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Intermediate Short Report: Frontal Impact Cost-Benefit and Potential Options

MJ Edwards and D Hynd

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J Nelson	D Hynd
(Project Manager)	(Technical Referee)

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Contents amendment record

This report has been amended and issued as follows:

Version	**Date**	**Description**	**Editor**	**Technical Referee**
1	12/05/11	1st draft submitted to EC project officer	MJE	DH
2	13/05/11	Updated to include note from EC project officer in Section 3.3 ‘Way Forward’.	MJE	DH

Contents

1 Introduction

This work has been performed under Contract No: ENTR/09/030, service request, 'Frontal Impact Crash protection – substitute and additional technical representation on behalf of the EC'. The EC project officer (Peter Broertjes) requested that an intermediate short report be produced (ref email 6th April) with the following objectives:

- Compile a list of the cost and benefit studies relevant to the current discussions within the GRSP informal group on frontal impact to change UNECE Regulation 94. To summarise the results of these studies.
- List the potential options for changes to UNECE Regulation 94 and to comment on the advantages / disadvantages of these options.

2 Summary of Benefit and Cost Studies

The following studies were reviewed and summarised:

- VC-Compat for improved frontal impact compatibility (Nov 2006)[1]
- APROSYS for the introduction of a Full-width test (July 2008)[2]
- German accident data analysis presented at GRSP informal group on frontal impact in two parts (May 2009 and Dec 2009)[3][4]
- Japanese benefit analysis for the introduction of a Full-width test presented at GRSP informal group on frontal impact (Oct 2010)[5]
- THORAX benefit analysis for potential benefits arising from improved dummy as developed by THORAX project (Oct 2010)[6]

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[1] VC-Compat (2006). 'An estimation of the costs and benefits of improved car-to-car compatibility on a national and European scale' Public Deliverable No. 24, http://vc-compat.rtdproject.net/

[2] APROSYS (2008). 'Cost Benefit Analysis for Introduction of Advanced European Full Width (AE-FW) Test', Deliverable 123B, http://www.aprosys.com/

[3] German accident data analysis (May 2009). 'Frontal Impact Protection – German Accident Analysis', Doc No FI-05-02e, GRSP, Informal group on frontal impact, 5th meeting, http://live.unece.org/trans/main/wp29/wp29wgs/wp29grsp/fi_5.html

[4] German accident data analysis (Dec 2009). 'Frontal Impact Protection – German Accident Analysis II', Doc No. FI-07-02e, GRSP, Informal group on frontal impact, 7th meeting, http://live.unece.org/trans/main/wp29/wp29wgs/wp29grsp/fi_7.html

[5] Japanese benefit analysis (2010). 'Effect Evaluation on the Implemented Full-Width Impact Standard for Reduction of Fatalities as well as the Number of the Seriously Injured', Doc No. FI-09-07, GRSP, Informal group on frontal impact, 9th meeting, http://live.unece.org/trans/main/wp29/wp29wgs/wp29grsp/fi_9.html

[6] THORAX (2010). 'Estimate of injury reduction potential for different occupant sizes and ages, and total benefit expected to arise from the project'. Deliverable D1.2, http://www.thorax-project.eu/

2.1 VC-Compat (Nov 2006)

Benefits and costs were estimated for improved frontal impact car-to-car compatibility for Europe (EU15). As a definite set of test procedures to assess a car's compatibility was not defined, the study was undertaken based on assumptions about how a compatible car would perform. Overall these assumptions were that the impact energy in the accident would be absorbed in a more controlled manner which would prevent compartment intrusion in accidents below the severity of the current test, i.e. about 56 km/h.

The benefit studies, based on GB and German data, predicted the benefit of improved compatibility for EU15 to be between 721 and 1,332 lives saved and between 5,128 and 15,383 seriously injured casualties mitigated per year. This is between 4 and 7% of car occupant fatalities and between 4 and 11% of car occupant seriously injured casualties. In 2004 there were approximately 33,000 fatalities on the road in the EU15 of which approximately 54% were car occupants. The variation between the minimum and maximum is significant illustrating the uncertainty of the estimation.

To determine the value of the reduction in casualties, the number of lives saved and seriously injured casualties prevented was multiplied by the average cost of a fatality or a seriously injured casualty. The benefit for fatalities and seriously injured casualties was then summed to give the total financial amount saved. The estimate of the cost for each fatality and serious casualty is different in GB and Germany. The European benefit for the casualties saved is predicted to be between €1.9 billion and €6.5 billion for the EU15 each year.

The cost of implementing compatibility was estimated by Fiat based on the cost of modifying a current car, including both the increased manufacturing costs to the industry and the increased running costs to the consumers. The total annual cost was calculated by multiplying the cost for each car by the number of new cars registered in the EU15 every year. Fiat calculated a best and worst case scenario depending on factors such as the current safety performance level of the car (Euro NCAP 5 star or 4 star) and the number of cars manufactured, and predicted an annual cost between €1.5 billion and €4.0 billion per year.

The cost-benefit ratio, defined as value of benefit divided by cost of implementation, was predicted to be between about 4.5 and 0.5. It should be noted that this cost-benefit has been calculated for the steady state, when the entire vehicle fleet is compatible. The benefit will be less during the initial years as compatible cars are introduced into the fleet.

The GB benefit analysis predicted that between approximately 5% (67) and 8% (124) of the GB's killed front seat car occupants would be saved and between 5% (732) and 13% (1876) of seriously injured casualties would be prevented if improved frontal impact compatibility were implemented. The lower estimate was made based on a model that assumed that improved compatibility prevented all injuries caused by *contact with a front interior* ***intruding*** *structure* below an impact severity of ETS 56 km/h, while the upper estimate was based on a model that prevented all injuries caused by *contact with a front interior structure* below this severity.

Another significant finding of the GB work was the high frequency of moderate (AIS 2) and life threatening (AIS 3+) injuries sustained by car occupants due to seat-belt induced loading. The majority of thoracic injury was not prevented by the injury reduction models.

The German benefit analysis methodology was based on the observation that in the car-to-car tests carried out within the VC-Compat project, the compartment intrusions start at lower impact speeds or delta-v than in the Euro NCAP tests with the same car models. These car models showed no remarkable compartment intrusions at 64 km/h impact speed or delta-v values around 68 km/h in the Euro NCAP test program. The offset deformable barrier used in Euro NCAP testing can be assumed to represent a fully compatible car front structure. In the car-to-car tests however compartment intrusions were observed at lower impact speeds between 50 and 56 km/h or delta-v between 54 and 60 km/h. This difference of collision speeds is assumed to be the potential of higher energy absorption capability of car front structures with good compatibility. For the analysed car models of the VC-Compat test program it was estimated that these car models could absorb in car-to-car accidents about 30% more kinetic energy if they possessed a fully compatible front structure.

Based on this assumption, for cars with good front structure compatibility, the injury risk for car occupants was shifted to about 8 km/h higher collision speeds. By comparing these injury risk curves to the original unshifted curves and taking into account factors such as the speed distribution in frontal car impacts in Germany, the benefit was calculated. It was estimated that the implementation of improved frontal impact compatibility would save about 8% of Germany’s killed front seat car occupants and prevent about 4% of the seriously injured front seat car occupant casualties.

There are a number of limitations to the benefit estimates, the main one being that the possible benefit of improved frontal impact compatibility for side impacts has not been considered.

2.2 APROSYS (July 2008)

Analyses were performed to estimate the potential benefit and costs of introducing a Full-width test into European legislation. The performance requirements and associated limits of a Full-width test have not been finalised yet, so the analyses performed give only an indicative estimate of the potential benefit. The benefit was estimated for the EU15 countries by scaling the results of a study which estimated the benefit for GB. It was assumed that the introduction of a full-width test in Europe would encourage improved restraint systems, which in turn would reduce restraint-induced injury to the thorax and abdomen in frontal collisions with an impact severity less than the test severity (56 km/h) with little or no compartment intrusion. The level of injury reduction was assumed to be a maximum of 2 AIS levels for injuries to the thorax and/or abdomen, with no injuries being reduced to a level lower than AIS 1.

Using this assumption and GB accident data it was estimated that the potential benefit was a reduction in annual car occupant fatalities in GB by up to approximately 3 percent (47 occupants) and serious casualties by up to approximately 6 percent (812 occupants). Scaling this to Europe (EU15 countries) gave a benefit of up to 430 fatalities and 6,017 seriously injured prevented. This equates to a monetary benefit of up to about €2,000 million.

An analysis was performed to estimate the cost of introducing a full-width test into European legislation based on two assumed levels of performance limits. The cost estimated for the EU15 countries per year to enable new registrations to comply was about €240 million to meet performance limits similar to US FMVSS 208 and about €460 million to meet limits similar to UNECE Regulation 94. The analysis was based on the modifications required to enable a Fiat Bravo to meet the test requirements. Hence it was implicitly assumed that the performance of the Fiat Bravo in a full-width test was representative of the performance of all cars in the European fleet.

It should be noted that more stringent performance requirements than the UNECE R94 equivalent ones and other measures may be needed to deliver all of the estimated potential benefit. This would require additional modifications to the car, possibly even adaptive restraint systems, which would obviously increase the cost. In addition, it should be noted that the criterion used to control thoracic injury in regulatory testing with the Hybrid III dummy is the sternal deflection. It has been found that this criterion does not correctly assess the effectiveness of improved restraint systems observed in accidentology [Petitjean, 2002][7]. This indicates that it may also be necessary to upgrade the dummy test tool and / or the thoracic injury criterion to enable a better assessment of the restraint system and ultimately deliver all of the potential benefit.

2.3 German accident data analysis (May 2009 and Dec 2009)

This analysis was presented in two parts presented in GRSP frontal impact working group meetings in May 2009 and Dec 2009. To clarify a number of points in the presentations the author (Claus Pastor) was contacted.

The first part of the analysis used German national accident data (2005 – 2007). It focused on front-to-front two-car accidents (21,764 in data sample). A statistical model of injury risk as a function of accident severity, partner protection and self protection was developed using a matched pair approach. Model parameters included car mass, frontal impact NCAP rating and occupant age and gender. A generic benefit assessment was performed to investigate:

- An increase in crashworthiness (increase self protection) of small cars
- An increase in crashworthiness (increase self protection) of all cars
- An adjustment to the restraint to protect female occupants better
- An adjustment to the restraint to protect female and elderly occupants better
- A better distribution of the crash energy between impact partners

The largest effect was seen for the better distribution of crash energy between impact partners. The next largest effects were seen for adjustments to the restraint system. However, what changes one would make to the test procedure to drive these changes was an open question.

The second part of the analysis used German national data but expanded the data set by one year (2005 – 2008) and added the parameter 'Year of initial registration'.

The first section of this analysis focused on front-to-front two-car accidents. Investigation of the mass ratio distribution finds that it has changed little from 1983 to

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[7] Petitjean(2002). A. Petitjean, M. Lebarbe, P. Potier et al. (2002) Laboratory reconstruction of real world frontal crash configurations using the Hybrid III and THOR dummies and PMHS. Proc. 46th Stapp Car Crash Conference, n°2002-22-0002, pp. 27-54. Society of Automotive Engineers, Warrendale, PA.

1996 to 2005-2008. However, the mass of all segments of cars has increased throughout these years. Investigation of the distribution of injuries with mass showed that a greater proportion of fatal and serious injuries occurred in compact, small and mini cars, which is not surprising. Investigation of the distribution of injuries with mass ratio showed that for all cars high mass-ratios were over-represented for fatal and serious injuries, which again is not surprising. However, this effect was not as great for new cars possibly because of their improved self-protection levels. A paired comparison found that tackling issues such as gender and age would cover a greater proportion of the casualties than compatibility mass-ratio related issues and hence give a higher benefit.

The second section of this analysis focused on single-car frontal impacts. As expected no mass effect was found. However, there did appear to be age and gender effects.

2.4 Japanese benefit analysis (Oct 2010)

An analysis was performed to estimate the benefit of the full-width test in Japan. The methodology used was as follows:

- The target population was identified
    - Frontal vehicle-to-vehicle or single-vehicle accidents
- The fatality and serious injury rates were calculated for vehicles which were not compliant with the full-width test.
- These injury rates were used to calculate the number of fatalities and serious injuries assuming that all cars were not compliant with the full-width test.
- The number of fatalities and serious injuries prevented by the full-width test was calculated by subtracting the actual number of fatalities and serious injuries.

Using 2009 accident data, it was estimated that 1,271 deaths and 5,905 serious injuries were prevented in Japan in 2009 as a result of the introduction of the full-width test into Japanese legislation. This equates to about 50% of the initial target population.

It should be noted that this analysis was based on the injury rates for cars that did not meet the requirements of the Full-Width test. Compared to cars that meet the requirements of the Full-Width test these cars will generally be much older. Confounding factors, such as the age of the car, were not taken into account in the analysis and hence the estimate made should be regarded as an upper limit to the possible benefit.

*In Japan in 2009 there were approx 5,000 road accident fatalities. If it is assumed that approx 50% of these were car occupant fatalities then there were about 2,500 car occupant fatalities. If the full-width test had not been introduced in Japan there would have been (2,500 + 1,271 = 6,771) car occupant fatalities. Hence the benefit in percentage terms is 1,271/6,771 * 100 = 19% of car occupant fatalities. This is very high compared to the APROSYS estimate of 3% of car occupant fatalities.*

2.5 THORAX benefit analysis (Oct 2010)

The main aim of the THORAX project is to develop an improved thorax for the THOR dummy. Analyses were performed to estimate the potential benefit of reducing thorax injury using the following four safety interventions:

1. A more sensitive dummy thorax that is capable of supporting a drive towards advanced restraint systems offering improved protection for the torso.
2. A new thorax injury risk function to represent ages of the occupant population having a lower tolerance to torso loading.
3. An additional size of dummy available for representing a different size of occupant as well as the mid-sized male (either smaller or larger than the mid-size).
4. Extending the scope of frontal impact testing to include another configuration:
   a. Introduction of a full-width test.
   b. Introduction of a small-overlap test.
   c. Introduction of another test procedure to safe-guard against injuries caused in low-speed impacts (of a speed lower than that represented by the current procedures).

Accident data from the UK CCIS database was used for the study. The representativeness of the UK data used was checked by comparison with data from France.

Options 1 and 2 gave similar benefits of up to about £30 million to £40 million for the EU27 whereas option 3 gave a much greater benefit of up to £154 million. However, option 4c gave the greatest benefit of up to £247 million, which when combined option 2 could give a benefit of up to £300 million. The main reason for the greater benefits predicted for particular options was the greater target population sizes.

2.6 Summary and Discussion

The results of the analyses above are summarised in Table 1 below.

Table 1: Summary of benefit analyses

No	Analysis description	Change / counter-measure introduced	Benefit predicted (% of car occupant fatalities & serious injuries)	Benefit / cost ratio	Comment
1	VC-Compat (2006)	Improved impact energy absorption leading to improved compartment integrity	Fatal 4% to 7% Serious 4% to 11%	4.5 to 0.5	This takes no account of any benefits in side impact
2	APROSYS (2008)	Introduction of full-width test leading to improved restraint systems	Fatal Up to 3% Serious Up to 6%	Approx 4.0	
3	German accident data (2009)	No specific	Noted that addressing issues such as gender and age likely to give larger benefits than addressing mass-ratio compatibility issues	N/A	
4	Japanese full-width test (2010)	Introduction of full-width test leading to improved restraint systems	Fatal Max of 19%	N/A	Japan already has full-width test so this analysis predicts benefit which Japan has already realised. It should be noted that analysis does not take into account confounding factors and as such is an over-estimate.
5	Thorax (2010)	No specific	Noted that for thorax injuries, addressing the issue of injuries in accidents at severities lower than the current test severity (and in particular for older occupants) will offer greater benefit than addressing issues such as size and gender mainly due to the increased target population sizes.	N/A	

Way Forward

The FIMCAR project intends to deliver test and assessment procedures to improve the structural interaction of cars in frontal impacts. Structural interaction is one component of compatibility (structural interaction, frontal force matching / compartment strength) so the benefit of implementing these procedures in regulation is likely to be less than that predicted by the VC-Compat project for compatibility as a whole. However, the benefit predicted by VC- Compat for compatibility did not take into account any benefit that might occur for side impacts which could be substantial, in particular if features to improve side impact compatibility, such as lower load paths to engage the sill, were enforced in regulation.

The THORAX project intends to deliver an improved thorax for the THOR dummy. The main purpose of the improved dummy is to provide a tool that can assess better the performance of restraint systems and hence be used to enforce their introduction. The benefits of this are variable depending on how it is done. However, analysis showed that the benefit, in terms of thorax injuries, was predicted to be greater if issues such as lower severity accidents and older occupants were addressed compared to issues such as gender and size.

The GRSP informal group for frontal impact is considering the how the frontal impact Regulation 94 could be updated in the short-to-medium term.

The summary table above indicates that to deliver the maximum benefit from a change to Regulation 94 both compatibility and the restraint related injuries, in particular those at severities lower than the severity of the current test, need to be addressed. In addition, if side impact compatibility could be addressed as well this would increase benefits further.

Potential options are listed and discussed briefly in the next section.

3 Potential options for changes to UNECE Regulation 94

UNECE Regulation 94 comprises an offset frontal impact crash test conducted at 56 km/h, with a 40% overlap between the impacting vehicle and a wall with a deformable front face. The test is conducted with a Hybrid III 50th percentile male dummy in each of the outboard front seating positions (i.e. driver and front seat passenger), and the risk of injury is assessed for the head, neck, thorax, femur and lower leg of both dummies. Vehicle-based requirements, such as steering wheel displacement, are also assessed.

The current aim of the GRSP Informal Group on Frontal Impact (IG FI) is to deliver a clear plan to GRSP in May 2011 for an update to Regulation 94 in the short / medium term. The group has identified the following important issues:

- Change of test severity in offset test
- Introduction of full-width test in frontal impact
- Protection of female occupants
- Protection of older occupants
- Protection of rear occupants
- Geometric requirements for compatibility, i.e. improved structural interaction

Recent research has raised the possibility that the protection designed into current restraint system technologies may be optimised for the younger mid-sized male occupants because these are the occupants represented by the 50th percentile dummy used in the Regulation 94 test. Casualty gain might be achieved through using different injury criteria, injury risk functions or crash test dummies that represent user groups other than those represented by the current 50th percentile dummy. These user groups include female, older and small stature occupants.

At this stage the way forward is unclear. The main issues include:

- The need for an initial assessment of the possible options for the way forward taking into account likely constraints
- A pragmatic limit of 2 on the number of full-scale crash tests, 1 offset and 1 full-width
- The timescales for the THOR dummy which at present appear to be somewhat uncertain (however, NTHSA's intended timescales for an agency decision are: THOR 50th 2013, THOR 5th 2014)
- The lack of indication of likely impact (including benefit) of possible options

The potential options for changes to Regulation 94 are listed under the following two headings:

- Test configuration options
- Dummy options

3.1 Test configuration options

3.1.1 *Introduction of full-width test*

The main purpose for the introduction of a full-width test is to improve the performance of the restraint system. There are two sub-options related to test speed:

- Full-width test at an impact speed of 50–56 km/h to address fatal and life threatening serious injuries.
- Full-width test at low speed (e.g. 40 km/h) with more stringent performance limits to address life threatening injuries in lower severity accidents.

Figure 1 shows the distribution of casualties in injury severity groups with accident severity.

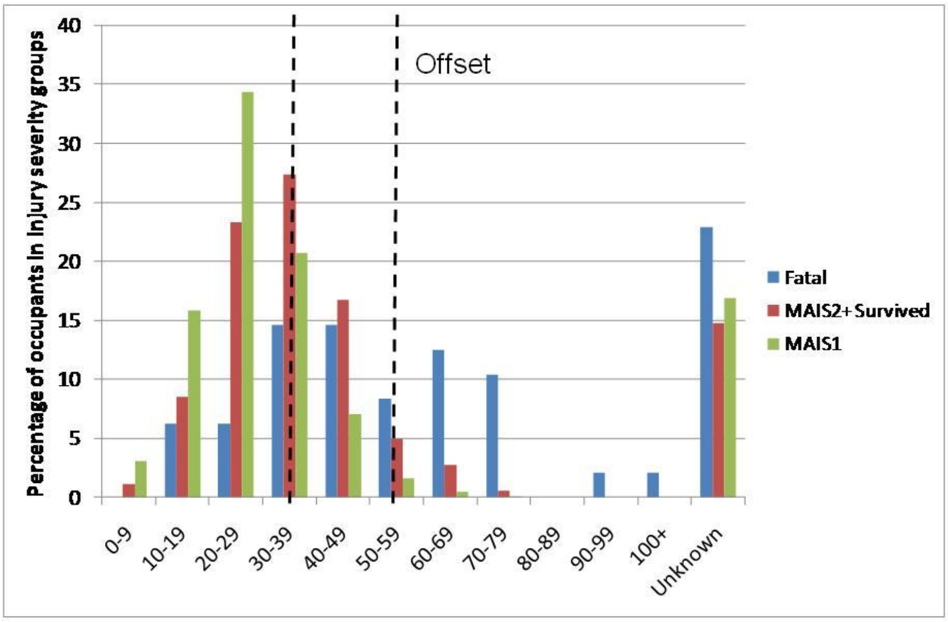

Figure 1: Percentage of casualties in injury severity groups with accident severity (Estimated Test Speed) for UK CCIS data

It can be seen that the severity of the current offset test (approx 50–56 km/h) and the performance limits (e.g. chest deflection 50 mm for a 50% risk of AIS 3+ injury) generally have been set to improve protection for the fatal and MAIS 3+ injured casualties (test severity is somewhere near the middle of the distribution of the fatally injured casualties). Because many of these casualties are involved in accidents with a high overlap, to improve their protection further a full-width test of a similar speed is needed (which would give a more severe deceleration pulse than the current test) with performance limits similar to the current offset test.

However, to improve protection for MAIS 2+ injured casualties a test with a lower severity and more stringent performance limits set to reduce the risk of AIS 2+ injuries is needed (40 km/h is somewhere near the middle of the distribution of MAIS 2+ survived casualties). One of the objectives of introducing a full-width test is that it should provide a different compartment deceleration pulse to the current offset test (or

PDB test) to assess the restraint system over a range of pulses and hence ensure that it is not sub-optimised for a single pulse. To achieve this objective the deceleration pulse for a lower severity test (e.g. full-width at 40 km/h) should be softer than the deceleration pulse of the partner test (current ODB test or PDB test if offset test changed).

A comparison of compartment deceleration pulses from 40 km/h and 56 km/h FWRB, 56 km/h ODB, 60 km/h PDB tests is shown in (Appendix A). Unfortunately, a complete test data set was not available for one car. Hence, a comparison was made using different cars of similar size category. It was found that in terms of peak acceleration, both 60 km/h ODB and 60 km/h PDB were more severe than a 40 km/h full-width test.

Although this is a first indication that a 40 km/hr full-width test has a softer deceleration pulse than the current ODB and PDB tests, it should be noted that much further work, including tests necessary to complete a data set for the same car and a more complete assessment of the severity of the pulses looking at parameters other than peak acceleration such as average acceleration, to compare the severity of the tests is needed before a definite conclusion could be made. Following this more work would be needed to set appropriate performance limits to enforce the fitment of restraint systems which perform appropriately. Ideally this would be restraint systems which adapt to give optimum performance for different deceleration pulses, occupant size and weight, i.e. smart restraint systems.

There are also two further sub-options for the full-width test related to the barrier, the first a rigid barrier (FWRB) and the second a deformable barrier (FWDB). These options are related mainly to the assessment of the vehicle’s compatibility and hence the FIMCAR project should provide sufficient information to decide a preferred option. However, it should be noted that the deformable barrier does represent a vehicle-to-vehicle impact better than the rigid barrier in the initial stages of the impact which is particularly relevant for the triggering of the restraint system.

Test speed 50-56 km/h

Advantages

- Easier for harmonisation than lower speed test, as is already part of regulation in other countries.
- Will ensure that cars are not designed to be very stiff and have inadequate energy absorption capability in their front-ends, which is important if the PDB test is introduced.

Disadvantages

- Benefits may not be that high because many cars likely to already meet standard as test already in regulation in other countries. However, benefit could be increased by use of THOR dummy.

Test speed 40 km/h

Advantages

- Could enforce the use of smart restraint systems which perform over a range of impact speeds without the need for additional sled tests or simulation (see below).
- Has potential to offer larger benefit than 50-56 km/h test because the target population is larger and may be become even larger as the population ages.

Disadvantages

- Not as easy for harmonisation as 50-56 km/h test.
- May not prevent design of very stiff cars with insufficient front-end energy absorption capability. Note: the authors do not believe that this will be the case if the performance limits are set appropriately. However, it should be noted that in a lower speed test the vehicle deformation will be less and the vehicle's stiffness is only assessed over its deformation in the test.
- Will encourage the fitment of smart restraint systems which will allow greater occupant forward motion in lower speed impacts. This could possibly be less safe in accidents which have an oblique component because a large forward motion could increase the chance of occupant injury, e.g. a head strike on an interior component such as an A pillar or cant rail (IIHS paper raised this issue for load limiters having low loads). Note: it is unknown whether or not this could be an issue.

3.1.2 Replacement of current ODB test with PDB test

The current strategy in FIMCAR for assessment of a vehicle's compatibility (structural interaction potential) is:

- To assess the alignment of its main structures using force measurements from a Load Cell Wall (LCW) in a full-width test (rigid or deformable face to be decided), and
- To assess how well its structures spread load (e.g. bumper crossbeam, lower load path) using deformation measurements from a Progressive Deformable Barrier (PDB) test. Hence, the PDB test will be necessary for the assessment of compatibility assuming that the FIMCAR project progresses to its current strategy.

The PDB test should also help to equalise the test severity for different masses of vehicles although how necessary it is to do this and the extent to which it will do this are not understood clearly.

One issue that has been raised with the PDB test is that it has a large energy absorption capability and this could allow the design of very stiff cars which have insufficient energy absorption capability in their front-ends for impacts with rigid objects. The introduction of a full-width test should help to mitigate this problem because it would not be possible to design a restraint system to meet the dummy injury requirements for the high compartment deceleration levels that would be seen with a very stiff car. However, precisely how much a full-width test would limit a car's stiffness depends on the dummy injury requirements that would be set. At present vehicles meet the current regulatory performance limits easily. Therefore, these limits would need to be made more stringent if it was decided that it was necessary to use this test to limit the stiffnesses of vehicles to their current values. It appears that there is an unwritten understanding in the GRSP IG FI that a PDB test would not be introduced without a full-width test.

Advantages

- Will enable the assessment of a vehicle's compatibility (structural interaction) as currently being developed by FIMCAR.
- Should help to equalise test severity for vehicles of different masses to some extent (reduce it for heavier vehicles comparatively) and thus help reduce the frontal force levels of heavy vehicles.

Disadvantages

- It has a large energy absorption capability which could allow the design of very stiff cars with insufficient energy absorption capability. For this reason it should not be introduced without the introduction of a full-width test as well.
- There is much opposition to the PDB test by German industry. The main reasons are that its benefit is unclear and there is uncertainty about the use of a deformation-based metric. These issues should be addressed by the FIMCAR project.

3.1.3 Introduction of supplementary tests / simulation to ensure performance for a diverse range of occupants

Sled tests would be performed with different size and weight dummies using the deceleration pulse from the full-scale crash test. The purpose of these tests would be to encourage the fitment of smart or adaptive restraint systems which would optimise the restraint performance for occupants of difference size and weight. Restraint trigger times could be obtained from the full-scale test assuming that they were not dependent on occupant size and weight. Possibly, simulations could be used instead of tests with validation of the model by comparison with the results from the full-scale tests.

3.1.4 Introduction of supplementary tests / simulation to ensure performance for different speeds

Sled tests would be performed with at different impact speeds. This option has the problem of how the deceleration pulse and restraint trigger times would be determined. The purpose of these tests would be to enforce the fitment of restraint systems which would optimise the restraint performance for different impact speeds / severities. As above, possibly simulations could be used instead of sled tests.

3.1.5 Summary of options

Option 1 Full-width test

a. Speed 50-56 km/h or low speed (40 km/h)
b. Rigid or deformable face

Option 2 – Replace ODB with PDB (with introduction of full-width test)

Option 3 - Supplementary tests / simulation

a. To ensure performance for diverse range of occupants
b. To ensure performance for difference speeds – only needed with option 1a, not needed for option 1b.

3.2 Dummy options

There are four main issues that need to be considered when selecting the appropriate dummy for the front impact regulation:

1. Dummy, e.g. Hybrid III or THOR
2. Size of dummy, e.g. 50th percentile male, 5th percentile female or 95th percentile male
3. Injury criteria, e.g. chest compression or head performance criterion
4. Performance limits, e.g. chest compression of 50 mm

These dummy issues need to be aligned with the safety priorities identified from the accident data, as highlighted in the summary of benefit studies, Section 2. One of the biggest remaining issues in frontal impact accidents is the mitigation or prevention of thorax injuries; thorax injuries have been shown to be particularly prevalent with older occupants and in accidents at substantially lower severity than the current regulatory test. This implies that thorax biofidelity and injury assessment are key attributes for the dummy to be used in an updated frontal impact test procedure. It also implies that other aspects of the dummy that affect how the thorax is loaded during a frontal impact are also important. For the frontal impact dummy, this means that the biofidelity of the knee-thigh-hip region (involved with dashboard interaction), biofidelity of pelvis interaction with the seat and restraint system and biofidelic spine motions are all important. However, how well the dummy meets the requirements necessary to drive future safety developments will also need to be balanced with its availability and readiness for regulatory use.

3.2.1 *Hybrid III 50th percentile male*

This is the dummy currently used in the driver and front seat passenger positions in Regulation 94.

Advantages

- As currently used in Regulation 94, i.e. current dummy size, injury criteria and performance limits

Disadvantages

- The THOR dummy has been developed to overcome long-identified deficiencies in the biofidelity and injury assessment capability of the Hybrid III family of dummies, particularly with respect to modern seat-belt and airbag restraint systems

3.2.2 *Hybrid III 5th female or 95th percentile male*

These are the small female and large male versions of the Hybrid III dummies. They have essentially the same configuration and instrumentation as the 50th percentile male dummy.

Advantages

- Already available and most labs already have these dummies

- The same injury criteria and scaled performance requirements are already available
- Previous work particularly identifies the 5th percentile female as a relevant size for at least one seating position

Disadvantages

- Ditto Hybrid III 50th percentile male

3.2.3 Hybrid III with multi-point chest compression measurement

Several of the projects reviewed in Section 2 highlighted that because head protection has improved greatly in modern vehicles, the thorax (or chest) is now the body region with the greatest risk of serious or life-threatening injury in frontal impacts. The current Hybrid III dummy assesses chest injury risk at a single point in the upper-middle part of the thorax (at the mid-sternum), using two injury criteria: peak compression, and peak VC (which is the product of the compression and the rate of compression). The peak compression is related to the risk of skeletal injury, and the VC is related to the risk of internal organ injury.

Proposals have been made that the injury assessment capability of the Hybrid III dummy could be improved by using multi-point compression measurement, similar to that used on the THOR dummy. Indeed, various prototype dummies with different four-point compression measurement systems have been publicised over the years. Other than the instrumentation, these are standard Hybrid III dummies. The two main multi-point chest compression instrumentation options are:

- THMPHR (THorax for Multi-Point and High Rate testing). This uses four IR-Traccs to measure chest compression at four points and has been available as a prototype for around 10 years. It has been reported that greater rib compressions are measured in some tests with THMPHR compared with the standard Hybrid III rib compressions. However, because these measurements are made at locations remote from the standard Hybrid III measurement, it is not known whether these greater measurement correlate with a greater risk of injury. This system is not listed in the Humanetics catalogue, but is understood to be available.
- RibEye. This uses a non-contact optical system to make measurements at up to 12 (2D systems for the Hybrid III 50th male and 5th female) or 6 (3D systems for the Hybrid III 50th male) locations on the rib cage. These systems are available from Humanetics.

In addition to the instrumentation, there are several other considerations relevant to a discussion of multi-point chest compression measurement: injury criteria and performance requirements. Three main options for injury criteria and performance are discussed below:

1. *Current criteria (maximum compression and VC), with the current performance requirements at each measurement location*
    - These are already available, and it is likely that the criteria will be relevant at the new measurement locations; however, it is not known whether the performance limits would be valid at the new measurement locations

    - If the measurement points are close to the mid-sternum position, then consideration could be given to using the current mid-sternum performance limits. This may allow a comparable assessment of risk for different measurements positions, which would allow the dummy to assess the risk of injury regardless of the exact position of the seat-belt.
    - The chest compression injury risk function is known to be different for different restraint systems, e.g. different combinations of seat-belt and airbag loading. Indeed, this is one of the biggest limitations of the Hybrid III thorax injury risk assessment. If the same criterion is used with a multi-point measurement system, the same major disadvantage would be carried over to the new assessment, which could severely limit any benefit arising from the use of the updated dummy. The main limitation is that improved airbag restraint, and reduced localised chest loading from the seat-belt, is not encouraged (and may even be penalised) using this criterion.
2. *Current criteria (maximum compression and VC), with new performance requirements appropriate to each measurement location*
    - This option would also suffer from the disadvantage that the criterion may limit the development of improved restraint systems; nevertheless, it may offer some improvement over the current single-point measurement.
3. *New criteria and performance requirements (e.g. the criteria being developed in the THORAX FP7 project for use with the updated THOR thorax)*
    - This option offers the most potential to improve the chest injury assessment on the Hybrid III dummy; it may be possible to make the injury assessment independent of the restraint condition, which would be a big step forward in guiding the development of improved restraint systems
    - Work would be required to develop dummy-specific constants for the criteria (i.e. the constants would be expected to be different for THOR and Hybrid thoraces), and dummy-specific injury risk curves from which performance criteria could be selected. This is likely to be a comparable scale of work to that already being undertaken for THOR in the THORAX project. This implies that the timescale and cost for the work would be comparable with that for the THOR, in which case it may be preferable to use the THOR because it offers additional improvements in biofidelity and injury assessment to many of the body regions.

Advantages

- The baseline dummy already exists in several size options
- The instrumentation is available

Disadvantages

- The multi-point chest compression instrumentation has not been widely evaluated in the Hybrid III

- Performance requirements for the standard injury criteria at the new measurement points have not been proposed
- Injury criteria that make full use of the extra measurement capability have not been proposed, although it may be possible to transfer the injury criteria for the updated THOR dummy that are being developed in the THORAX project
- Performance requirements for the new THORAX injury criteria are not available
- Performance requirements have to be developed specifically for the dummy to which they will be applied, and further work would be required to derive Hybrid-III-specific criteria and requirements; this work could be as extensive (in time and cost) as that required to complete the work on the THOR dummy in the THORAX project

3.2.4 Hybrid III with alternative chest injury metrics

At the last GRSP IG FI meeting, there was a presentation regarding a chest injury metric that was first published at the Stapp conference in 2003 (Petitjean, 2003)[8]. This metric, called the equivalent deflection, uses a combination of the standard Hybrid III mid-sternum chest compression measurement and the shoulder belt force measured between the shoulder of the dummy and the upper seat-belt anchorage. Some recent validation of the metric was presented during the IG FI meeting, but the present authors are not aware of any other validation of the equivalent deflection criterion.

It appears that the criterion effectively limits the shoulder belt force and it may be equivalent to setting a maximum load on shoulder belt force limiters. Several issues with the equivalent metric are apparent at this time, and others may become known if further validation of the metric is undertaken:

- The criterion was developed with a human body model that was published in the late 1990s. Considerable development of human body models has occurred since then, and during the presentation it was noted that the work needed to be checked with a current human body model. It was also noted that the coefficients used in the calculation of the equivalent deflection metric should be checked with updated injury data and current statistical methods.
- The robustness of the metric may be dependent on the belt position on the sternum. This may be mitigated by the use of multi-point chest compression measurements, but this would require further validation.
- Because the metric uses an external measurement – shoulder belt force – it is not strictly an injury criterion. Because it uses an external measurement, there is a risk that the metric is specific to the restraint conditions assessed during its development, and it may not work as effectively with other restraint conditions. For instance, some restraint systems provide very high pelvis restraint forces, and allow the thorax to rotate forwards, whereas other systems allow the pelvis to come further forward until the knees interact with the dashboard, the thorax translates, rather than rotates, forward. These two restraint options give a different interaction between the shoulder belt and the thorax and it is not clear whether the equivalent deflection metric would work correctly with both restraint

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[8] Document number FI-11-05 at http://live.unece.org/trans/main/wp29/wp29wgs/wp29grsp/fi_11.html

options. Considerable effort may be required to validate the criterion across the full range of vehicle and restraint system types.

- It is not known how inflatable shoulder belt systems, which have been recently introduced by Ford, would interact with the shoulder belt force measurement.

Advantages

- It is proposed that the equivalent deflection metric enables a better distribution of load between the airbag and the shoulder belt, which would reduce the risk of thorax injury

Disadvantages

- The metric depends on an external measurement – the shoulder belt force – so it is not a direct measurement of injury risk
- It relies on a correlation between external belt force, internal chest compression, and injury risk that has been demonstrated for an out-of-date human body model, and further work is required to update the coefficients with a current, well-validated human body model
- The metric has had only had limited validation with different vehicles and restraint types

3.2.5 THOR

The THOR dummy has been developed over many years with the objective to address many of the limitations identified with the Hybrid III dummy, and thereby offer improved injury risk assessment in frontal impacts. The dummy development has been led by NHTSA, with evaluation and contributions from many organisations world-wide. The focus has been on the 50th percentile male dummy, but one prototype 5th percentile female dummy was produced in 2006.

The THOR prototype was evaluated in the EC 4th Framework project ADRIA, and the THOR-alpha was evaluated in the 5th Framework project FID. The FID project also developed the THOR-FT, which was heavily based on the THOR-Alpha updated with handling, durability and instrumentation improvements intended to ensure that the dummy was suitable for use in European Regulation. Since then, NHTSA have updated the dummy to THOR-NT and more recently co-ordinated further updates via SAE Working Groups, which has resulted in the recent release of a 'ModKit' to bring the dummy up to the current build level.

In parallel, the THORAX FP7 project is developing an improved thorax, and particularly improved instrumentation and injury criteria for use with the new thorax. The intention is to offer a tool that enables the best possible guidance on restraint system tuning in frontal impacts. It is intended that the THORAX update will be applied to the 'ModKit' version of the THOR 50th percentile male dummy. The THORAX schedule is for hardware development, injury criteria, dummy validation testing (biofidelity, durability, repeatability and reproducibility etc.) to be complete by the end of March 2012, and an assessment of dummy performance with modern restraint systems evaluated in sled tests over the following year.

NHTSA has recently published its schedule for the THOR dummy, which included an Agency decision on the 50th male dummy in mid-2012 and on the 5th female dummy in mid-2013. The Agency decision is defined as a '*decision about whether the program or project is ready and worthy to move from the research stage into the rulemaking stage, whether the program or project requires further research, or whether the potential benefit does not warrant further allocation of resources. This "agency decision" is based on many factors, including estimates of the target population, readiness of technology, potential effectiveness of countermeasures, development of a test protocol, and what information remains unknown.*' It is understood that NHTSA would want to introduce the 50th male and 5th female THOR dummies into US regulations at the same time and not stagger the introduction.

The main issues relating to the THOR dummies are:

- Improved biofidelity for most body regions, which has a number of benefits including:
  - Improved kinematics give better interaction with the diagonal shoulder belt, which means that head excursion is more humanlike and problems with the head missing the airbag are more likely to be detected
  - Improved pelvis shape, pelvis and thigh flesh specifications, and knee-thigh-pelvis biofidelity mean that the relative contribution of the dashboard, seat, belt and airbag to the restraint of the occupant will be more realistic, which will improve the accuracy of the injury assessment
  - Numerous other biofidelity and injury assessment improvements, which would be expected to enhance the value of the test procedure(s) and deliver greater injury reduction by encouraging improved crash energy management and better restraint systems
- The THOR dummy has multi-point chest compression measurement as standard, and injury criteria for the multi-point system will be available at the same time or earlier than they will be available for the Hybrid III multi-point compression measurement system
- Development status
  - The THOR 50th male dummy is well developed, but not finalised. The THORAX project is working on the thorax hardware and criteria, and the whole dummy is currently being evaluated by NTHSA. It appears that the THORAX and NHTSA timescales are well aligned, but there is the possibility that the evaluation programmes will find problems that need to be addressed before the dummy can be considered ready for regulation. While there is no known intention to change the timescales, it should be considered possible that they will change.
  - Only one THOR 5th percentile female prototype dummy is available, so the dummy development is less well advanced than the 50th male dummy. It is understood that NHTSA intend to base updates to the 5th percentile female on the ModKit for the 50th percentile male, so the experience gained with the 50th male dummy should reduce the risk of delays to the 5th female dummy finalisation. Nevertheless, the timescale for the Agency decision seems challenging.

3.2.6 Summary

- Current Hybrid III 50th percentile male

    - This is the most straight-forward option, but will deliver the minimum benefit with the updated regulation
- Hybrid III 50th percentile male and 5th percentile female
    - The use of a smaller dummy in at least one of the four front seating positions that would be available with two frontal impact tests is indicated by the accident data used in the benefit analyses
    - The Hybrid III 5th percentile female dummy is already available in most crash laboratories
    - However, both dummies have the same limitations with respect to biofidelity and injury assessment capability
- The Hybrid III could be used with multi-point compression chest measurement near the mid-sternum
    - This would improve the detection of compression in this region, whatever the position of the seat-belt
    - However, this option would have the same serious limitation as the current dummy, i.e. the assessment of risk is known to vary with the relative contribution of the seat-belt and airbag, and this relative contribution is unknown
- The Hybrid III could be used with more general multi-point chest compression across the thorax
    - The work required to validate the criteria and injury risk functions to be used with this instrumentation would be as extensive as that required for the THOR
    - The Hybrid III is not as biofidelic as the THOR in other important respects, such as the flexibility of the spine and the shape of the pelvis, that will affect how the thorax is loaded by the restraint system. This will reduce the potential to improve restraint design compared with a more biofidelic dummy.
    - It is possible that this option could be implemented more quickly than THOR, because only the instrumentation and some minor modifications to the thorax and spine would be required, which is a smaller manufacturing task that making a complete THOR dummy
- The Hybrid III could be used with the ‘equivalent deflection’ criterion proposed at the 11th GRSP IG FI meeting
    - It is proposed that this will help to encourage lower load limits, which offers the potential to improve restraint for older occupants
    - However, the criterion uses a measurement that is external to the dummy (seat-belt load), which is not the preferred approach for assessing injury risk. It seems apparent that considerable work would be required to update the coefficients used in the calculation of the criterion, and to validate the criterion for different restraint philosophies.
- THOR
    - THOR development has been focussed on overcoming many limitations that have been identified with the current regulatory dummy, which will be particularly important for encouraging further improvements in restraint

system performance in frontal impacts. In particular, the biofidelity and injury assessment capability of the dummy are particularly improved.

  - The main risk with THOR is the timescale for finalisation of the 50th percentile male and 5th percentile female dummies.

3.3 Way forward

This section briefly describes some of the authors' thoughts for the way forward. The main issues that need to be addressed to determine the way forward are:

- Test configuration
  - Full Width test
    - Test speed; higher speed (50-56 km/h) or (low speed ~ 40 km/h)
      - No specific work planned currently to address this issue. However, THORAX project benefit analysis indicated that introduction of test procedure to safe-guard against injuries caused in low speed impacts would give highest benefit of options considered.
    - Rigid or deformable face
      - FIMCAR project is expected to address this issue.
  - Offset test
    - PDB or ODB
      - FIMCAR project is expected to address this issue (PDB test is required for the assessment of a car's compatibility).
  - Other
    - Supplementary tests / simulation may be needed to enforce the introduction of restraint systems which adapt to offer optimised protection for different accident severities and occupants of different weights and sizes.
      - No specific work planned currently to address this issue.
- Dummy
  - HybridIII or THOR
    - THOR is the better option; however timescales for when it will be ready for regulatory use are uncertain.
    - THORAX project is expected to address remaining issues with THOR (i.e. improved thorax and associated injury criteria).

If timescales for THOR remain uncertain then one possible option for the way forward is to introduce test configuration changes using the HybridIII dummy and then upgrade later to the THOR dummy. This type of approach has been used in the past; Directives have been written containing articles which specify that certain aspects of the Directive should be reviewed by a given date and the Directive updated as appropriate.

Note inserted at request of EC project officer (Peter Broertjes) to express the position of the Commission

A step-by-step phase in type approach could be deemed acceptable provided that this did not entail vehicle manufacturers having to adapt vehicle designs during the course of their lifecycles. In such a case a 'grandfathering' clause could be used so that the new rules would apply only to completely new vehicle designs. This type of approach (step-by-step) could potentially facilitate an earlier introduction of life-saving vehicle enhancements, but could, at the same time, also avoid an unacceptable burden for the vehicle industry.

Appendix A Comparison of deceleration pulses

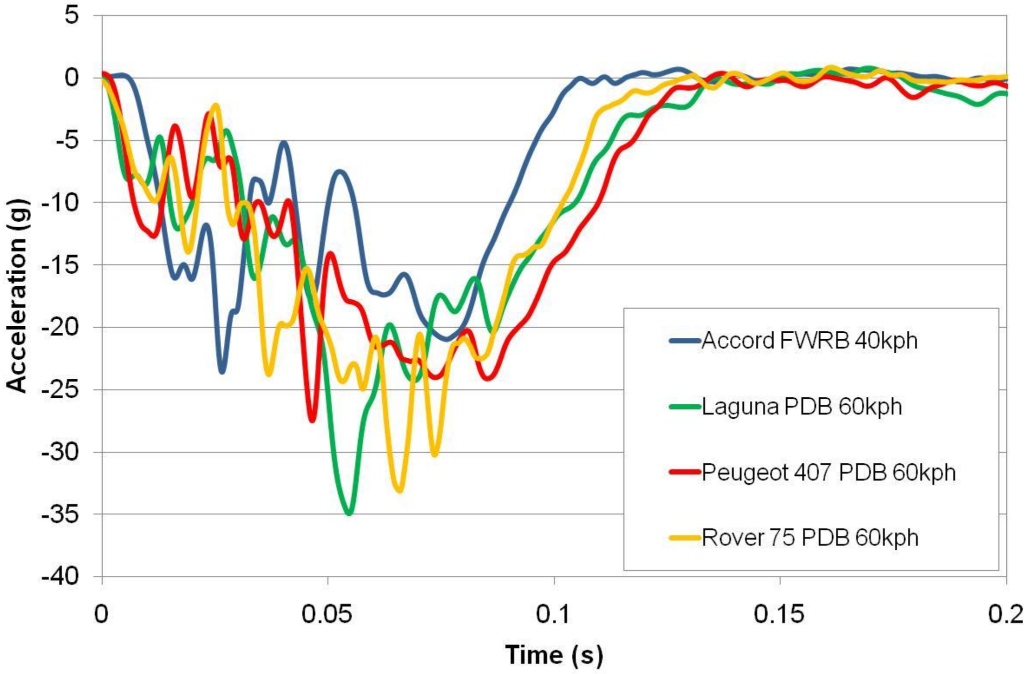

Figure 2: Comparison of 40 km/h Full-Width Rigid Barrier (FWRB) compartment deceleration pulses for Accord with 60 km/h PDB pulses for Laguna, Peugeot 407 and Rover 75 showing PDB pulses have higher decelerations than 40 km/h FWRB pulse

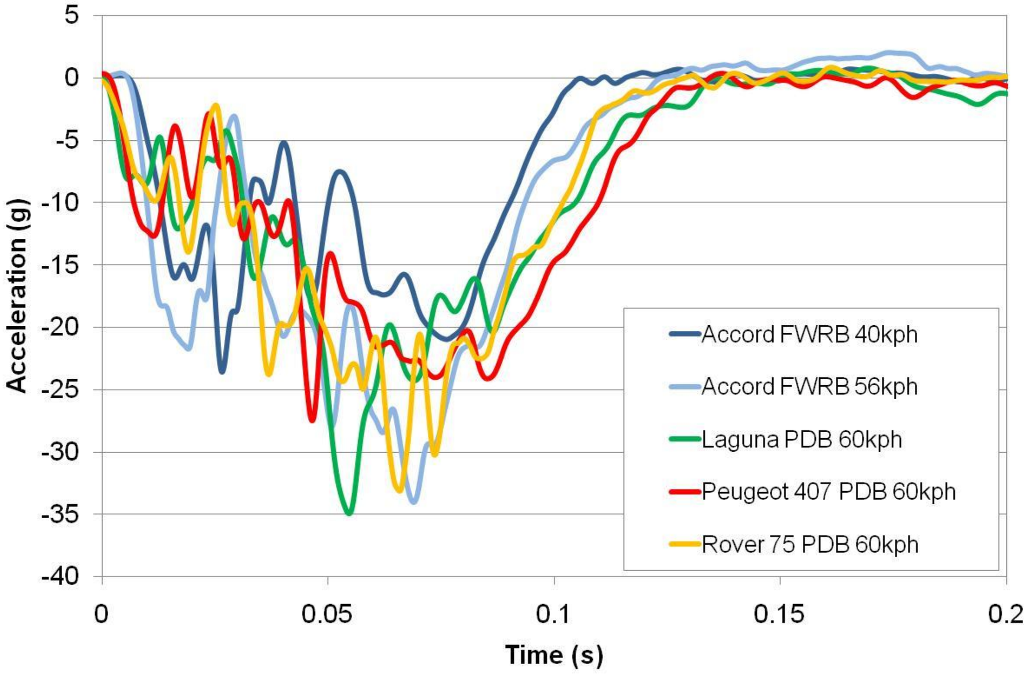

Figure 3: As figure above but with addition of 56 km/h FWRB pulse showing that 56 km/h FWRB pulse is more severe than PDB pulse (Note: observation that Laguna has more severe pulse than other vehicles – see figures below - needs to be taken into account to draw this conclusion)

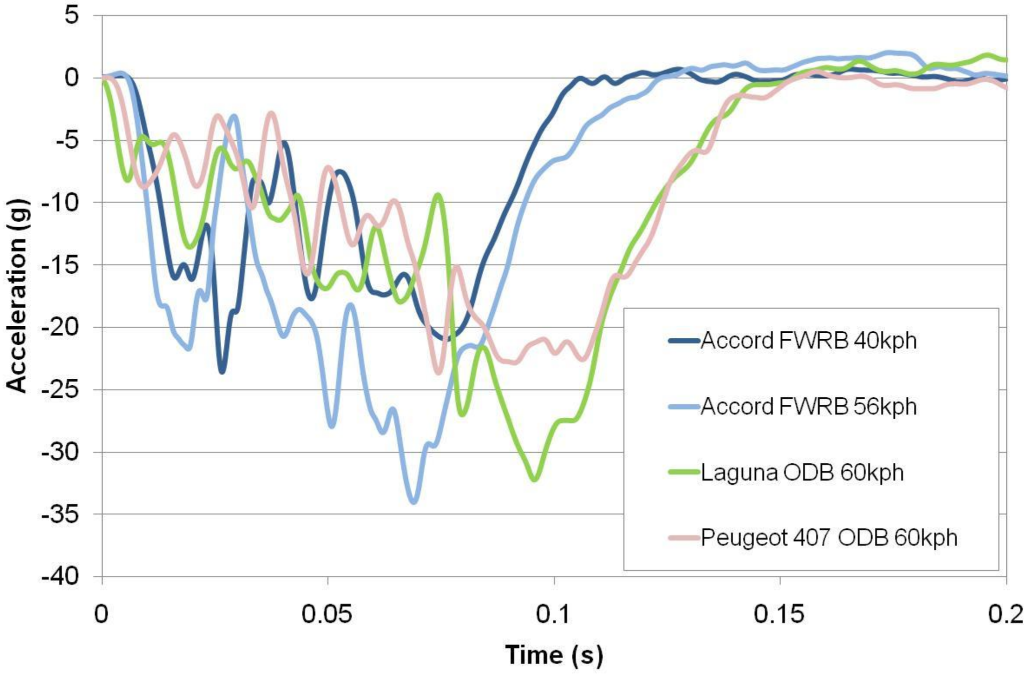

Figure 4: Comparison of 40 km/h and 56 km/h FWRB compartment deceleration pulses for Accord with 60 km/h ODB pulses for Laguna and Peugeot 407

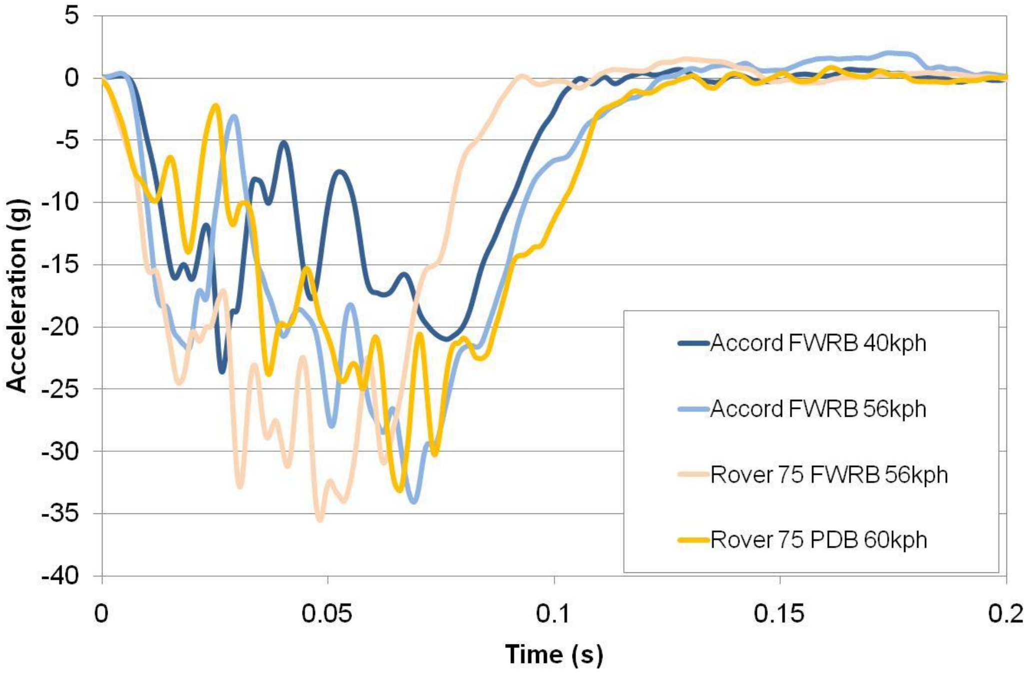

Figure 5: Comparison of pulses for Accord and Rover 75 showing variation in FWRB pulses

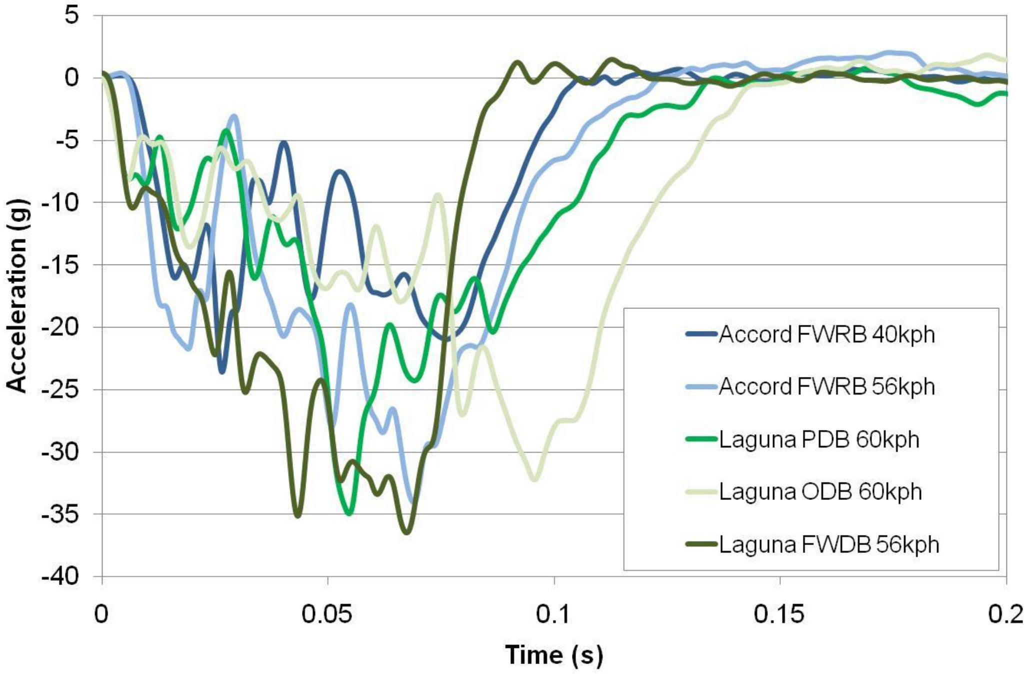

Figure 6: Comparison of pulses for Accord and Laguna showing higher decelerations for Laguna in full-width tests