FWRB (1) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red. Note: For vehicles marked with an asterisk, the vehicle's structural height was adjusted to compensate for the fact that the LCW ground clearance was not 80 mm in the test.

Whether or not a second stage for the metric is required is still under debate. Ideally all vehicles would align their PEAS or other forward structure with the common interaction zone and hence meet the Stage 1 requirements and consequently there would be no need for a second stage. Unfortunately, in the real world there are some vehicles which cannot align their forward structure with the common interaction zone because of other requirements, for example a high approach angle requirement for off-road vehicles (Figure 3.23). To assess the compatibility of these types of vehicles a second stage is needed. However, because these vehicles form a relatively small proportion of the vehicle fleet, an alternative possibility is that they could be made exempt from this requirement.

An additional part of the debate is centred on the question if not having a second stage for the metric would be design restrictive. Examples of the case in question are cross-over vehicles. These vehicles are often raised versions of their car counterparts. The result of this is that the PEAS (main rails) are no longer in alignment with the common interaction zone. To compensate for this most manufacturers have added SEAS below the PEAS to help ensure good structural interaction. However, often this SEAS is positioned rearwards of the front of the PEAS and consequently this type of vehicle would not meet the requirements of the metric with a single stage. In theory this type of design will give poorer structural interaction than a design with a forward structure in alignment with the common interaction zone because the more rearward structure will interact later in the impact. However, if the difference is small then one could argue that it should be permitted and a second stage is required. If the difference is large one could argue the opposite. Work is planned in FIMCAR Work Package 6 to investigate this issue with car-to-car crash tests and simulations in order to quantify the likely difference.

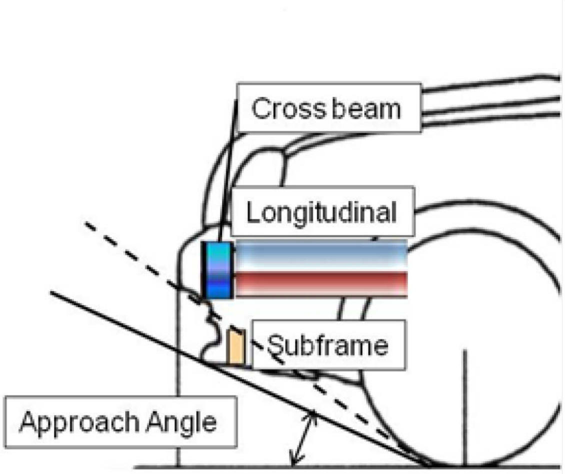


Figure 3.23: Approach angle – dotted line shows that for a high approach angle a high position of the longitudinal is required with subframe structure placed rearwards.

The options for a second stage are (1) Over-Ride Barrier (ORB) test, (2) FWRB assessment at a later time and (3) assessment using the PDB test. Some work has been performed to investigate these options.

(1) For the ORB test a number of issues have been raised. The first of these is described in Section 3.1.2.4. In summary, the test does not detect SEAS crossbeam structures adequately. A deformable element in front of the ORB may be necessary to address this issue. The second issue is that the GRSP IG FI has indicated that an additional supplementary test is not desirable because they wish to keep the number of tests to a minimum.

(2) The FWRB assessment at a later time has been investigated but a number of issues have been raised which question its feasibility. The first of these is that at a later time in the impact there is the possibility that engine dump loading could confuse the assessment. However, there is the possibility that this could be overcome by ensuring that the assessment is made before engine dump occurs by using an accelerometer mounted on the engine to detect when this occurs. The second issue is the detection of blocker beam type SEAS which are attached to the PEAS only. This type of SEAS may not be detected consistently because deformation of the PEAS behind where the blocker beam is connected can result in the blocker beam moving rearwards and not contacting the wall to load it.

(3) Initial studies have been performed to investigate the possibility of using a PDB test as a second stage to assess SEAS. The results of this work have indicated that this approach could be feasible but much further work would be required to develop an assessment.

In summary, all of the options for a second stage have significant issues. If it is decided that a second stage is needed much further work would be required to resolve them assuming that it is possible.

FWRB Metric (2)

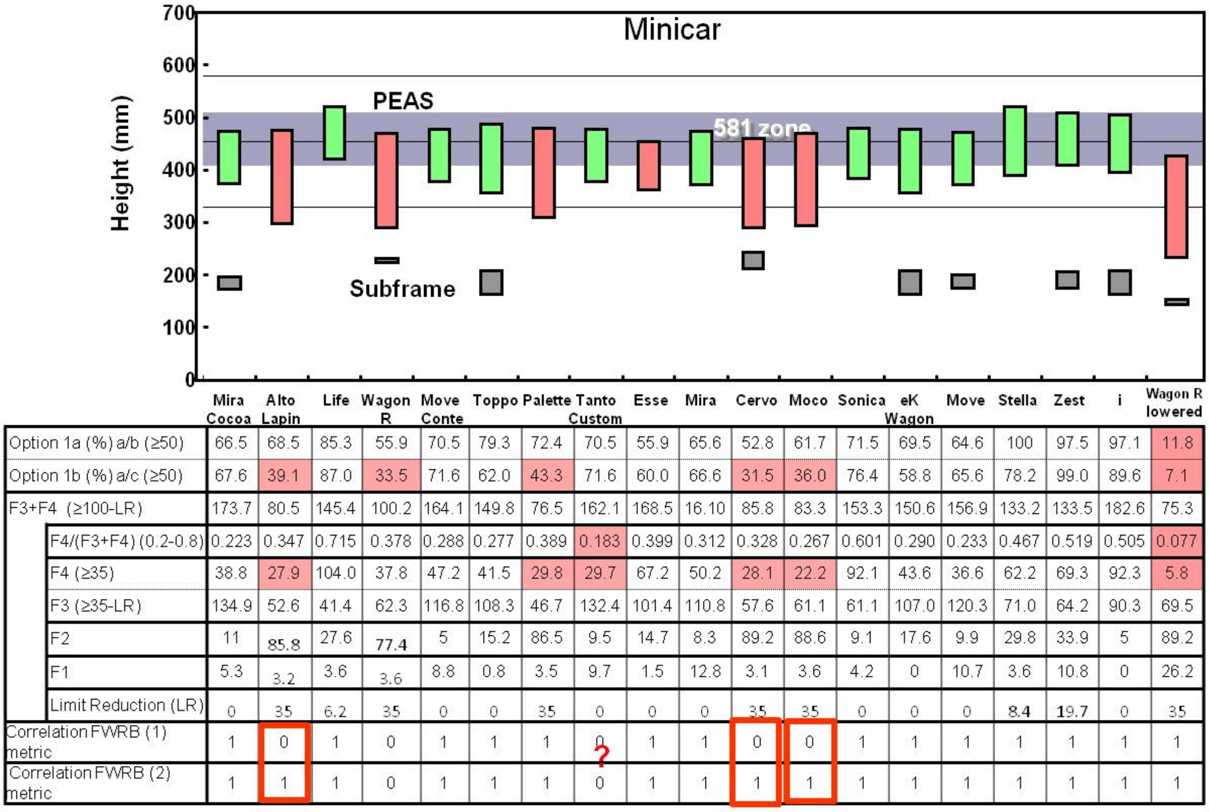
This metric is a development of FWRB (1) to ensure that vehicles that have forward located structures (i.e. forward lower load paths) positioned below the common interaction zone are not discouraged and if possible encouraged. The concept of this metric is that vehicles with forward lower load paths are encouraged by lowering the Row 3 load requirement (bottom half of common interaction zone) if sufficient load is applied to Rows 1 and 2.

The LCW 1st (F1), 2nd (F2), 3rd (F3) and 4th (F4) row forces maximums are measured at the time when the total LCW force is 200 kN and the following performance limits are applied:

F4+F3 ≥ (100 kN – LR)
F4 ≥ 35 kN
F3 ≥ (35 kN – LR)
Limit Reduction (LR) = Min [(F2+F1-25 kN); 35 kN]
Note: If (F2+F1-25 kN) is less than 0 then its value is 0

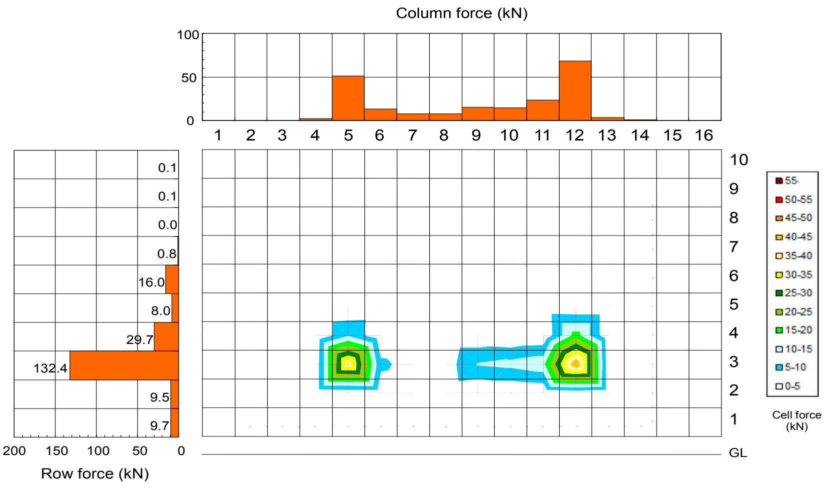
This metric ensures that the vehicle still has some ‘high’ structure in alignment with the top half of the common interaction zone to help prevent it being overridden, but also ensures it has some ‘lower’ structure in alignment with Rows 1 and 2 (instead of Row 3 as for FWRB (1)) to help prevent it overriding other vehicles.

Verification of this metric for Japanese minicars is shown below (Figure 3.24). It should be noted that the correlation of this metric assessment with the geometric assessment is improved compared to FWRB (1) metric, in particular for the Alto Lapin, Suzuki Cervo and Nissan Moco vehicles. This is because this metric has a load requirement of 35 kN in Row 4 which these vehicles fail to meet because their rails do not overlap Row 4 sufficiently. It should be noted that there is still an issue of the lack of correlation for the Tanto Custom for this metric as well as for FWRB metric (1). The explanation to why this occurs is not clear. However, it may be a result of the high loading on Row 3 possibly caused by some component attached to the engine loading the wall (Figure 3.25). This issue needs to be resolved if either of these metrics are chosen as the final proposal.



	Mira Cocoa	Alto Lapin	Life	Wagon R	Move Conte	Toppo	Palette	Tanto Custom	Esse	Mira	Cervo	Moco	Sonica	eK Wagon	Move	Stella	Zest	i	Wagon R lowered
Option 1a (%) a/b (≥50)	66.5	68.5	85.3	55.9	70.5	79.3	72.4	70.5	55.9	65.6	52.8	61.7	71.5	69.5	64.6	100	97.5	97.1	11.8
Option 1b (%) a/c (≥50)	67.6	39.1	87.0	33.5	71.6	62.0	43.3	71.6	60.0	66.6	31.5	36.0	76.4	58.8	65.6	78.2	99.0	89.6	7.1
F3+F4 (≥100-LR)	173.7	80.5	145.4	100.2	164.1	149.8	76.5	162.1	168.5	16.10	85.8	83.3	153.3	150.6	156.9	133.2	133.5	182.6	75.3
F4/(F3+F4) (0.2-0.8)	0.223	0.347	0.715	0.378	0.288	0.277	0.389	0.183	0.399	0.312	0.328	0.267	0.601	0.290	0.233	0.467	0.519	0.505	0.077
F4 (≥35)	38.8	27.9	104.0	37.8	47.2	41.5	29.8	29.7	67.2	50.2	28.1	22.2	92.1	43.6	36.6	62.2	69.3	92.3	5.8
F3 (≥35-LR)	134.9	52.6	41.4	62.3	116.8	108.3	46.7	132.4	101.4	110.8	57.6	61.1	61.1	107.0	120.3	71.0	64.2	90.3	69.5
F2	11	85.8	27.6	77.4	5	15.2	86.5	9.5	14.7	8.3	89.2	88.6	9.1	17.6	9.9	29.8	33.9	5	89.2
F1	5.3	3.2	3.6	3.6	8.8	0.8	3.5	9.7	1.5	12.8	3.1	3.6	4.2	0	10.7	3.6	10.8	0	26.2
Limit Reduction (LR)	0	35	6.2	35	0	0	35	0	0	0	35	35	0	0	0	8.4	19.7	0	35
Correlation FWRB (1) metric	1	0	1	0	1	1	1	0 ?	1	1	0	0	1	1	1	1	1	1	1
Correlation FWRB (2) metric	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1

Figure 3.24: Correlation of FWRB (1) and FWRB (2) metrics with geometrical assessment of vehicle's structures for Japanese mini-cars showing better agreement for FWRB (2) metric.



Peak cell force distribution (≤ 200 kN 4.1 ms)

Figure 3.25: LCW peak cell force distribution at 200 kN for Tanto Custom Japanese minicar.

The position of a possible second stage for this metric is the same as for FWRB (1) metric.

FWRB Metric (3)

For both the FWRB (1) and FWRB (2) metrics the load distribution on the wall is assessed at the time when the total LCW force is 200 kN. As mentioned above, the main reason for this was to ensure that the assessment was made before significant engine dump loading occurred. However, for certain vehicles, in particular Japanese mini-cars which do not have crush cans, engine dump loading can occur before the LCW total force is 200 kN. For the Daihatsu Esse minicar engine dump loading on Row 4 at a LCW total force of 200 kN can be seen (red circle in Figure 3.26). Engine loading of this magnitude may not be seen in a car-to-car impact and hence may lead to an incorrect assessment of the vehicle's structural interaction potential.

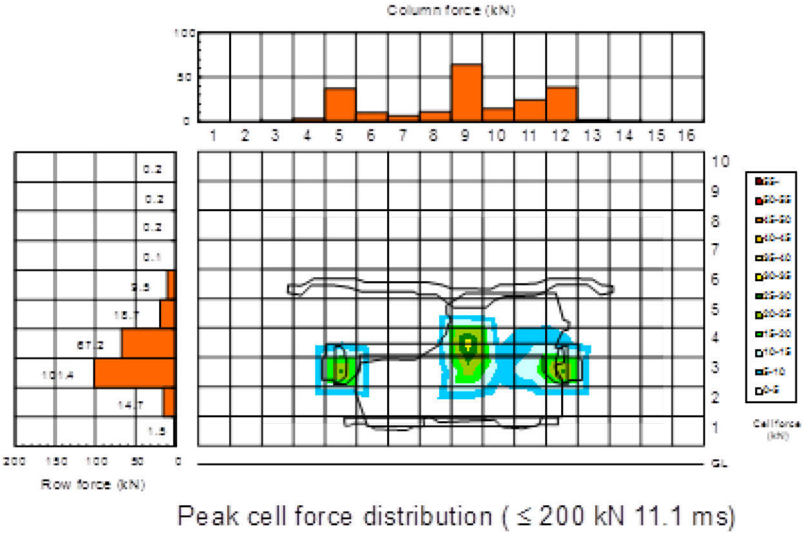


Figure 3.26: LCW peak cell force distribution at 200 kN for Daihatsu Esse minicar.

To resolve this problem FWRB metric (3) was developed based on the concept of making the assessment earlier in the impact if engine dump loading is present and applying performance limits based on the total LCW force at that time.

FWRB metric (3) is calculated as follows:

- Measure the engine deceleration when the LCW force equals 200 kN
    - If the engine deceleration < 500 m/s^2
        - Determine max F3 and F4 when total LCW = 200 kN
        - Apply following performance limits
            - F3 ≥ 35 kN
            - F4 ≥ 35 kN
            - F3 + F4 ≥ 100 kN
    - If engine deceleration > 500 m/s^2
        - Determine time when engine deceleration = 500 m/s^2 (t_{ENG500}).
        - Determine total LCW force at time t_{ENG500} ($F_{T\ ENG500}$)
        - Determine F3 and F4 at time t_{ENG500} ($F3_{ENG500}$; $F4_{ENG500}$)
        - Apply following performance limits:
            - $F3_{ENG500} \geq (35/200)\ F_{T\ ENG500}$ kN
            - $F4_{ENG500} \geq (35/200)\ F_{T\ ENG500}$ kN
            - $F4_{ENG500} + F3_{ENG500} \geq (100/200)\ F_{T\ ENG500}$ kN

Notes:

1. 500 m/s^2 was chosen for the engine deceleration because this is approximately the max deceleration of car's compartment in a full width test.

For the Daihatsu Esse the FWRB metric (3) assessment is made at 9.6 ms into the impact instead of at 11.1 ms had no engine dump loading been present (Figure 3.27). The required row load performance limits were met easily (Figure 3.28).

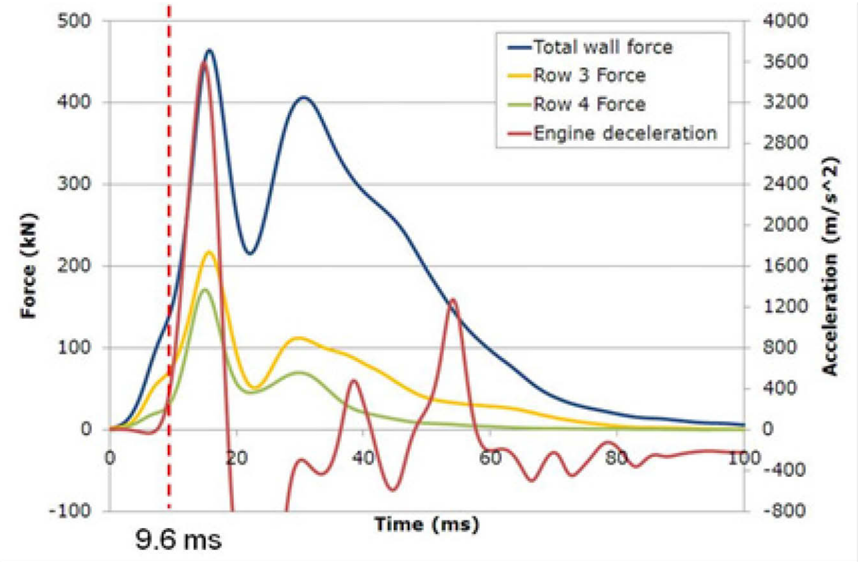


Figure 3.27: LCW total and row forces and engine deceleration for Daihatsu Esse.

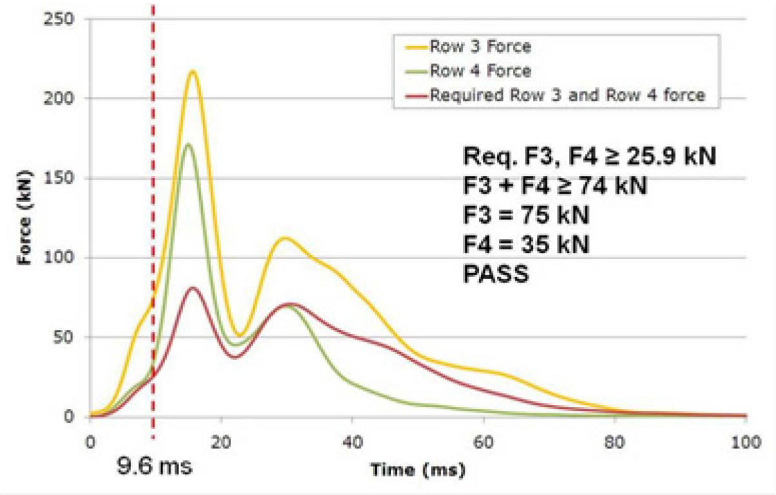


Figure 3.28: FWRB metric (3) assessment of Daihatsu Esse car earlier in impact (9.6 ms) showing that proposed performance requirements are met.

It should be noted that using FWRB metric (3) does not change the correlation of the metric assessment with the geometric assessment. This is because there were no cars in the data set for which engine dump loading affected the result of the metric assessment. However, it is theoretically possible that engine dump loading could affect the result of the assessment, for example a car could be designed with no structure in alignment with Row 4 and the engine positioned such that it loaded Row 4 to meet the Row 4 load requirement before the LCW total force reached 200 kN. This car could meet the requirements of the FWRB (1) and FWRB (2) metrics but would fail to meet an assessment earlier in the impact, i.e. the FWRB (3) metric requirements.

This metric still could be incorporated into FWRB metric (2) if it is decided that it is needed, i.e. if it is decided that the issue of engine dump loading with Japanese mini-cars is a significant problem which manufacturers may exploit to cheat the test.

Discussion and Conclusions

Three metrics have been developed for the FWRB test. The first two of these are based on an assessment of the force distribution on the LCW when the LCW total force is 200 kN. This is to ensure that the assessment is made before engine dump loading occurs and is hence not incorrectly influenced by it. The 3rd metric is a possible upgrade to the 2nd metric to ensure the correct assessment of a limited number of cars (some Japanese minicars) for which engine dump loading occurs before the LCW total force is 200 kN. For the test data available these metrics show reasonable correlation with a geometric assessment of the vehicles based on the principles of the US voluntary commitment to improve the compatibility of LTVs.

It is believed that FWRB metric (2) is a better way forward than FWRB metric (1). This is because FWRB metric (2) contains a mechanism to not discourage and possibly encourage vehicles to have load paths below the common interaction zone, whereas FWRB metric (1) does not. These load paths have been shown to help a vehicle’s structural interaction potential. If it is decided that the issue of engine dump loading with Japanese mini-cars is a significant problem, it is recommended that the FWRB metric (2) should be upgraded to incorporate FWRB metric (3) to overcome this problem.

For all the metrics developed it is still uncertain whether or not a second stage for the assessment of vehicles that do not have their most forward structures in alignment with the common interaction zone is necessary. Because development of a second stage is a substantial task limited work has been performed on its development to date. This can be done when it is certain it will be needed. At present work is planned in FIMCAR Work Package 6 to try and clarify whether or not a second stage is needed.

It should be noted that some FIMCAR partners have expressed concern about the metrics that have been developed, in particular the meaningfulness of an assessment so early in the impact, i.e. at 200 kN LCW total force. For some vehicles this point occurs before the vehicle’s crush cans have crushed completely and their main crash structures start to deform. Hence, the concern is that the metrics developed do not assess the performance of the vehicle’s relevant crash structures directly and therefore could incorrectly assess the vehicle’s structural interaction potential. This is a valid concern. One can envisage a problem for vehicles which have a forward structure (i.e. crush cans) which is at a different height to its main crash structures. However, most vehicles have their forward structure in alignment with their main crush structures so its height is representative of the main crash structures. Even so for many vehicles the cross-sectional height of the crush cans is not as large as the cross-sectional height of the main crash structure (longitudinals or PEAS). Ideally, the assessment should be made later in the impact but if this is done problems with engine dump loading occur. Hence, the current metrics for the FWRB represent the best compromise. However, if structures need to be evaluated later in the impact then the FWDB test metrics is probably the best way forward because the deformable element was developed to attenuate engine dump loads and hence enables an assessment even when engine loading is present.

3.3.3 Frontal Force Matching

In the description of compatibility characteristics, the FIMCAR consortium has listed "**Front End Force / Deformation"** as an area of compatibility that should be addressed. Within this area the concepts have been broken into two main subgroups as shown in Table 3.

Table 3: Compatibility Issues for Frontal Forces.

Front End Force / Deformation	
Deformation forces of frontal structures	**Energy Absorption Management**
Describes the frontal unit's deformation forces relative to the compartment strength of a partner vehicle	Vehicle frontal structure can absorb crash energy

"Deformation forces of frontal structures" is often discussed as "force" or "stiffness" matching and builds on the concept of sharing crash energy between the collision partners with a focus on car-vehicle impacts. "Energy absorption management" is related to the capacity of the structure in single vehicle crashes. *FIMCAR has determined that actions related to the deformation forces are not critical to resolve within the FIMCAR project but should be investigated.* Energy absorption is higher priority for FIMCAR but is not within the scope of this deliverable. An implicit assumption is that a crash barrier with minimal energy absorption capacity will ensure a minimum level energy absorption in the vehicle.

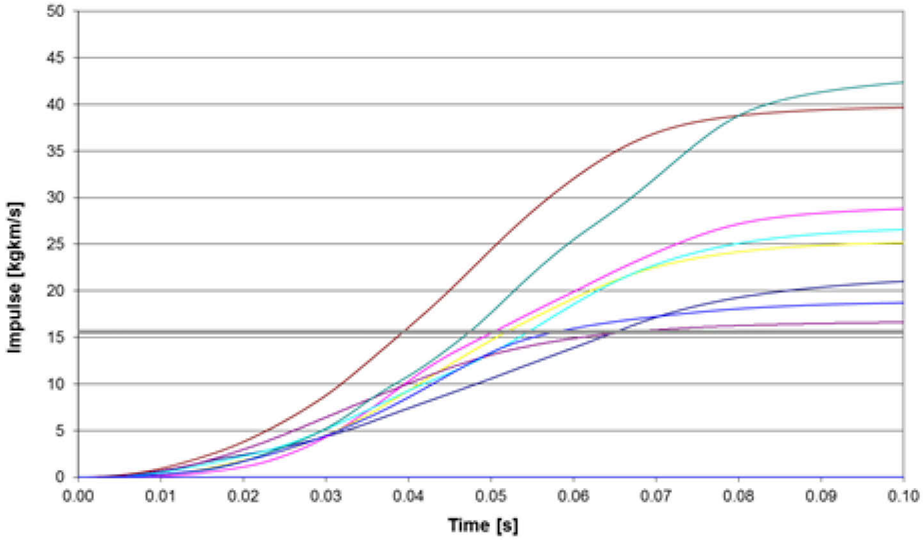
The basic physics of a collision were revisited in the development of a new performance criterion for frontal force levels. In a crash, the collision forces act over the period when the vehicles undergo a delta-v governed by their masses. Using this concept, one could specify that the force levels exchanged between the two vehicles should never exceed the compartment strength of the weakest vehicle. The concepts of impulse and momentum can be used to relate the car-to-car collision to the car-to-barrier collision. The momentum transfer between the vehicles causing the resulting delta-v can be considered equivalent to the impulse imparted on the barrier face during a crash test.

The proposed metric is based on a reference collision that causes a 1,000 kg vehicle to experience a velocity change of 56 km/h (15.6 m/s). Although the delta-v can be higher depending on the closing speed and mass ratio, the assumption is that a small car compartment can at least support the frontal forces developed in the US NCAP 56 km/h full width impact. The resulting momentum/impulse magnitude is 15.6 kgkm/s. Using the relationship that impulse is the integral of force and time, the numerical integration of the total wall forces can be used to establish the point in time when 15.6 kgkm/s is obtained. This specifies the time window in which the forces of the vehicle must be less than a specific load that will not cause compartment collapse in the partner vehicle.

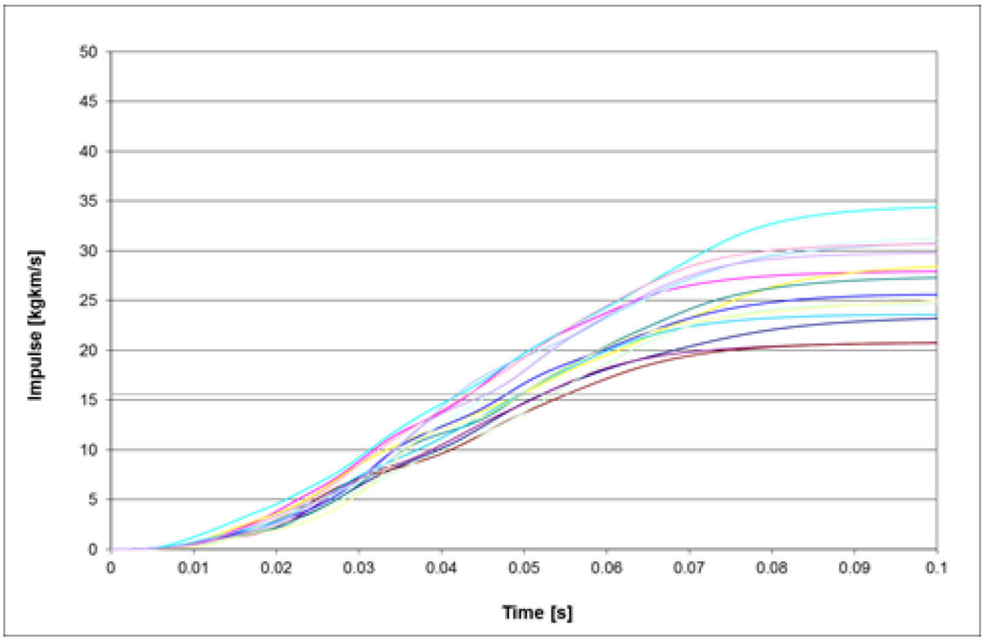
The threshold value for compartment collapse is still under discussion for offset tests although a value of 400 kN has been proposed for light cars [Faerber 2007, Edwards 2007]. Compartment collapse values for full width tests have not been truly investigated. However, since both car rails are loaded in a full width tests and tests have higher wall loads than offset tests, the 400 kN proposed for offset tests must be increased. A review of US NCAP forces suggests that a 600 kN force may be an initial threshold force for consideration. This value also represents a 60 g deceleration pulse for a 1,000 kg vehicle and is a challenge for restraint system designs in current vehicles.

3.3.3.1 Evaluation

Data from available full width deformable and rigid barrier tests were evaluated for this metric to establish the potential for this concept. As a starting point, Figure 3.29 shows the impulse/time relationship for tested vehicles with mass ranges between 900 kg and 2,500 kg. In both the rigid and deformable barrier tests it can be seen that the reference impulse level of 15.6 kgkm/s occurs between 40 and 50 ms for most cars. The deformable barrier delays the impulse curves slightly compared to the rigid barrier.



a) Deformable Barrier Data



b) Rigid Barrier Data

Figure 3.29: Impulse/Time curves in Full Width tests.

There is an issue for the criterion as the full width barrier records higher wall forces than in a real car-to-car impact due to the “engine dump” the sudden stop of the drive train in contact with an immovable wall which is not encountered in car-tp-car crashes. Since the reference impulse level occurs late in the impact, the artificially high contact loads of the drive train over-estimates the crash loads of the vehicle.

The next evaluation was to compare the contact forces of the vehicles with the impulse to identify the potential for controlling the frontal forces with the momentum based criterion. This data (for the FWDB) is shown in Figure 3.30 where the blue vertical line provides the limit of the force control (i.e., only forces left of the blue line are of interest for this metrics).

The most important information to note in Figure 3.30 is that there are three vehicles that exceed the 600 kN threshold and they exceed the 600 kN quite early in the crash. These vehicles are heavy vehicles over 1,800 kg. Figure 3.30 shows also the results of deformable barrier tests which attenuate the engine dump. Review of the rigid barrier tests showed that the engine dump effect was more pronounced and the 600 kN limit was observed for vehicles much lighter than 1.800 kg.

To understand if the forces measured in a crash against a barrier are similar to a car-to-car crash, the data from car-to-car and car-to-barrier tests were compared. The most noticeable effect was that the barrier force and the estimated contact forces for small cars were reasonably similar when a larger collision partner is involved. The FWRB is theoretically equivalent to a full frontal crash with an identical vehicle. However, the heavier vehicle experiences lower crash loads when in contact with a smaller collision partner than when in contact with a barrier. This is due to the physical limitation of the small collision partner to provide sufficient resistance to activate the heavy vehicle's structures and generate the same contact loads as in the fixed barrier test. As a result, the heavy vehicle force in a barrier test over-predicts its reaction forces against a smaller collision partner. There is the possibility to scale the contact forces by the mass ratio of the collision partner but this may not have sufficient accuracy for regulatory application.

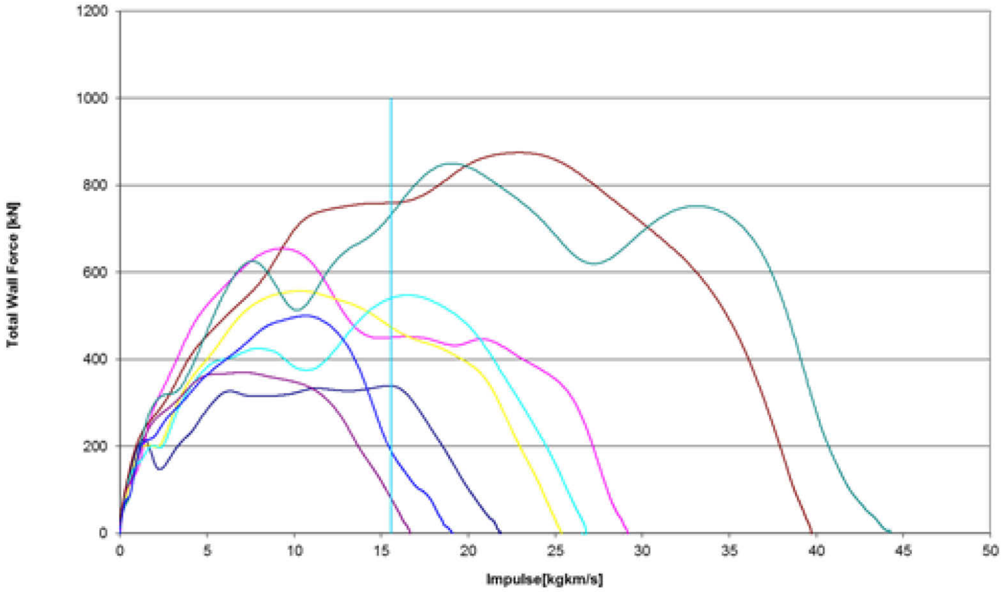


Figure 3.30: Load/Impulse curves for different vehicles.

3.3.3.2 Summary and Recommendations for FIMCAR

After reviewing the existing procedures (KW 400) and proposed impulse matching approach presented above, it is recommended not to pursue frontal force/stiffness matching criteria in FIMCAR. Deliverable D1.1 [Thompson 2013] and activities in WP6 have lowered the priority of developing this type of parameter, based on accident analyses.

The existing approaches to controlling force levels using a full width test were not suitable for the following reasons:

1) The forces in a full width test can overestimate the contact forces between vehicles due to the artificially high forces measured on a fixed barrier.
2) The crash loads measured on a barrier are not representative of a vehicle-to-vehicle collision when vehicles of different masses are involved. In particular, the heavy vehicle forces are overestimated.

4 VERFICATION OF TEST AND ASSESSMENT PROCEDURE

During the development of the metrics for the full width tests several issues arose which required further investigation. The initial issues which arose and the investigations performed using numerical modelling to resolve them are reported below. Issues which arose later and those which required test work to investigate them (such as load spreading of the deformable element and repeatability and reproducibility) will be reported in Deliverable 3.2 (Full width test protocol) / Section VIII.

In the following section, for both the FWDB and FWRB tests, the issues investigated are described together with the results and conclusions of the investigations. It should be noted that the numerical modelling work was performed by WP5 partners using the FE models that they developed for this project.

4.1 Issues

In this section an overview is given of the initial issues which have been investigated and the work undertaken to resolve them.

Table 4: List of issues and work undertaken to resolve them.

No.	Issue	Background	Method
1.	Towing hook FWRB	To investigate the effect of position on LCW force distribution and criteria. Is the load in LCW Row 3 and 4 influenced by a hard point such as the height of towing eye?	Simulation of different positions of towing eye against FWRB (Request 2)
2.	Towing hook FWDB	As above but for the FWDB	Simulation of different positions of towing eye against FWDB (Request 2 and 9)
3.	Bumper crossbeam at different height relative to longitudinals	The effect of the position of a bumper crossbeam on the LCW force distribution criteria and the performance of this car in a car-to-car test should be analysed	Analysis of previous crash test data. Also, simulation of bumper crossbeam positioned at same height as longitudinals and positioned completely below them for FWRB FWDB and car impacts (Request 1)
4.	Cross over vehicles	Investigate effect of ride height on the FWDB and FWRB assessment criteria	Simulation of cross over vehicles (Request 6)
5.	Step effects	A requirement of the FIMCAR consortium was that the metrics should not have a step effect	Simulations with the Parametric Car Models (PCM) by raising and lowering them in a stepwise manner (Request 7)

Simulations were used to address the issues listed in the Table 4 and hence verify the test and assessment procedures. As mentioned above the simulations were performed by WP5. To perform the required simulations WP3 made ‘requests’ to WP5. The results of the initial simulation Requests 1, 2 and 6 are described below. It should be noted that additional simulations were requested at a later date (Requests 7 and 9). The results of these simulations will be described in Deliverable 3.2 / Section VIII.

4.2 Results and Conclusions

In the following section the work undertaken is explained and analyses the issues in Table 4. The simulations are explained separately. In addition the analyses will be discussed, conclusions given, and how WP 3 decided to proceed.

4.2.1 Influence of Towing Hook on Full Width Metrics (Requests 2 and 9)

For both test procedures, FWRB and FWDB, the question came up, whether or not the loads in Row 3 and 4 of the LCW are influenced by a hard point such as the towing eye or the screw thread of this towing eye. To investigate the effect of the position on the LCW force distribution and the criteria, simulation of different positions and styles of towing eye against FWRB and FWDB have been conducted.

4.2.1.1 Protruding Towing Eye - FWRB (Request 2)

For these requests, simulations with a parametric car model PCM (category Executive) were conducted using different towing eye positions whereby the LCW force distribution and criteria were analysed. The towing eye design is simplified and consists of the towing eye itself and the towing eye support (see Figure 4.1) that is mounted on the right longitudinal with four spot-welds (see Figure 4.2).

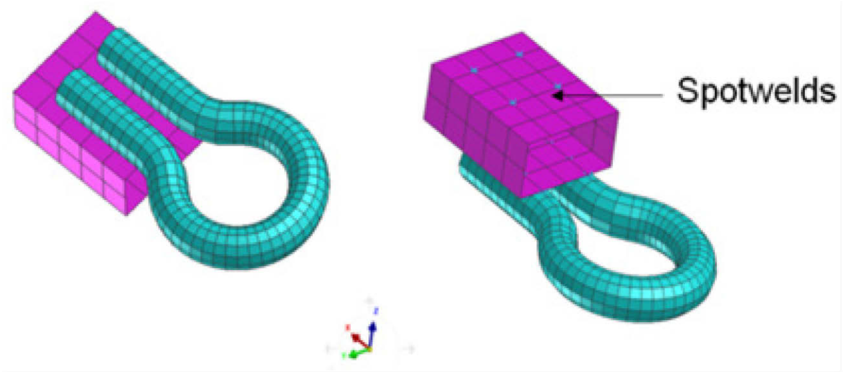


Figure 4.1: Towing eye with towing eye support.

Several assumptions (e.g., mass of towed vehicle 1,500kg, safety factor 2, material steel, only normal stress) for the design of the towing eye were made to identify the listed design parameters:

- Towing eye
    - Eye diameter = 70mm
    - Section diameter = 20mm
    - Penta elements
- Towing eye support
    - 60 x 30 x 75 mm (WxHxL)
    - t = 10 mm

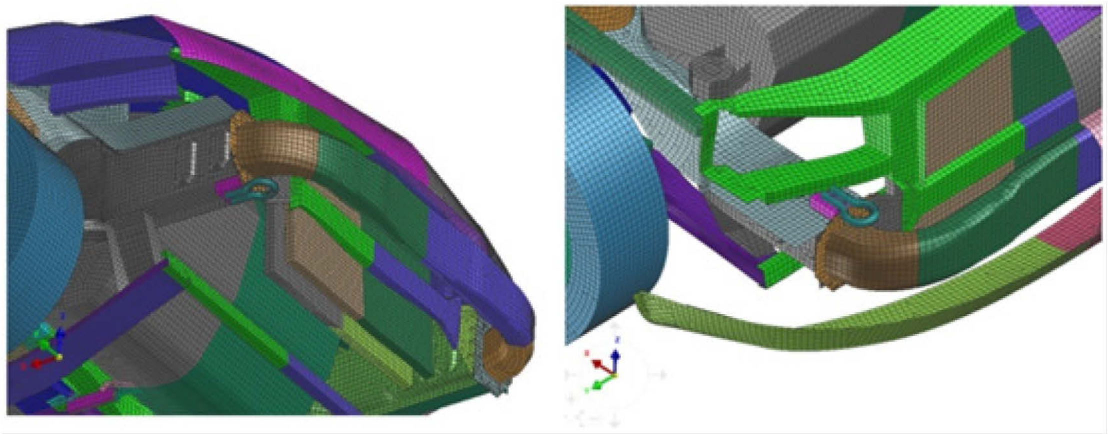


Figure 4.2: Mounting position of the towing eye on right longitudinal (left below longitudinal, right above longitudinal).

The towing eye was attached at two different positions at the right longitudinal, Figure 4.2. The impact location of the towing eye on the LCW was for the upper towing eye Row 5 and for the lower towing eye Row 3.

The simulations were conducted in general for both, the FWRB and the FWDB barrier. The unfiltered load cell wall forces of the FWRB test (basis, lower towing eye and upper towing eye) are shown in Figure 4.3. The impact of the towing eye is especially viewable in Rows 3 and 5 at around 15 ms (marked by red circles). These peaks disappear by application of the CFC60 filter which is recommended by SAE and ISO for load cell wall data.

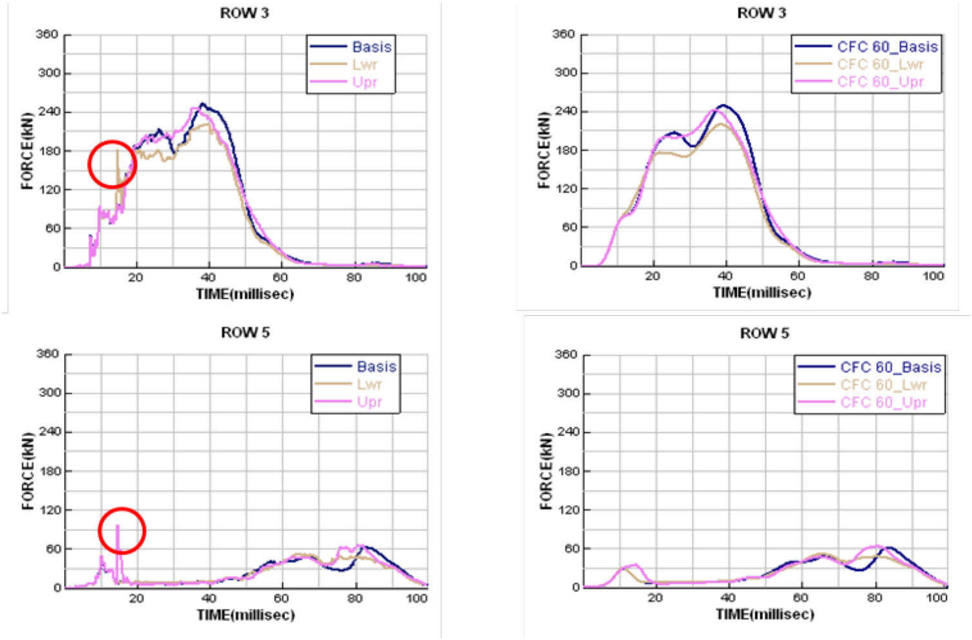


Figure 4.3: FWRB - Row 3 and 5 forces (left – unfiltered; right – filtered with CFC 60) (Impact of towing eye is marked by red circles).

The measured results of the FWRB test for Row loads 1 to 4 are summed up in Table 5. The towing eye produces no influence towards the FWRB metric functionality, when the CFC 60 filter is applied.

Table 6: Application of simulations to metrics – FWRB.

			w/o towing eye	**lower towing eye**	**upper towing eye**
FWRB (1) (Original metric)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		F3+F4 [kN]	166.7	166.9	167.2
		0.2 ≤ F4/(F3+F4) ≤ 0.8	0.62	0.63	0.62
FWRB (2) (Original metric with limit reduction)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		F3+F4 [kN]	166.7	166.9	167.2
		F3 [kN]	62.6	62.5	62.9
		F4 [kN]	104.1	104.4	104.4
		F1 [kN]	0.0	0.0	0.0
		F2 [kN]	1.5	1.4	1.4
		LR	0.0	0.0	0.0
FWRB (3) (Metric including engine dump)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		$a_{eng.force=200kN}$ [g]	6.1	6.3	6.3
		$t_{engine500}$ [ms]	-	-	-
		F3+F4 [kN]	-	-	-
		F3 [kN]	-	-	-
		F4 [kN]	-	-	-

Conclusions Towing Eye FWDB and FWRB Simulations

The simulations regarding the towing eye issues on the FWRB showed that in general the towing eye influences load cell wall readings if no filtering is applied to the load cell wall data. But if the data is filtered as recommended by the ISO standards, the small peaks are smoothed. In response to this finding the application of CFC 60 filtering is recommended to avoid undesirable influences due to hard points such as a towing eye.

4.2.1.2 Protruding Towing Eye - FWDB (Request 2)

The same simulation process was undertaken for the FWDB barrier with the parametric car models. In contrast to the FWRB test results, the towing eye may produce relevant force peaks even if the CFC 60 filter (see Figure 4.4, red circles) is applied. Additionally, dependent on the location of the towing eye different results could be achieved.

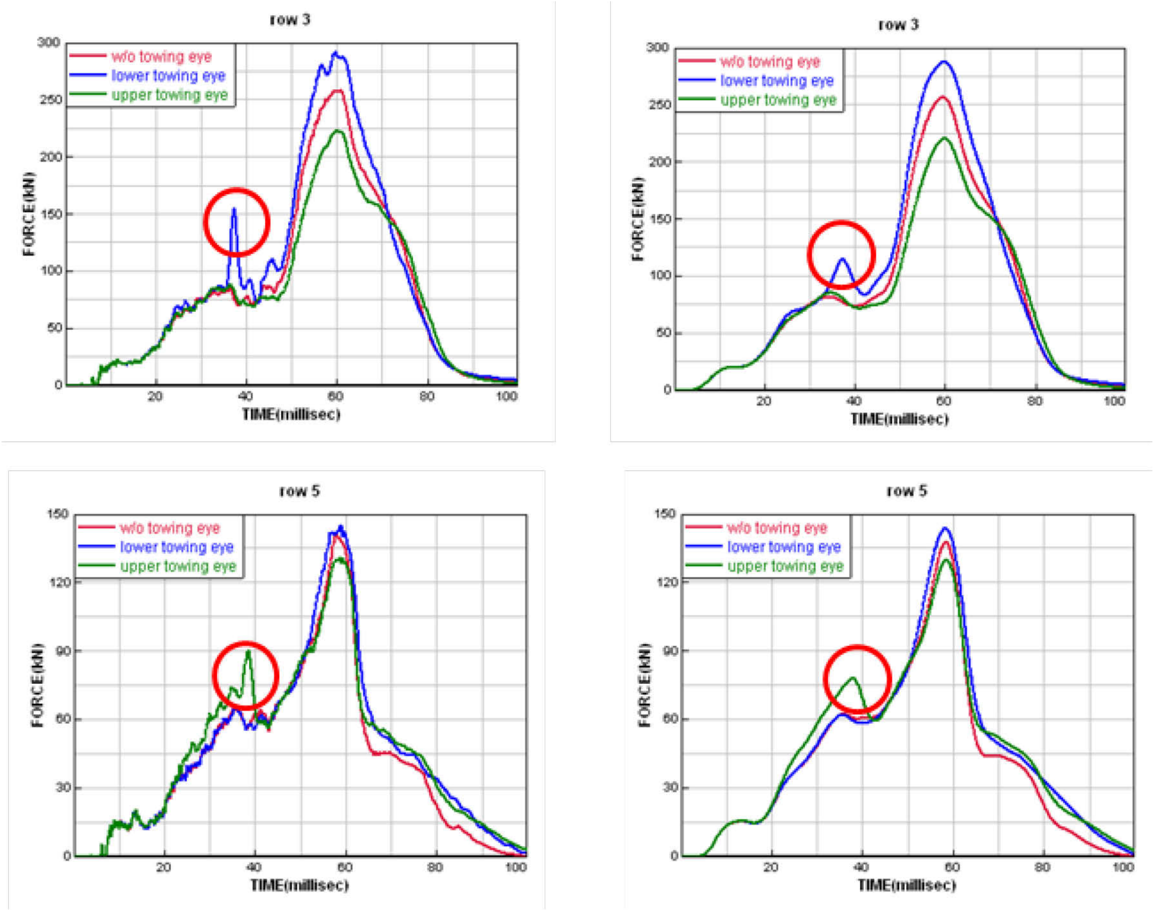


Figure 4.4: Row 3 and 5 forces (left – unfiltered; right – filtered with CFC 60) in x-direction (Impact of towing eye is marked by red circles).

Due to the deformable element in front of the rigid wall the towing eye was forced to deform in another way than in the FWRB test. This deformation applied enough forces to the wall to influence the sum forces of the corresponding row. Furthermore two different deformation behaviours could be observed (see Figure 4.5).

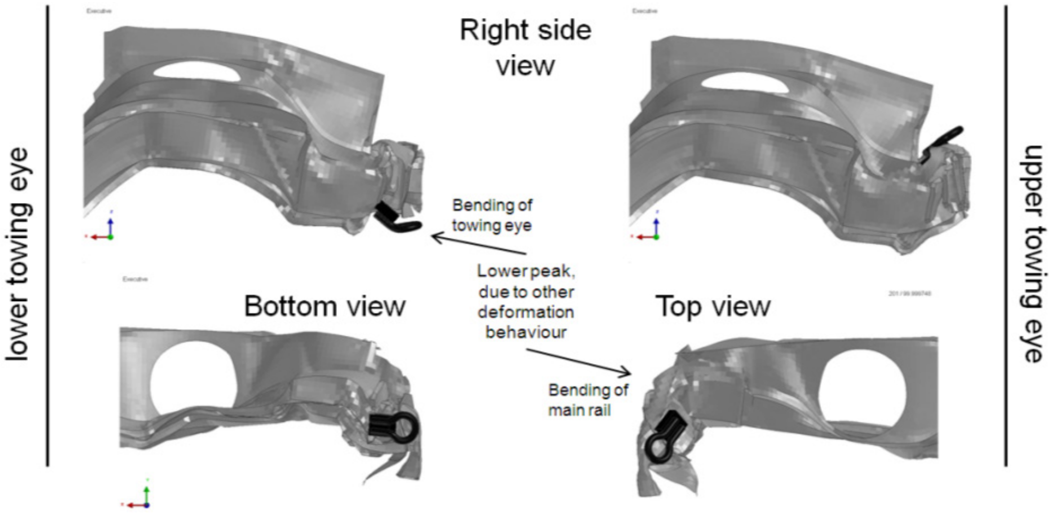


Figure 4.5: FWDB – Front structure deformations with lower and upper towing eye.

Table 7 summarises the measured load cell wall forces in the FWDB test according to Request 2 and indicates that this specific towing eye attached on the parametric car model can possibly influence the metric.

Table 7: Application of towing eye simulations to metrics – FWDB.

			w/o towing eye	**lower towing eye**	**upper towing eye**
FWDB (1)	up to LCW force 400 kN	$t_{sumforce=400kN}$ [ms]	37.3	43.0	40.9
		F3+F4 [kN]	257.33	247.0	245.7
		F3 [kN]	94.9	85.3	71.3
		F4 [kN]	163.2	161.7	174.4
FWDB (2)	up to 40 ms	F3 [kN]	89.8	94.3	72.2
		F4 [kN]	170.7	161.3	168.9
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	380.2	391.7
		0.2 * F_{t40} [kN]	78.7	76.0	78.3
		F3 [kN]	89.8	94.3	72.2
		F4 [kN]	170.7	161.3	168.9

4.2.1.3 Screw Thread - FWRB (Request 2)

Since today's vehicles are only equipped with a screw thread to attach a towing eye on the car, it seemed reasonable to model a rigid screw thread to investigate the influence in the test procedures. Following this the simulations were repeated simulating this screw thread.

The simplified (rigid) model of a screw thread was implemented at two different typical locations (see Figure 4.6).

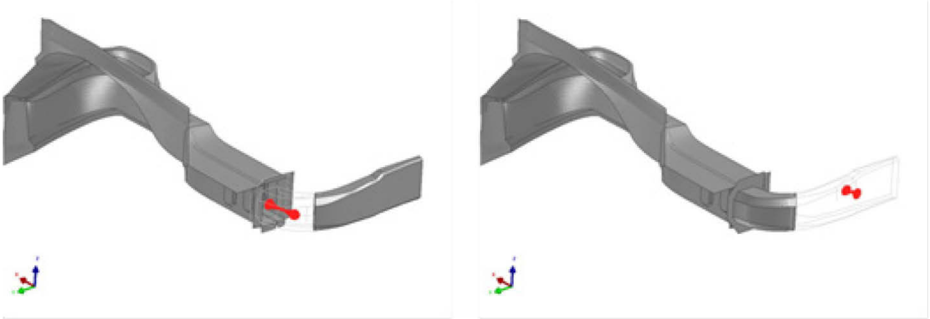


Figure 4.6: Screw thread at two different locations (left – in front of the longitudinal; right – on the right half of the cross beam).

The two models were crashed against the FWRB and FWDB. The results are comparable with those coming from the towing eye simulations. The screw thread has hardly any influence on the force distribution in the FWRB configuration, Table Table 8.

Table 8: Application of screw thread simulations to metric – FWRB.

			w/o towing eye	**longitudinal**	**center of right half of x-beam**
FWRB (1)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		F3+F4 [kN]	166.7	170.9	167.2
		$0.2 \leq F4/(F3+F4) \leq 0.8$	0.62	0.64	0.62
FWRB (2)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		F3+F4 [kN]	166.7	170.9	167.2
		F3 [kN]	62.6	61.9	63.3
		F4 [kN]	104.1	109.0	103.9
		F1 [kN]	0.0	0.0	0.0
		F2 [kN]	1.5	1.3	1.5
		LR	0.0	0.0	0.0
FWRB (3)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		$a_{eng.\_force=200kN}$ [g]	6.1	0.1	0.1
		$t_{engine500}$ [ms]	-	-	-
		F3+F4 [kN]	-	-	-
		F3 [kN]	-	-	-
		F4 [kN]	-	-	-

4.2.1.4 Screw Thread - FWDB (Request 2)

Compared with the FWRB simulations the screw thread influences the wall force, if there is a deformable element in front of the wall, Table 9.

.

Table 9: Application of screw thread simulations to metrics – FWDB.

			w/o towing eye	**longitudinal**	**center of right half of x-beam**
FWDB (1)	up to LCW force 400 kN	$t_{sumforce=400kN}$[ms]	37.3	42.0	40.7
		F3+F4 [kN]	257.33	258.0	251.6
		F3 [kN]	94.9	74.4	69.9
		F4 [kN]	163.2	183.6	181.7
FWDB (2)	up to 40 ms	F3 [kN]	89.8	71.3	68.4
		F4 [kN]	170.7	177.2	178.5
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	364.9	384.6
		0.2 * F_{t40} [kN]	78.7	72.9	76.9
		F3 [kN]	89.8	71.3	68.4
		F4 [kN]	170.7	177.2	178.5

The conducted simulations showed that a local high stiffness, like a towing eye or its screw thread, works different in the two test procedures. Where it has no influence in FWRB tests, the stiff parts are responsible for other deformation behaviour of the front structures and therefore another force distribution on the wall.

To understand the deformation mechanisms observed in the FWDB simulations caused by the stiff parts the simulations were repeated with more detailed vehicle models (GCM). This was formulated in a new simulation Request 9.

4.2.1.5 Towing Hook (Screw Thread) – FWRB (Request 9)

The Generic Car Model used for this analysis was the GCM1A, i.e. the representative of Supermini class characterised by a frontal structure without the third load path. The screw thread is located inside the right crashbox and it is connected to it through a flange: this is a typical solution adopted in order to avoid/minimise the interferences between the rigid screw thread and the walls of crashbox during their folding caused by frontal impacts. GCM1A model was run against the load cell rigid wall at 56 km/h with and without the rigid screw thread (see next **Figure 4.7**).

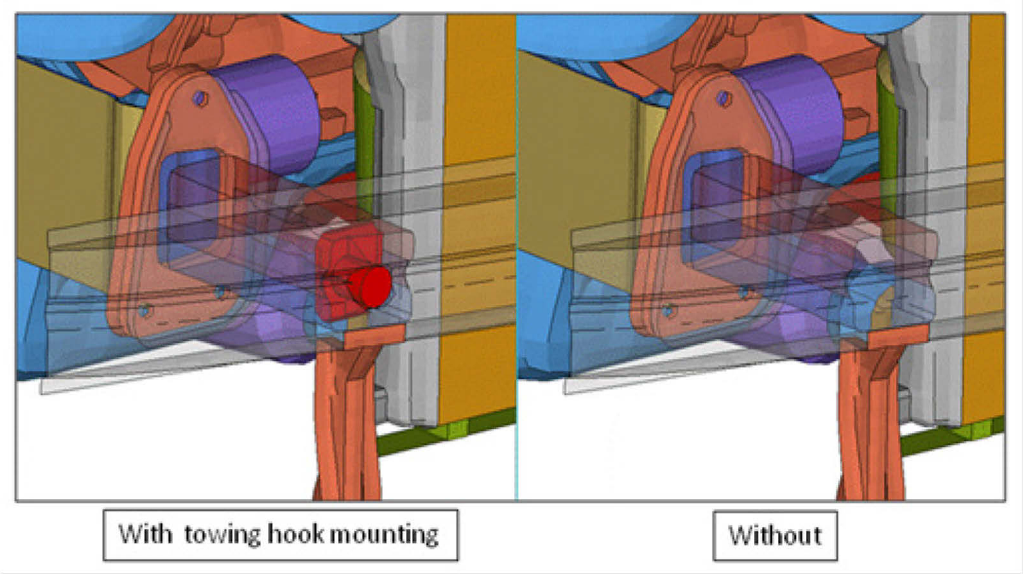


Figure 4.7: GCM1A– Right front crashbox with and without towing hook mounting.

Due to the just explained concept behind this typical solution for the towing hook mounting, no effects were detected on the load cell wall outputs as a consequence of its removal from the crashbox. In particular, the output of the load cell (named E3 in the used barrier model) directly impacted by the concerned part of the vehicle structure was examined and no differences were highlighted, for both filtered and unfiltered load cell signals. The next two figures visualise these obtained results.

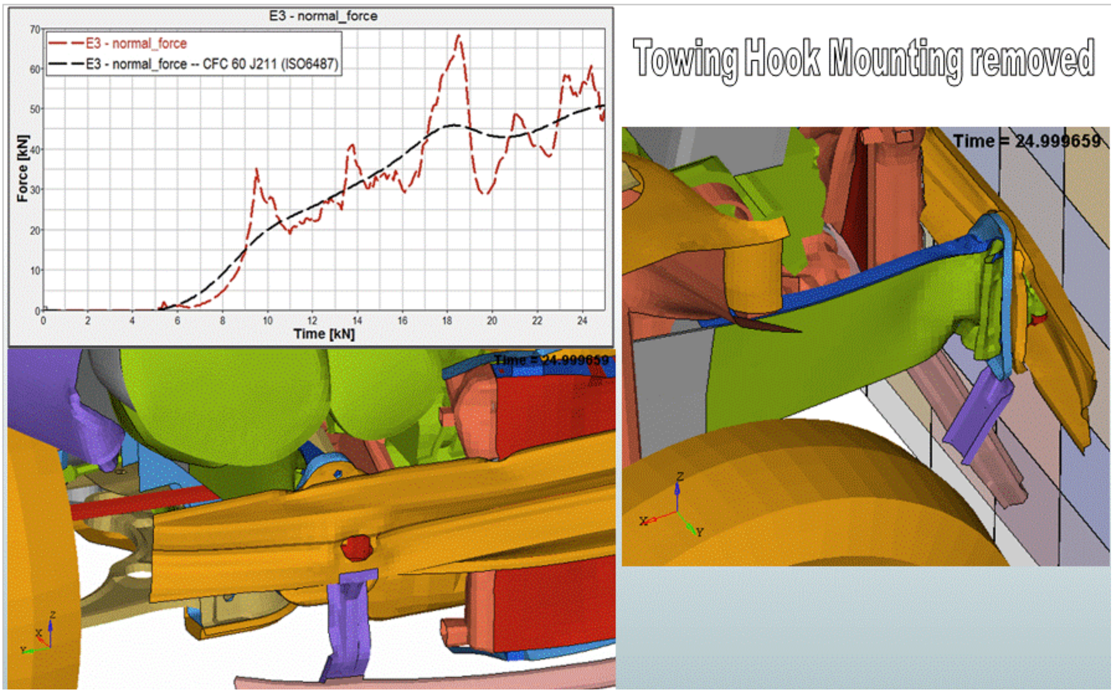


Figure 4.8: Load on directly impacted cell: run without towing hook mounting.

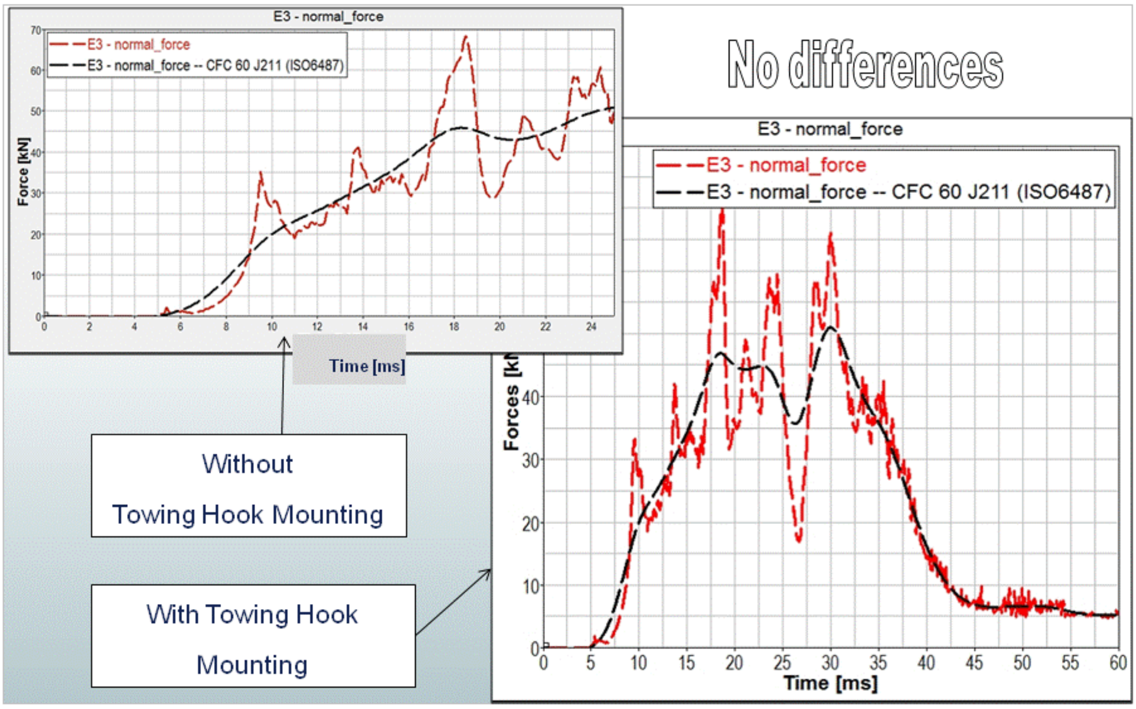


Figure 4.9: Load on directly impacted cell: comparison between runs with and without towing hook mounting.

4.2.1.6 Towing Hook (Screw Thread) – FWDB (Request 9)

The same simulation process was done for the GCM1A impact against FWDB barrier at 56 km/h. The presence of the deformable element changes the deformation mode of the crashbox, w.r.t. the collapse observed in the impact against the rigid wall: in fact the crashbox now is subjected to a downward bending, instead of collapsing axially in folding (see **Figure 4.10**, were the deformed structures, with and without towing hook mounting, are shown against the complete deformable element in the upper part and with the first layer of FWDB masked in the lower part).

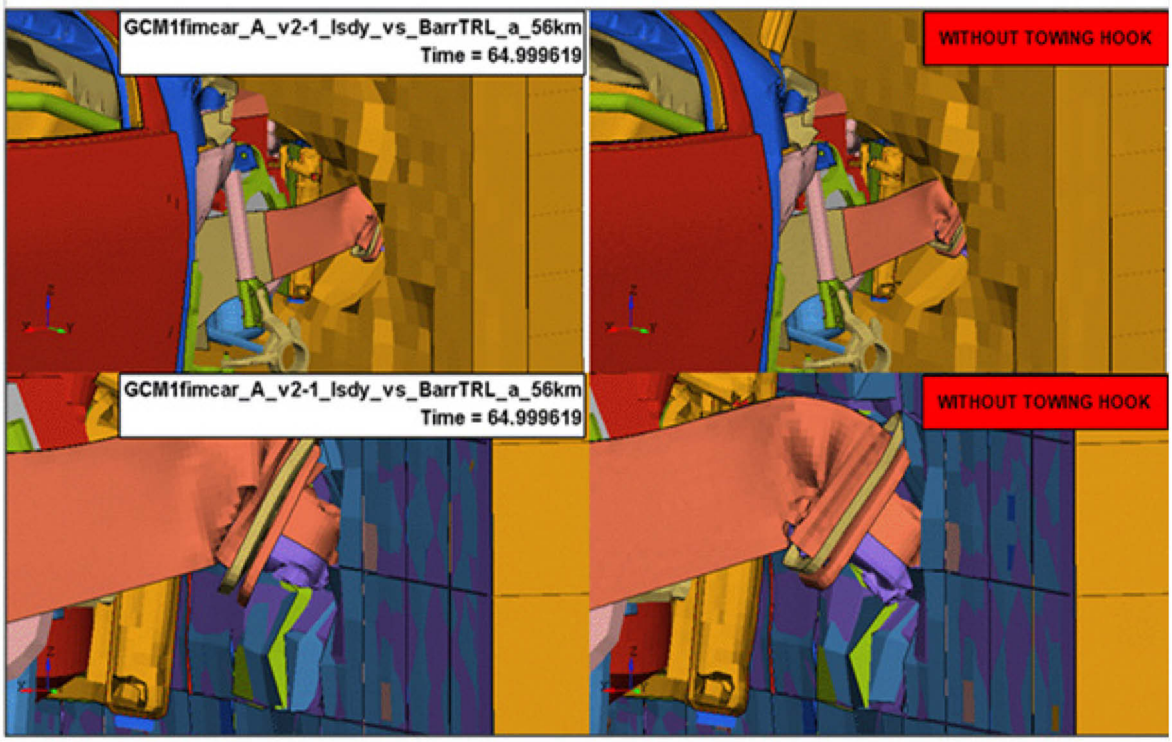


Figure 4.10: GCM1A-to-FWDB: structural deformations with and without towing hook mounting.

Some very slight differences were detected when the total barrier forces and the loads in Row 3 and Row 4 were compared for the two simulations: the analysis of the deformed shape of the crashbox and main rail highlighted only few small local differences in the way the section walls collapse. However, these differences are not affecting significantly the overall collapse mode of the structure and if the outputs from the two load cells directly behind the area covered by the concerned structure (named E3 and E4 in the model) are examined, no significant differences between load–time histories are detected, for both unfiltered and filtered signals.

The following Figure 4.11, Figure 4.12 and Figure 4.13 show the above mentioned situation.

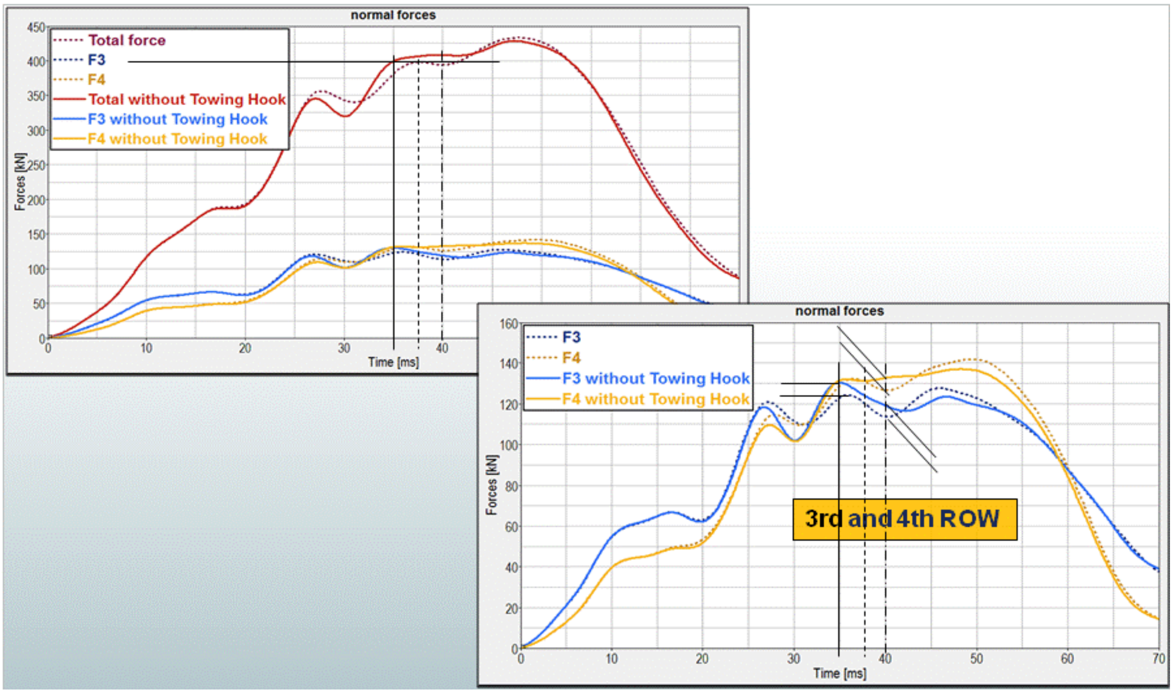


Figure 4.11: GCM1A-to-FWDB: Total, 3^{rd} and 4^{th} row forces vs. time plots, with and without towing hook mounting.

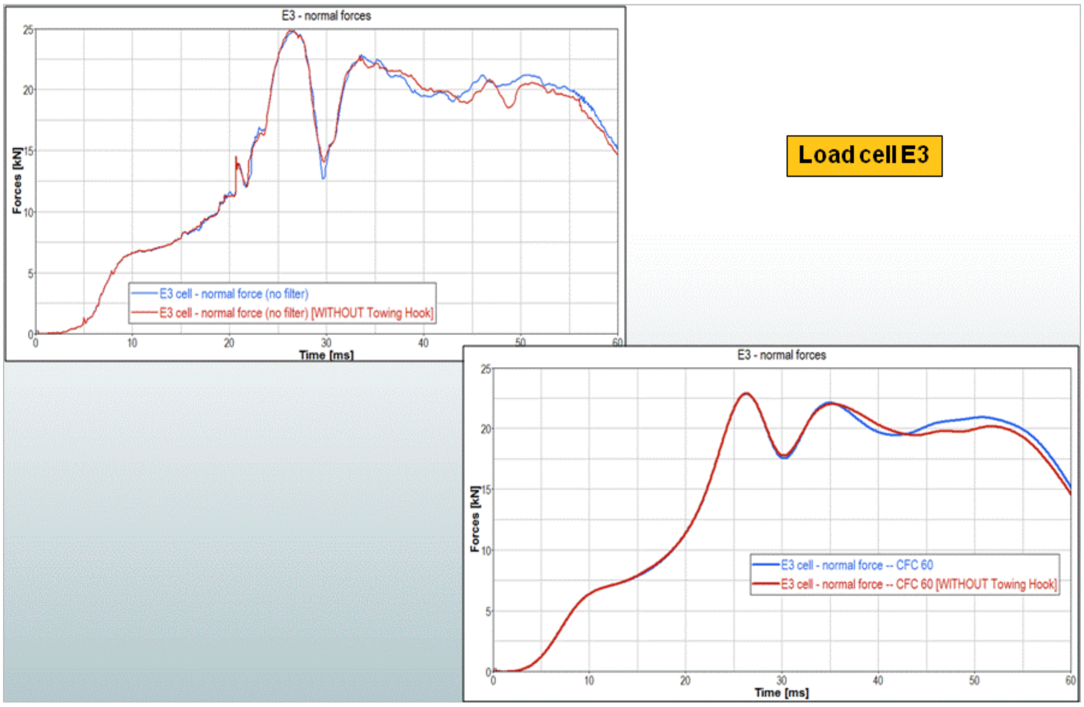


Figure 4.12: Load on (lower) directly impacted cell: comparison between runs with and without towing hook mounting.

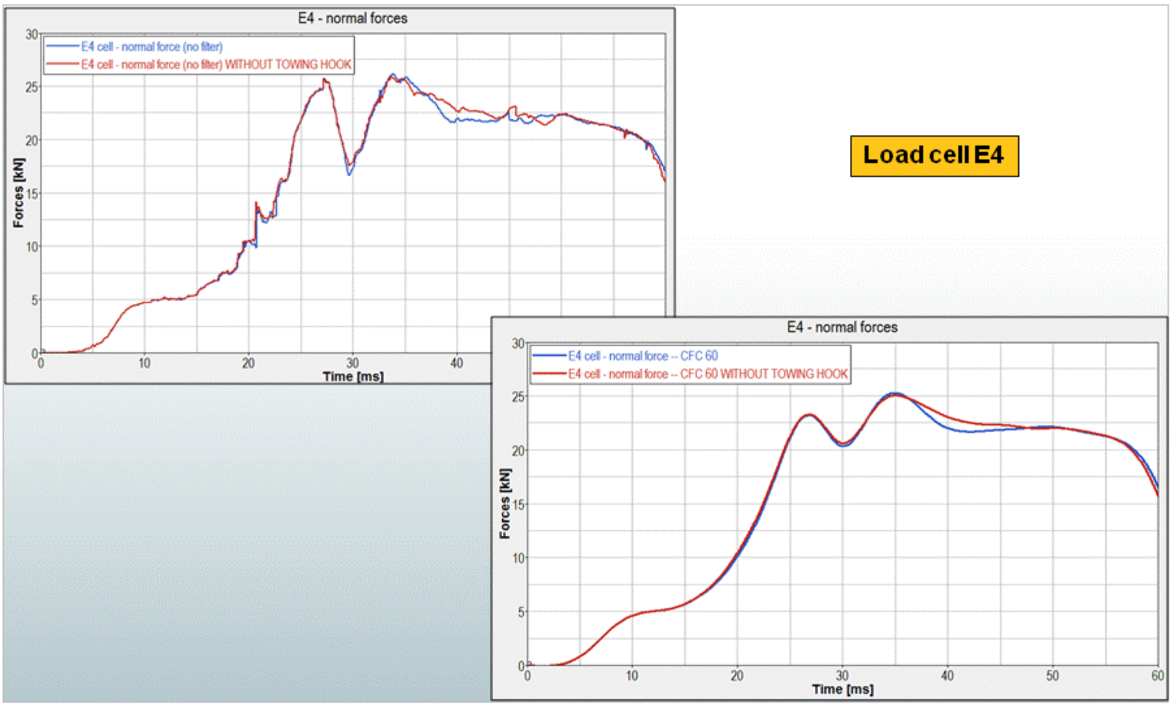


Figure 4.13: Load on (lower) directly impacted cell: comparison between runs with and without towing hook mounting.

4.2.1.7 Conclusions from Requests 2 and 9

For the FWRB differences in the LCW readings were observed using the PCM approach and protruding towing eyes before filtering. However, applying the standard filter for load cell wall data (CFC 60) the effect disappeared. In addition the influence was not observed when the standard bolt-in type was used. For FWDB the old type of towing eye could influence the metric even with a CFC 60 filter. However, the bolt-in type of towing eye used on modern vehicles showed no influence with a CFC 60 filter.

4.2.2 Variable Cross Beam Height (FWRB and FWDB) (Request 1)

For this request the parametric car model, category “Executive” was chosen as the basis model and the “Super Mini” is used exclusively for car-to-car simulations. Within the conducted simulations against the FWRB (test vehicle speed: 56 km/h) specified modifications (see Table 10) are considered in a four-step approach. The main objective of this simulation addresses the possibility to pass the metric with a cross beam which is attached in the preferred height while the location of the longitudinal is not. To investigate this objective goals are defined on the one hand to pass the metric anyway and on the other hand to compare the metric assessment and car-to-car simulations.

Table 10: Vehicle structure modifications used for Request 1.

Modification (abbreviation)	Description
mod_1	Increase the vertical position of the longitudinals and cross beam until the vehicle fails the metric
mod_2	Lowered cross beam and variations of connections and stiffness of the structures (cross beam below and within main rails)
mod_3(_1/2)	Cross beam below main rails, but in front of them, different connection stiffness
mod_4	Lowered cross beam (misalignment of structures)
mod_5	Same configuration like mod_4, but placed as far forward as possible

As first step the height of the longitudinals and the crossbeam is increased by 50 mm that implies failing of both metrics and is shown in Figure 4.14.

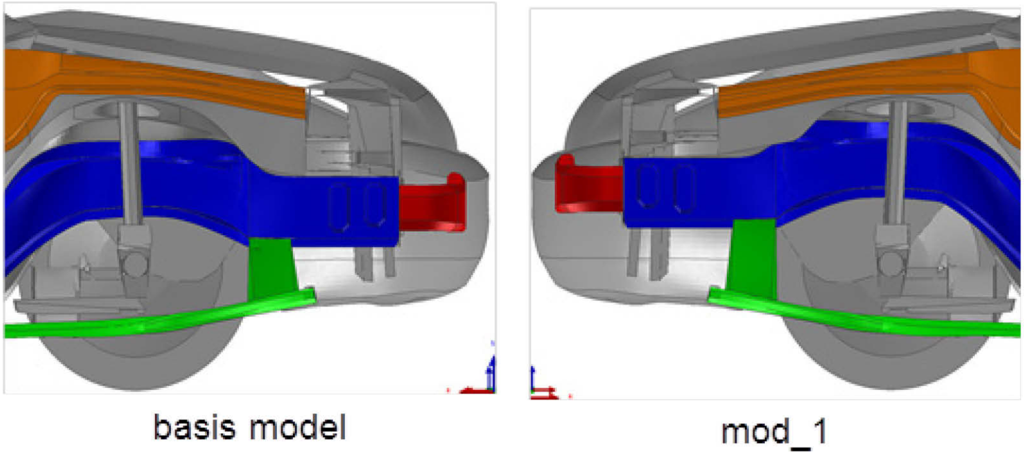

basis model
mod_1

Figure 4.14: Step 1 - modification 1.

In a second step, the height of the crossbeam is decreased. For that purpose the original connection between cross beam and longitudinals was deleted and a new one was designed. Hereby, connection issues appear on the one hand due to missing information about the real connection points and on the other hand the deformation behaviour of the longitudinals is strongly influenced by the plastic buckling. Furthermore, the new crossbeam is placed in front of the longitudinals with different stiffness. The modifications 2 and 3 are shown in Figure 4.15.

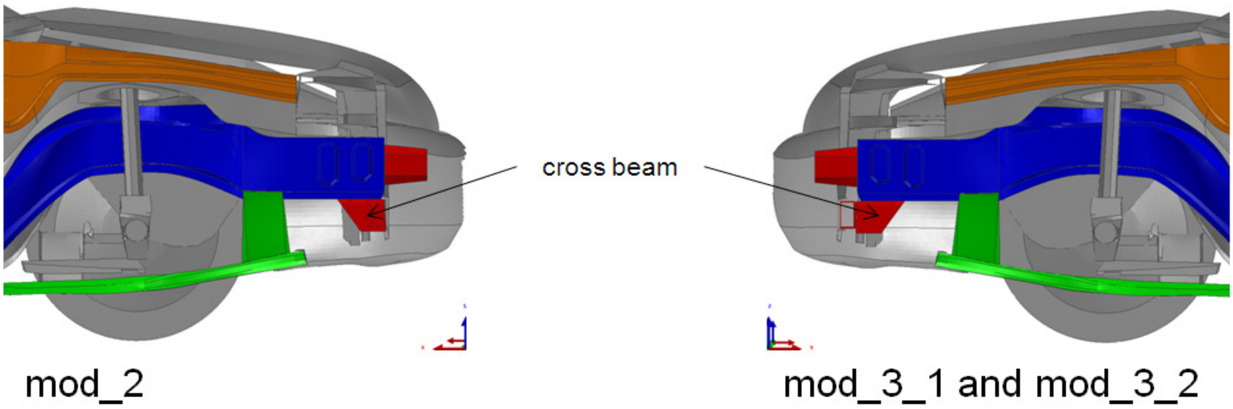


Figure 4.15: Step 2 - modifications 2 and 3.

In the third step the height of the crossbeam is decreased so that there is a geometrical mismatch between the crossbeam and the longitudinals (dotted line in Figure 4.16).

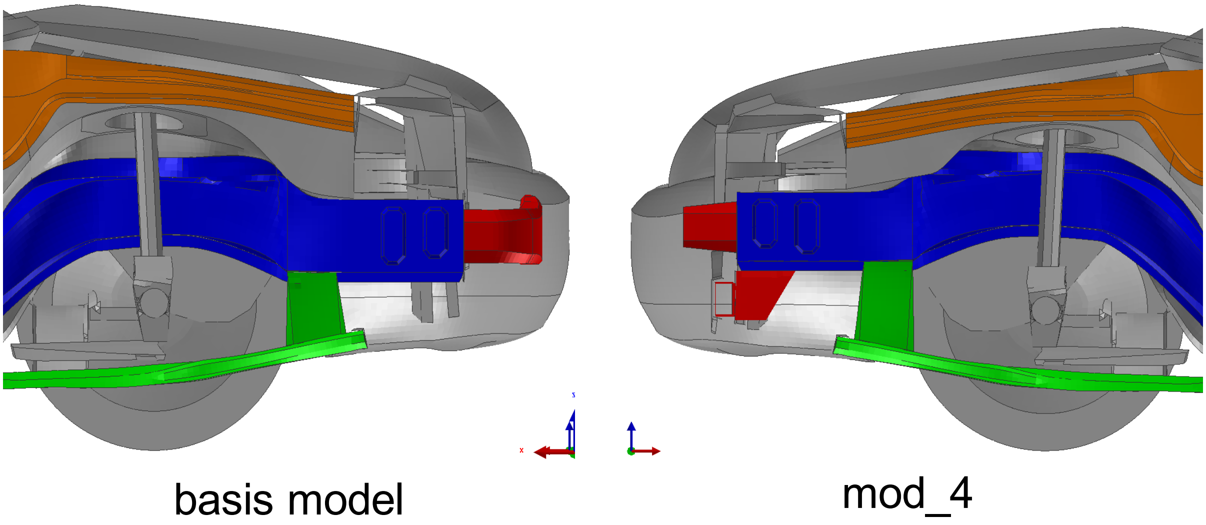


Figure 4.16: Step 3 - modification 4 against the basic model.

For the last modification the cross beam attachment of modification 4 was used. But the crossbeam was moved far as possible to the front bumper (see Figure 4.17). The intention of this was to check if the crossbeam is capable to apply enough forces to the wall to pass the metrics.

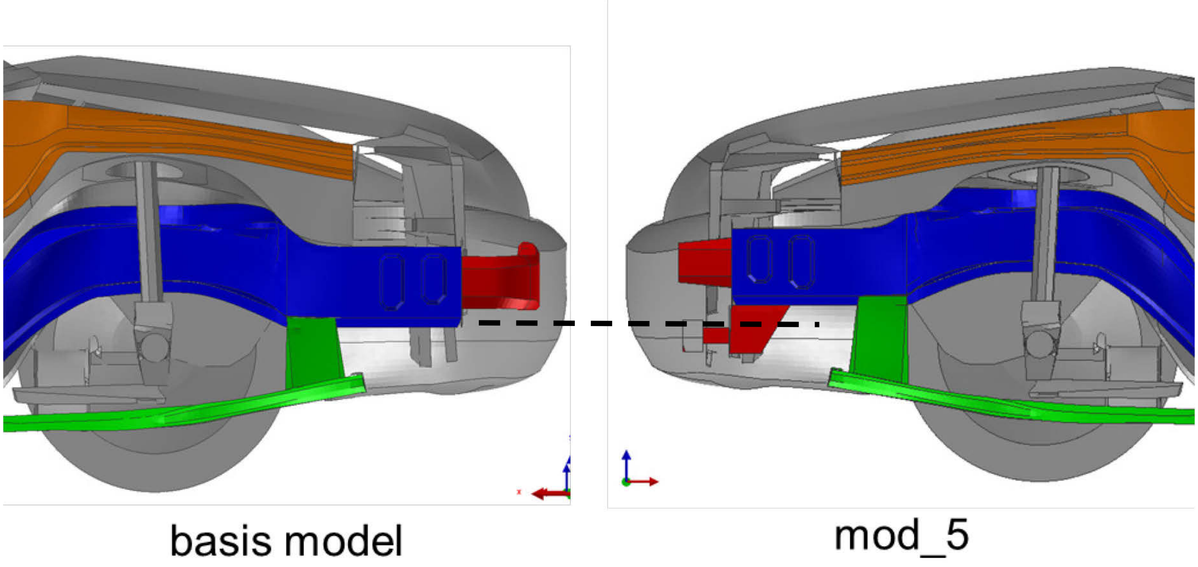
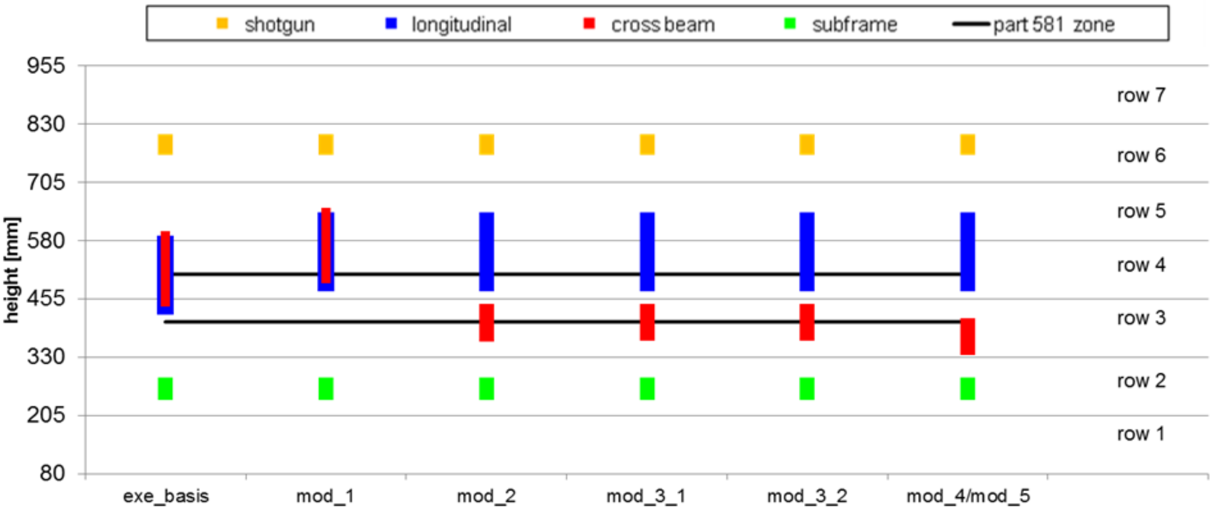


Figure 4.17: Step 4 - modification 5 against the basic model.

All modifications and hence modified heights of the energy absorption structures (EAS) are shown in Figure 4.18 together with the basic model and the part 581 zone (common interaction zone).



mod_1 = increased height of cross beam
mod_2 = cross beam below and within main rails
mod_3(_1/2) = cross beam below main rails, but in front of them, different stiffness of connection
mod_4 = lowered cross beam (misalignment of structures)
mod_5 = cross beam moved far as possible to front of vehicle

Figure 4.18: Geometric results of modifications 1 to 5.

The model with the different structure changes was tested against the FWDB and the FWRB. The final results for the different row load out of the conducted simulations for Request 1 and the metric application for the FWRB are summarised in Table 11.

Table 11: Application of simulations to metric – FWRB.

		basis	**mod_1**	**mod_2**	**mod_3_1**	**mod_3_2**	**mod_4**	**mod_5**
FWRB (1)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	F3+F4 [kN]	186.9	106.4	122.4	140.8	145.7	131.2	120.6
	$0.2 \leq F4/(F3+F4) \leq 0.8$	0.64	0.98	0.89	0.72	0.72	0.75	0.77
FWRB (2)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	F3+F4 [kN]	186.9	106.4	122.4	140.8	145.7	131.2	120.6
	F3 [kN]	67.5	2.3	13.03	40.0	40.4	32.2	28.3
	F4 [kN]	119.5	104.1	109.4	100.7	105.3	99.0	92.3
	F1 [kN]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	F2 [kN]	1.4	1.5	4.1	4.7	4.9	11.1	8.8
	LR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FWRB (3)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	$a_{eng.force=200kN}$ [g]	5.1	3.9	11.6	1.6	3.4	2.1	4.2

Within the analyses for the FWRB some remarkable observations were found:

- The wall force limit of 200 kN was reached later (10 ms → 17 ms) for the different modifications compared to the basis version. The engine dump occurs after ~55 ms.
- In the modification 3, an additional crossbeam was attached below and in front of the longitudinal. This modification (mod_3) was capable to apply enough forces to the LCW to fulfil the metrics of FWRB (1). However, the values were borderline.
- Modification 4 (structural mismatch with basis model) as well as modification 5 was not able to apply enough forces into Row 3 to pass the metric.

The final results out of the conducted simulations for Request 1 and the metric application for the FWDB are summarised in Table 12.

Table 12: Application of simulations to metric.

			basis	**mod_1**	**mod_2**	**mod_3_1**	**mod_3_2**	**mod_4**	**mod_5**
FWDB (1)	up to LCW force 400 kN	$t_{sum400kN}$[ms]	37.3	44.0	42.5	45.0	39.3	45.3	44.0
		F3+F4 [kN]	257.3	204.84	226.6	208.7	206.3	205.6	207.5
		F3 [kN]	94.1	36.9	61.6	56.3	70.4	50.0	55.4
		F4 [kN]	163.2	167.9	165.0	152.4	135.9	155.6	152.1
FWDB (2)	up to 40 ms	F3 [kN]	89.8	39.0	84.8	60.4	68.33	58.9	50.4
		F4 [kN]	170.7	158.0	120.6	133.3	147.9	137.4	99.1
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	376.4	367.7	371.3	412.1	377.4	307.5
		0.2*F_{t40}[kN]	78.7	75.3	73.5	74.3	82.4	75.9	61.5
		F3 [kN]	89.8	39.0	84.8	60.4	68.33	58.9	50.4
		F4 [kN]	170.7	158.0	120.6	133.3	147.9	137.4	99.1

Within the analyses for the FWDB following remarkable observations were found:

- The wall force limit for 400 kN was reached after a later time (37 ms versus 44 ms), whereby no engine dump occurred.
- The basic model fulfils the requirements for all proposed metrics.
- The modification 2 (lowered cross beam) also fulfils the requirements of the metrics while this was not the case for the other modifications.

Comparing the results for the FWRB and FWDB differences are identified in the deformation behaviour of the PEAS. The honeycomb hardness is responsible for the bending of the lowered crossbeam (no supporting structures behind the crossbeam) and hence the applied forces on the LCW in the FWDB test are lower than in the FWRB test. The vehicle would pass the FWRB test, but would fail the FWDB test. Figure 4.19 shows the varied results of the deformed crossbeam for both barrier tests.

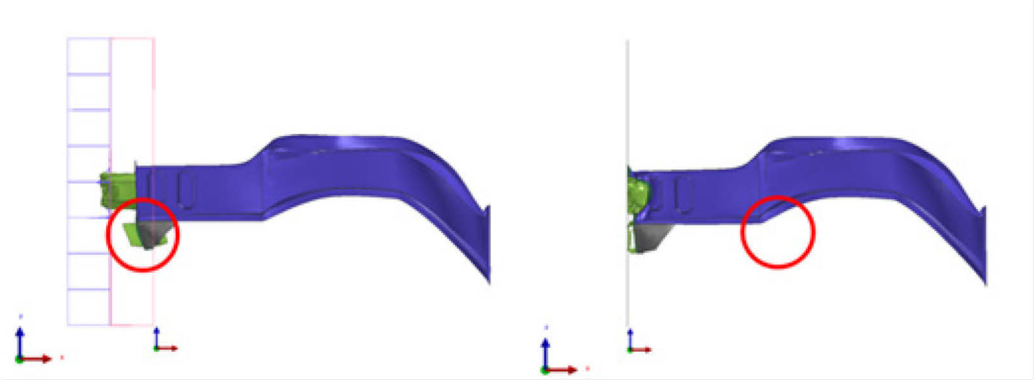


Figure 4.19: Deformation of the attached crossbeam in FWRB and FWDB test.

Conclusions Requests 1

When the test data from Japan was analysed, one vehicle was conspicuous. This vehicle has a crossbeam attached underneath the PEAS structure and this crossbeam produced forces in Row 3 and 4 although the PEAS were partially above these two rows.

In simulation Request 1, it was investigated whether or not adequate structures in Row 3 and 4 can be mocked up in FWRB and FWDB tests. The simulation results showed that depending on the specific design of the structure it is possible to influence the metric in particular with the rigid barrier. On the other side the deformable element in the FWDB test alters the deformation pattern in a way that the real load paths can be detected. Following this the FWDB is able to detect weak structures that are not supported by stiff structures behind them. In case of a collision these weak structure are not capable to offer the opposing car a possibility to interact properly.

4.2.3 Cross-Over Vehicles (Request 6)

The aim was to simulate cross-over vehicles in order to investigate the effect of differences in ride heights according to FWB assessment criteria. Simulations were conducted with the parametric car model (Large Family Car) which is tested against the FWRB and the FWDB. The cross-over version is modified by a horizontal offset of the barrier of 60 mm.

The simulation with the FWRB results in the LCW forces are shown in Figure 4.20 without the applied offset and in Figure 4.21 with the barrier offset of 60 mm.

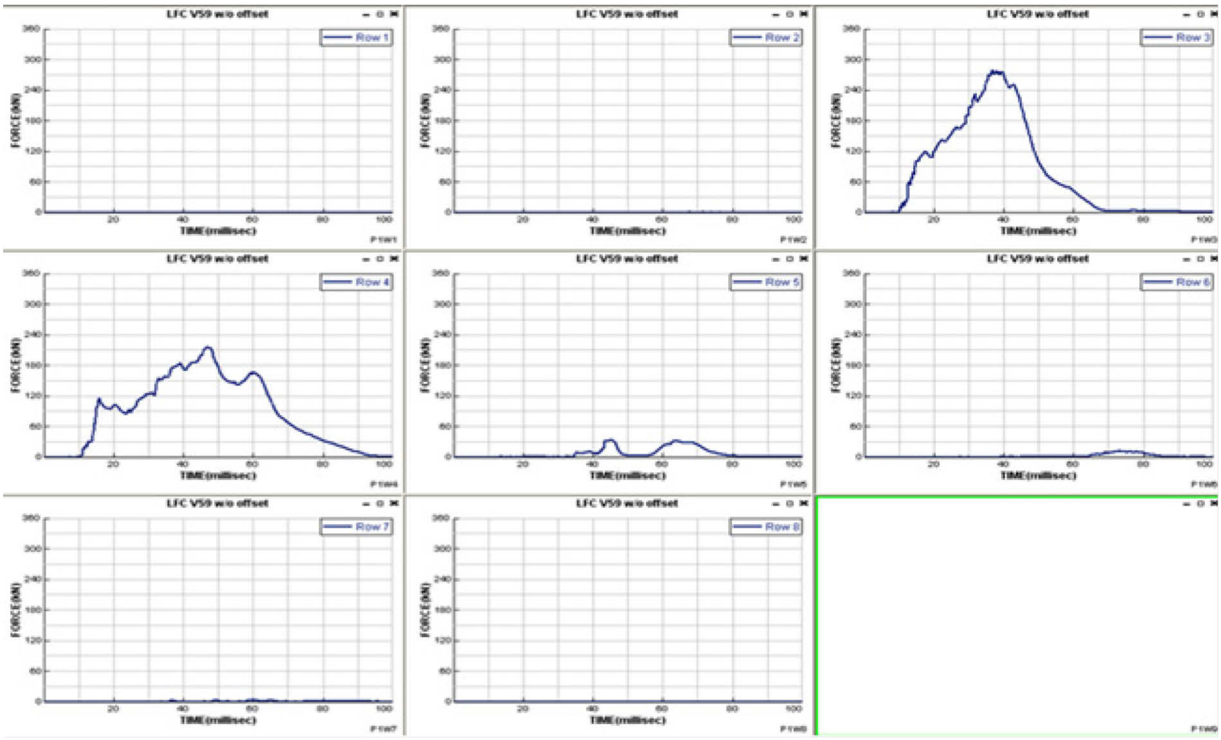


Figure 4.20: FWRB - Load cell wall forces in x-direction (without offset).

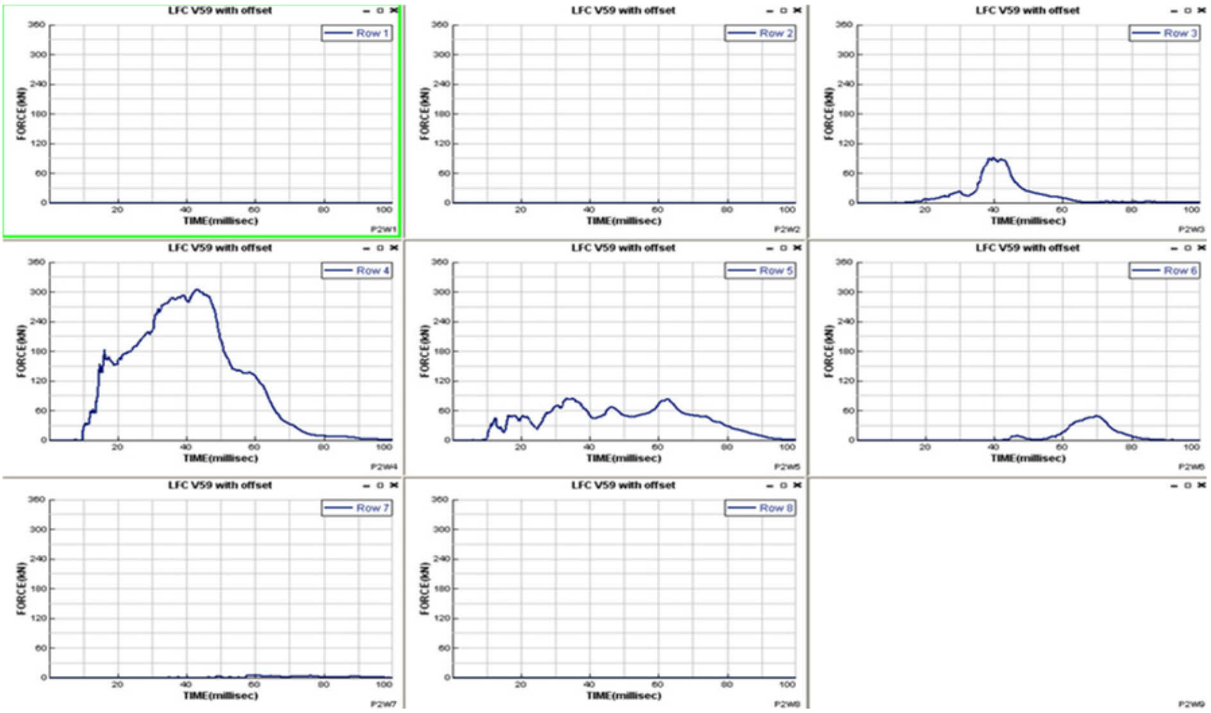


Figure 4.21: FWRB - Load cell wall forces in x-direction (with barrier offset).

Figure 4.21 summarises the measured load cell wall forces in the FWRB test with and without barrier offset according to Request 6 and indicates that the cross-over vehicle would fail the metric.

Table 13: Application of simulations to metric – FWRB

			LFC	LFC - offset
FWRB (1)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		F3+F4 [kN]	191.6	134.4
		0.2 ≤ F4/(F3+F4) ≤ 0.8	0.5	0.95
FWRB (2)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		F3+F4 [kN]	191.6	134.4
		F3 [kN]	94.9	7.1
		F4 [kN]	96.6	127.3
		F1 [kN]	4.8	0.0
		F2 [kN]	17.3	0.9
		LR	0.0	0.0
FWRB (3)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		$a_{eng.force=200kN}$ [g]	13	13

Repeating these simulations per Request 6 with the FWDB leads to the LCW forces (filtered with CFC60) shown in Figure 4.22. Hereby, both tests, with and without barrier offset are included.

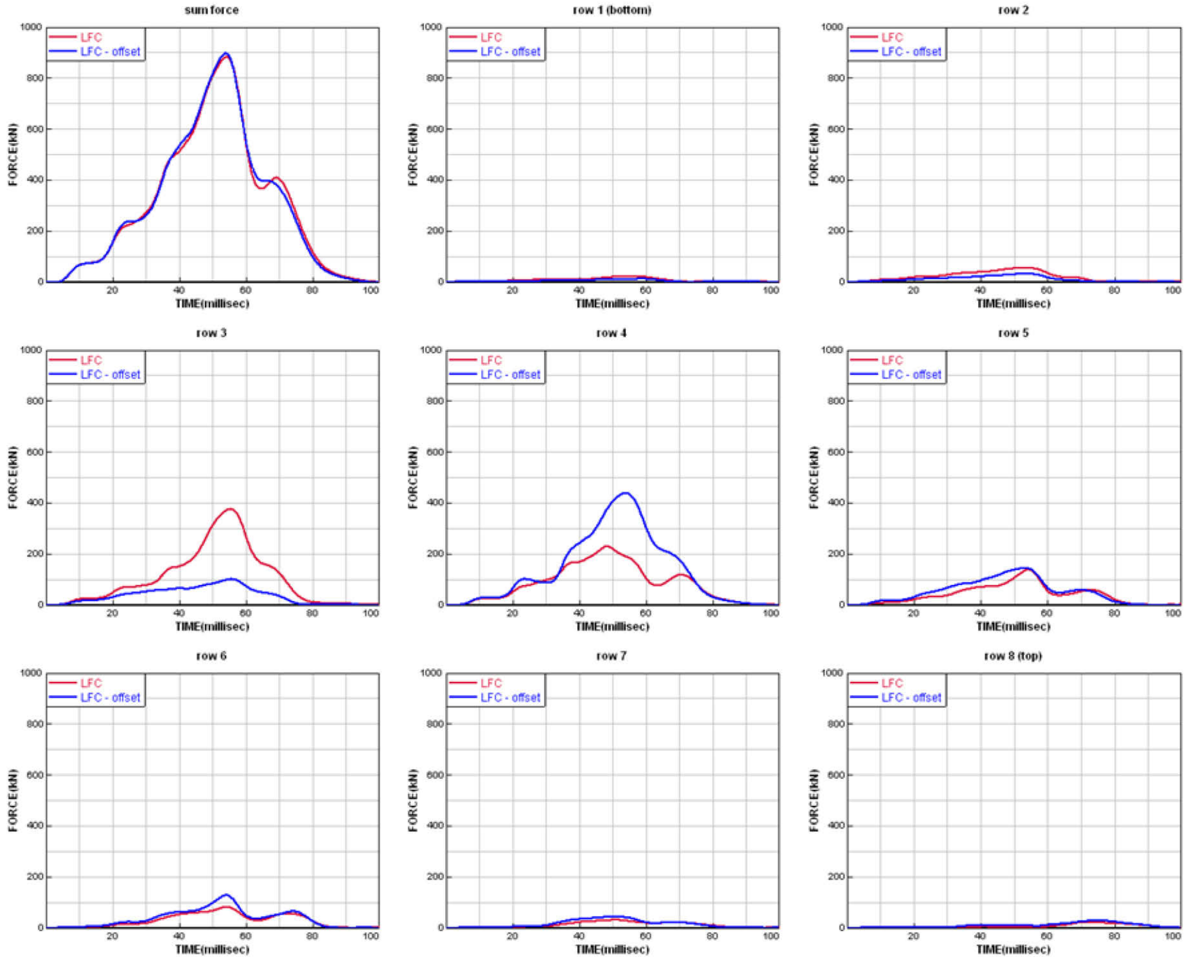


Figure 4.22: FWDB - Load cell wall forces (CFC60) in x-direction (with and without barrier offset). Table 14 summarises the measured load cell wall forces in the FWDB tests with and without barrier offset according to Request 6 and indicates that the cross-over vehicle would fail the metric.

Table 14: Application of simulations to metric – FWDB.

			LFC	LFC - offset
FWDB (1)	up to LCW force 400kN	$t_{sumforce=400kN}$ [ms]	34.7	34.9
		F3+F4 [kN]	247.2	213.7
		F3 [kN]	113.4	58.1
		F4 [kN]	133.8	155.6
FWDB (2)	up to 40 ms	F3 [kN]	149.9	63.8
		F4 [kN]	167.4	241.5
FWDB (3)	up to 40 ms	F_{t40} [kN]	511.9	532.2
		$0.2 * F_{t40}$ [kN]	102.4	106.44
		F3 [kN]	149.9	63.8
		F4 [kN]	167.4	241.5

Conclusions Request 6

If a vehicle will be raised in order to produce a so called “cross-over” vehicle, then it can possibly fail when the structure will not be changed in a correct manner. But to raise just the vehicle means also that there will not be enough structural alignment in a car-to-car crash. For those cars it is recommended to use secondary load paths that are placed within the common interaction zone. The question if the metrics can assess these secondary structures correctly is part of current investigations.

4.2.4 Step Effects (Request 7)

In this task the simulation Request 7 will be explained which was established by WP 3 to investigate possible step effects of the metrics. A requirement of the FIMCAR consortium was that the metrics should not have significant step effects. In order to investigate this, simulations with the parametric car models were conducted by raising and lowering them stepwise to check the continuity of the FWRB and FWDB metrics. After this work the results should be verified by additional car-to-car simulations. In the end the sensitivity of the impact heights on the full width assessment criteria were investigated.

For this investigation a large family car was used to test it against the FWRB and the FWDB. The simulation of different ride heights was realised due to vertical translation of the barrier heights. Figure 4.23 shows the test configuration for the Parametric Car Model in relation to the rows of the load cell wall.

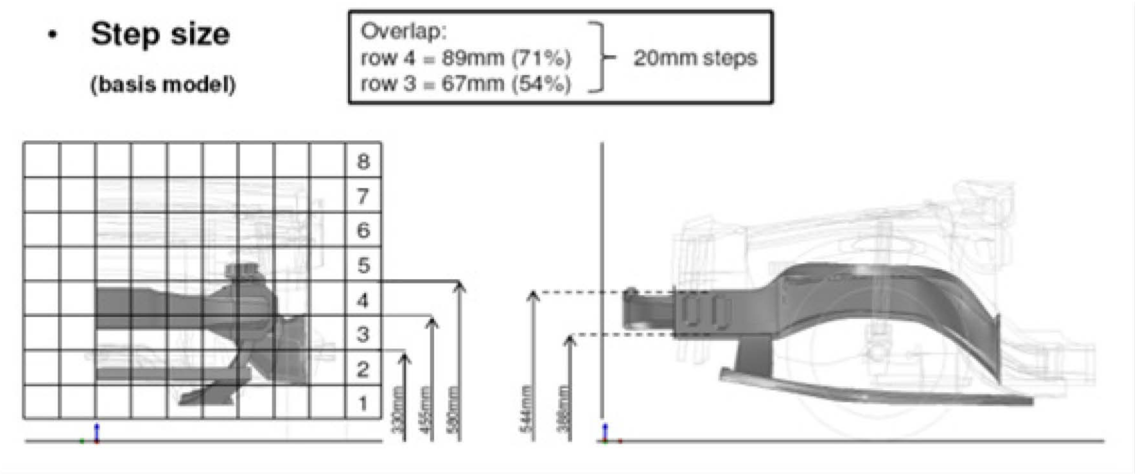


Figure 4.23: Test configuration for the investigation of step effects with PCM (large family car).

Figure 4.24 shows the results for the **FWRB**. On the left side the forces of the Row 3 and 4 are displayed by the formula F4/(F3+F4). On the right side the individual forces of Row 3 and 4 are displayed. A reasonable correlation can be observed. Also there were no strong step effects and a good correlation between overlap of the rows and the applied forces. The right picture shows that the forces in Row 4 are zero if there is no overlap with the structures in this row. But when the structures are increasing then the forces in Row 4 are also increasing and at the same time decreasing in Row 3.

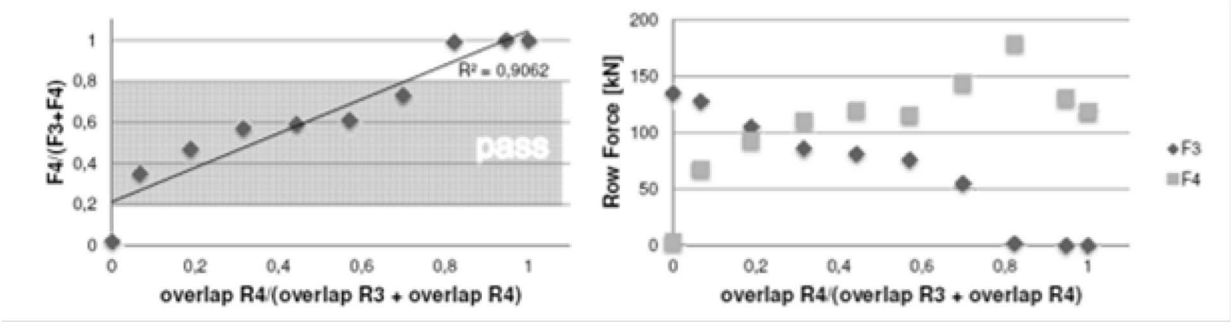


Figure 4.24: Influence of ride height on forces in Row 3 and Row 4 (FWRB), left picture shows the relation of Row 3 and 4 from the FWRB metric (1), right graph shows the individual forces of Row 3 and 4.

The results for the **FWDB** metrics are shown in Figure 4.25. The left graph shows the individual row forces up to LCW force 400 kN and the right picture shows the individual row forces up to 40 ms. The different ratings of the two metrics are showing no step effects. However a higher load spreading can be seen which is explainable due the barrier model.

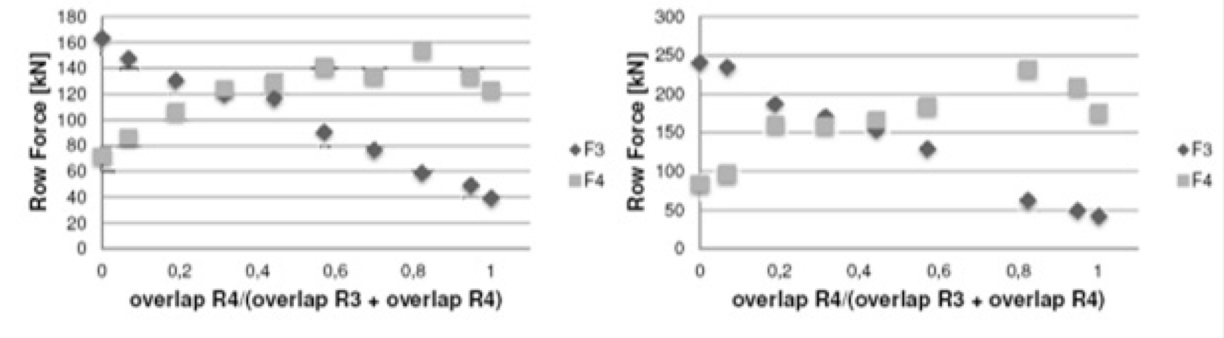


Figure 4.25: Influences of ride height on load spreading in Row 3 and Row 4 (FWDB), left graph shows the row forces up to LCW force 400 kN, right graph shows the row forces up to 40 ms.

Car-to-Car Crash Tests

In a next step car-to-car crash tests were performed. Referred to the FWRB tests results the following three configurations were chosen:

- Lowered vehicle that fails the metric against basis model (vertical offset = -40mm)
- Raised vehicle that fails the metric against basis model (vertical offset = +60mm)
- Borderline (lowered and raised) vehicles that passes the metric but were borderline (vertical offset = 100mm)

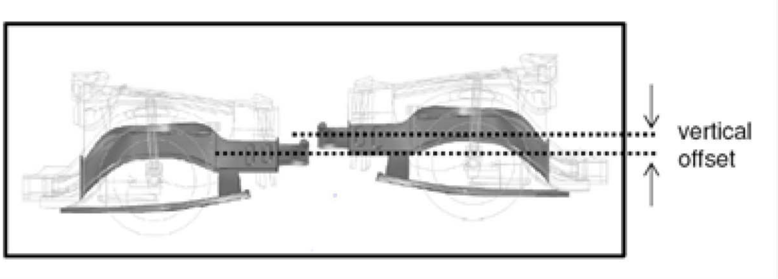


Figure 4.26: Definition of vertical offset in the car-to-car crash simulations.

These tests were conducted with 100% overlap and as well as with 50% overlap (see also Figure 4.27).

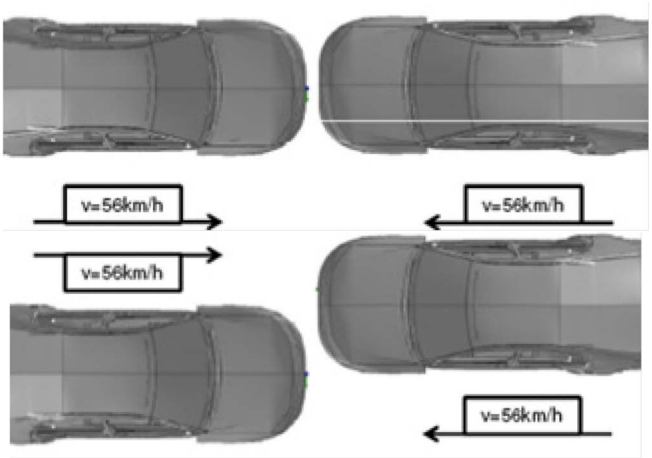


Figure 4.27: Test configuration with 100% overlap (left) and 50% overlap (right).

For the 100% overlap situation it could be seen that the overriding car has lower peak values for the deceleration of the cabin and that the intrusions of the firewall increases for the under-ridden car. These findings were confirmed by increasing the misalignment. The more the misalignment increases the more the differences of the loads increases and the incompatibility increases.

For the 50% overlap situation there were hardly any differences for the deceleration of the cabin detected. Also the intrusions at the firewall showed no trends. However, the under-ridden car shows higher a-pillar displacement then the opponent car.

Conclusions Request 7

In general the metrics seem to be robust and no step effects could be observed. The rating of the metrics correlates well with geometrical overlap of the PEAS. Intrusions and acceleration peaks indicate that crashes with “failed” vehicles are more incompatible then crashes of vehicles that passes the metric. Although the resolution of the LCW is limited to 125 mm the simulation results showed no step effects in the range of accuracy.

4.3 Conclusions

In this section a summary of the conclusions made for each of the issues will be made to give a comprehensive overview of the research taken.

Towing Hook FWRB

The simulations regarding the towing eye issues on the FWRB showed that in general the towing eye influences load cell wall readings if no filtering is applied to the load cell wall data. But if the data is filtered as recommended by the ISO standards, the small peaks are smoothed. In response to this finding the application of CFC 60 filtering is recommended to avoid undesirable influences due to hard points such as a towing eye.

Towing Hook FWDB

For the FWDB differences in the LCW readings were observed using the PCM approach and protruding towing eyes before filtering. However, applying the standard filter for load cell wall data (CFC60) the effect disappeared. In addition the influence was not observed when the standard bolt-in type was used. For FWDB the old type of towing eye could influence the metric even with a CFC60 filter. However, the bolt-in type of towing eye used on modern vehicles showed no influence with a CFC60 filter.

Variable Cross Beam Height

When the test data from Japan was analysed, one vehicle was conspicuous. This vehicle has a crossbeam attached underneath the PEAS structure and this crossbeam produced forces in Row 3 and 4 although the PEAS were partially above these two rows.

In simulation Request 1, it was investigated whether or not adequate structures in Row 3 and 4 can be mocked up in FWRB and FWDB tests. The simulation results showed that depending on the specific design of the structure it is possible to influence the metric in particular with the rigid barrier. On the other side the deformable element in the FWDB test alters the deformation pattern in a way that the real load paths can be detected. Following this the FWDB is able to detect weak structures that are not supported by stiff structures behind them. In case of a collision these weak structure are not capable to offer the opposing car a possibility to interact properly.

Cross-over Vehicles

If a vehicle will be raised in order to produce a so called “cross-over” vehicle, then it can possibly fail when the structure will not be changed in a correct manner. But to raise just the vehicle means also that there will not be enough structural alignment in a car-to-car crash. For those cars it is recommended to use secondary load paths that are placed within the common interaction zone. The question if the metrics can assess these secondary structures correctly is part of current investigations.

Step Effects

In general the metrics seem to be robust and no step effects could be observed. The rating of the metrics correlates well with geometrical overlap of the PEAS. Intrusions and acceleration peaks indicate that crashes with “failed” vehicles are more incompatible then crashes of vehicles that passes the metric. Although the resolution of the LCW is limited to 125 mm the simulation results showed no step effects.

5 DISCUSSION AND CONCLUSIONS

Starting with a review of previous work, candidate metrics and associated performance limits to assess a vehicle's structural interaction potential, in particular its structural alignment, were developed for both the FWDB and FWRB tests. Work was performed to develop a concept to assess a vehicle's frontal force matching. However, a metric has not been developed for frontal force matching because the focus was put on the development of metrics for the assessment of structural interaction in line with the FIMCAR strategy [Johannsen 2011].

- The FWDB and FWRB tests both have advantages and disadvantages. The metrics developed for these tests also have advantages and disadvantages. FIMCAR WP3 members have discussed these advantages and disadvantages and recommend that priority is given to the further development of the FWDB test and FWDB metric (3) as shown below [Figure 5.1]. However, this does not rule out the possibility of switching priority back to the FWRB test if issues are found with the deformable barrier test in the future. It should be noted that the FWRB test is already a defacto worldwide standard test and hence has an advantage from the harmonisation point of view.

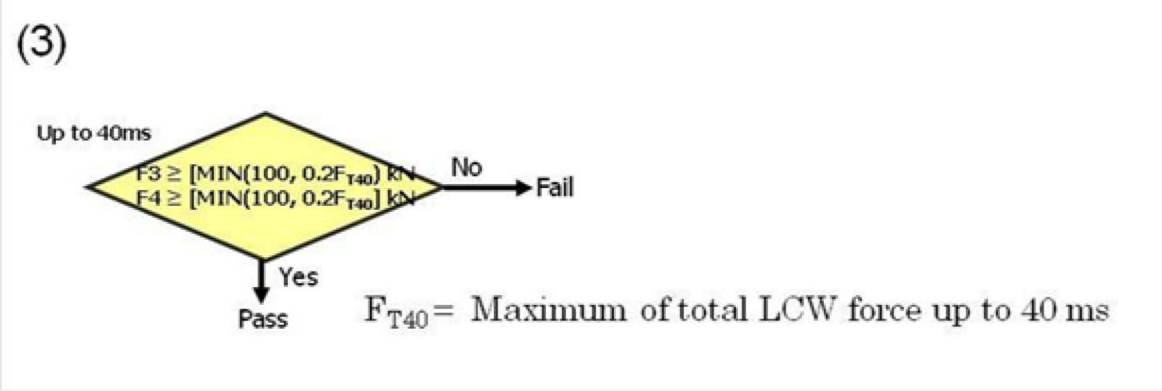


Figure 5.1: FWDB metric (3) for FWDB test.

The reasons for prioritising the full width test with the deformable element and the FWDB metric (3) are:

- The FWDB test has the edge technically over the FWRB test because there is no need for a supplementary test. Also the structural interaction assessment is made later in the impact than for the FWRB test which, because the vehicle's crash structures are more fully loaded, allows a more meaningful assessment of them. The deformable element also has the advantage that the crash loading of the structure is more representative of a vehicle-to-vehicle crash at the beginning of the impact. This is important to help ensure more realistic crash sensor triggering.
- The FWDB metric (3) is recommended because its correlation with a geometric assessment of the vehicle is as good as the other FWDB metric candidates, it is a single stage metric which follows the spirit of keeping the metric as simple as possible and effectively it allows the mass of the vehicle to be taken into account in the performance requirements.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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8 GLOSSARY

AHOF:	Average Height of Force
AHOF400:	Average Height of Force during the first 400 mm impact travel
APROSYS:	EC funded project (FP6) Advanced Protective Systems
delta-v:	velocity change following a collision
EAS:	Energy Absorbing Structures
FWDB:	Full Width Deformable Barrier
FWRB:	Full Width Rigid Barrier
GCM:	Generic Car Models
GRSP:	Working Party on Passive Safety of UNECE
KW400:	Work dissipated in the deformation between 25mm and 400 mm of crush
LCW:	Load Cell Wall
NHTSA:	US National Highway Traffic Safety Administration
ORB:	Over Ride Barrier
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PCM:	Parametric car models
PEAS:	Primary Energy Absorbing Structures
SEAS:	Secondary Energy Absorbing Structures
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility