Transport Research Laboratory

Technical Assistance and Economic Analysis in the Field of Legislation Pertinent to the Issue of Automotive Safety:

Provision of information and services on the subject of the tests, procedures and benefits of the requirements for the development of legislation on Frontal Impact Protection

Final Report

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CPR 403

ENTR/05/17.01

CLIENT PROJECT REPORT

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Prepared for: Project Record: ENTR/05/17.01

Client: European Commission, DG Enterprise and Industry

(Peter Broertjes)

The views expressed are those of the authors and not necessarily those of the European Commission.

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Contents

Executive summary

The requirements of EU Directive 96/79/EEC and UNECE Regulation 94 have now been in existence for more than ten years. The GRSP working group in Geneva has recently started a review of the requirements of Regulation 94 which could potentially lead to proposals to amend this regulation.

TRL was commissioned by the European Commission (EC) to gather and evaluate all available information related to a potential update of Regulation 94 and to provide recommendations for updated testing requirements in the regulation for frontal impact protection, in particular those relevant to the review of Regulation 94 currently being performed by the GRSP working group.

From a review of the existing legislation, available accident data and proposed new and modified test procedures, potential options to improve Regulation 94 were identified. Two types of option were identified. The first type consisted of changes to the test configuration and / or the addition of new tests, referred to as 'main' options. The second type consisted of options which could be incorporated into the 'main' options, such as changes to the dummy test tool and / or assessment criteria, referred to as 'supplementary' options. The options identified were:

'Main' options

- o No change.
- o Replace the current R94 ODB test with a Progressive Deformable Barrier (PDB) test.
    - o As proposed by France at the December 2007 GRSP meeting.
- o Add a full width high deceleration test to the current UNECE Regulation 94 ODB test procedure.
- o Combination of options 2 and 3.

'Supplementary' options

Dummy related:

a. Incorporation of the THOR-Lx, and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy.

Other:

b. Extension of scope to include all vehicles of M1 category and N1 vehicles.
c. Steering wheel movement controlled through the addition of a 100 mm horizontal displacement limit.
d. Footwell intrusion controlled by assessment against a specifically developed criterion and associated pass or fail limit.
e. Assessment of protection afforded in rear seated positions.

It should be noted that these potential options were presented to the GRSP informal working group on frontal impact for their consideration at a meeting in March 2009.

In alignment with the 'better regulation' principles introduced by the Commission and the CARS 21 initiative, ideally a proposal to change regulation should contain the following three items:

- An evidence base showing the reason why the regulation needs to be changed.
- A detailed proposal showing how the regulation should be changed, i.e. additional test procedures and/or amendments required to current test procedures
- A regulatory impact assessment for the proposed change, i.e. an assessment of the benefits and the costs and other possible consequences

On this basis, each of the potential options identified was reviewed with consideration of whether it would satisfy the needs identified in the accident studies, its potential for unintended consequences, its potential for further development to include measures to assess and control compatibility, its relationship with present international requirement and cost benefit implications. Industry was consulted as part of this review

Overall it was concluded that before any of the main options would be suitable for regulatory application much further work is required, in particular to assess cost benefit implications.

Recommendations for the further work needed are given.

1 Introduction

Frontal impact protection is currently legislated for by EU Directive 96/79/EEC. In parallel with this Directive the UNECE Regulation 94 provides the same requirements under the 1958 agreement. The EU has recently acceded to this Regulation and thus will accept it as an alternative to the Directive. Indeed under the terms of the recently adopted proposal on a General Safety Regulation, which has now entered discussion in the European Parliament and Council, this existing Directive would be replaced by direct reference to the UNECE regulations.

The requirements of EU Directive 96/79/EEC and UNECE Regulation 94 have now been in existence for more than ten years. The GRSP working group in Geneva has recently started a review of the requirements of Regulation 94 which could potentially lead to proposals to amend this regulation.

TRL has been commissioned by The European Commission (EC) to gather and evaluate all available information related to a potential update of Regulation 94 and to provide recommendations for updated testing requirements in the regulation for frontal impact protection, in particular those relevant to the review of Regulation 94 currently being performed by a GRSP working group.

The specific objectives of the research were to review:

- All legislation currently in force, both within Europe and internationally, for frontal impact testing with a focus on the method of testing, the instruments used and the parameters applied for acceptance levels.
- Existing accident analysis literature for Europe as a basis for prioritising frontal impact accident scenarios for injury reduction.
- The dummies used in current frontal impact legislative testing (e.g. Hybrid III) and those currently under development (e.g. THOR; Test device for Human Occupant Restraint) to make recommendations on appropriate dummies for use in future regulatory frontal impact test procedures.
- Proposed new and modified test procedures for frontal impact testing and associated proposals and identify potential options for how future legislation may be improved.
- The potential options to improve future frontal impact legislation, including consideration of cost-benefit issues, and to provide recommendations for the way forward.

This is the final report for the project. The layout of the report is as follows. Section 2 describes the review of existing legislation. This review identified the differences between European legislation and that in the rest of the world, summarised the relationship between UNECE Regulation 94 and other secondary safety legislation and also summarised the relationship of legislation with consumer testing programmes. Section 3 describes the review of accident analysis literature, both European and worldwide, to help prioritise frontal impact configurations and injuries for consideration. Section 4 reviews the Hybrid III dummy used in current frontal impact legislative testing and the THOR dummy which is currently under development. Section 5 reviews proposed new and modified test procedures and identifies potential options for how Regulation 94 may be improved. Section 6 describes the cost benefit analyses found in the literature appropriate for use in the review of the potential options. Section 7 reviews the potential options identified in section 5. Finally, a summary of the conclusions and recommendations from the study is given in section 7.

2 Existing Frontal Impact Legislation

This Section reviews the legislation for frontal impact in Europe and how it compares with other regions of the World. The focus was on the method of testing, the instruments used and the parameters applied for acceptance levels. The relationship between the main crash tests and related component tests was also examined (for Europe), and finally, comment was made on the extent to which consumer testing aligns with legislative testing.

The section comprises four parts. The first part sets out the legislative frameworks in place for the approval of vehicles in Europe, and some other key regions of the world. The second part focuses on European frontal impact legislation, with consideration of the main legislative test procedures, other secondary safety test procedures, and consumer test procedures. The third part describes the frontal impact legislation in the rest of the world, once again, with consideration of the main legislative tests and any important consumer tests. The final part is a summary of the main findings, with particular emphasis on the implications of any changes to the European legislative tests.

2.1 Overview: the Legislative Framework

The certification of vehicles in Europe is based around the principle of type approval. With this approach, a production sample is tested and if it passes the tests and the production methods pass an inspection, vehicles or components of the same type are licensed for production and sale within Europe. The license is granted by a type approval authority, which is responsible for ensuring the conformity of production during the whole period of the approval.

EC Whole Vehicle Type Approval is based around EC Directives and provides for the approval of whole vehicles, in addition to vehicle systems and separate components. A Framework Directive lists a series of separate technical Directives that the vehicle must comply with. In order to gain Whole Vehicle Type Approval, the vehicle must meet the requirements of each of the applicable individual Directives. However, the Framework Directive also lists a series of UNECE Regulations that are considered equivalent to certain of the separate technical Directives and proving compliance with these Regulations forms an acceptable alternative to compliance with the relevant Directives.

The scheme was introduced in the 1970s through Directive 70/156/EEC and it became mandatory for M_1 category vehicles (i.e. passenger cars) in 1998. A recast new framework Directive, 2007/46/EC, has since been published and extends the mandatory application of requirements to larger passenger and goods vehicles. The main EC Directive prescribing the technical requirements for the frontal impact performance of vehicles is EC Directive 96/79/EC (as amended by 1999/98/EC). This includes a full-scale impact test into an offset, deformable barrier at 56 km/h. There is also a wide range of Directives that relate to other aspects of the passive safety of vehicles. These include Directives that assess the performance of vehicle equipment during dynamic or static tests intended to reproduce the conditions of a front impact collision. For example, EC Directive 76/115/EEC (as amended) applies to seat belt anchorages.

UNECE Regulations provide for the approval of vehicle systems and separate components, but not whole vehicles. The framework for UNECE approval is set out in the Agreement concerning the Adoption of Uniform Technical Prescriptions for Vehicles adopted in 1958 (referred to as the 1958 Agreement). It is administered by the World Forum for Harmonisation of Vehicle Regulations (WP 29), which is a subsidiary body of the UNECE. The 1958 Agreement was initially created for the UNECE region; however, it was opened to all countries in 1995. In 1998, Japan became the first non-European country to accede to the 1958 Agreement, followed by Australia in 2000, South Africa in 2001 and New Zealand in 2002. The underlying principle of the 1958 Agreement is the mutual recognition of approval certification between the signatories. The main UNECE Regulation for the frontal impact performance of vehicles is UNECE Regulation 94.

However, other Regulations reproduce the conditions of a frontal impact collision to assess the performance of vehicle equipment. For example, UNECE Regulation 16 relates to seat belts and restraint systems.

A new international agreement, known as the 1998 Global Agreement, seeks to promote international harmonisation through the development of Global Technical Regulations. The 1998 Global Agreement is open to countries that are not signatories to the 1958 Agreement. The first Global Technical Regulation (GTR No. 1) related to door locks and door retention components. There are currently nine Regulations at various stages of development but none of these control the frontal impact performance of vehicles.

Other regions of the World operate their own vehicle standards, or accept UNECE Regulations (as signatories to the 1958 Agreement). Some of the major regions outside Europe operating their own vehicle standards are: The United States; Canada; Australia; Japan.

The United States has not joined the 1958 Agreement and does not, therefore, recognise UNECE approvals. Instead, the National Highway Traffic Safety Administration (NHTSA) has a legislative mandate under Title 49 of the United States Code, Chapter 301, Motor Vehicle Safety, to issue Federal Motor Vehicle Safety Standards and Regulations (FMVSS). The main standard in use for the frontal impact performance of vehicles is FMVSS 208. The main components of the standard comprise a series of full-scale impact tests, usually into a rigid barrier, at various speeds. The barrier extends across the full width of the vehicle in most tests. The approach to vehicle approval in the United States is fundamentally different in philosophy to that in Europe. Most notably, the United States system is based around the principle of self-certification, whereby the manufacturer guarantees compliance with the relevant Standards before sale. The Government (through NHTSA) may verify compliance after the vehicle is on the market.

Canada has also not joined the 1958 Agreement, although some UNECE Regulations have been adopted. Vehicle legislation in Canada is based around the Motor Vehicle Safety Act (SC 1993, C.16, as amended by SC 1999, C.33). The Act, and its various regulations, (known as Canadian Motor Vehicle Safety Standards (CMVSS)) require that all vehicles introduced into the Canadian market meet comprehensive safety requirements. The main standard in use for the frontal impact performance of vehicles is CMVSS 208. Manufacturers are required to self-certify that their products comply with the Act; and all complying products carry a National Safety Mark. The Act is enforced by means of audit, product testing and defect investigation.

Australia became a signatory to the 1958 Agreement in 2000 and consequently accepts certain UNECE approvals in lieu of their national requirements. These national requirements are set out in the Federal Motor Vehicle Standards Act 1989 (Act No.65, as amended). This requires vehicles to meet national standards that cover a range of requirements. The national standards are known as Australian Design Rules. The main standards in use for the frontal impact performance of vehicles are Australian Design Rule 69/00 – Full Frontal Impact Occupant Protection and Australian Design Rule 73/00 – Offset Frontal Impact Occupant Protection. Australian Design Rule 73/00 requires that vehicles must comply with UNECE Regulation 94 and includes the Regulation in an Appendix. The Australian vehicle certification system is a type-approval system.

Japan was the first non-European country to join the 1958 Agreement and accept certain UNECE approvals. Motor vehicle legislation in Japan is set out in the Road Vehicles Act (Law No. 185 of 1951). This covers the safety and construction of vehicles and their environmental impact. The frontal impact performance of cars falls within Article 18 of the Safety Regulations of Road Vehicles. Two full-scale frontal impact tests are required: a full-width test into a rigid barrier at 50 km/h and a 40 percent offset test into a deformable barrier at 56 km/h. The test procedure and performance requirements for the full width test are described in a separate technical standard ‘Attachment 23’ while UNECE Regulation 94 is used as the offset test. The Japanese vehicle certification system is a type approval system.

2.2 Frontal Impact Legislation in Europe

This section of the report examines the legislation in Europe. The main focus is on the test procedures used to evaluate the performance of cars in a frontal impact. However, the relationship between the frontal impact test and relevant component tests for secondary safety is also discussed. Finally, comment is also made on the main consumer test procedure and how it aligns with the legislative test.

2.2.1 Test Procedures in the Legislation

EC Directive 96/79/EC (as amended by 1999/98/EC) and UNECE Regulation 94 are equivalent standards: they both include dummy and vehicle performance requirements, which are assessed by means of a full-scale crash test. The test procedure was developed by the European Enhanced Vehicle-safety Committee from the findings of an extensive research programme. During the test, the car is propelled into an offset, deformable barrier at 56 km/h. The car overlaps the barrier face by 40 percent, with first contact with the barrier on the steering-column side. This is intended to represent a car to car collision with both cars travelling at 50 km/h with a 50 percent overlap (Lowne, 1994). The deformable barrier absorbs some of the energy of the impacting car and this is the reason that the speed is higher in the test than in the equivalent car to car collision. Similarly, cars are less stiff than the barrier towards the outer edge, so the offset is reduced for the test. A schematic diagram of the test procedure is shown in Figure 2.1.

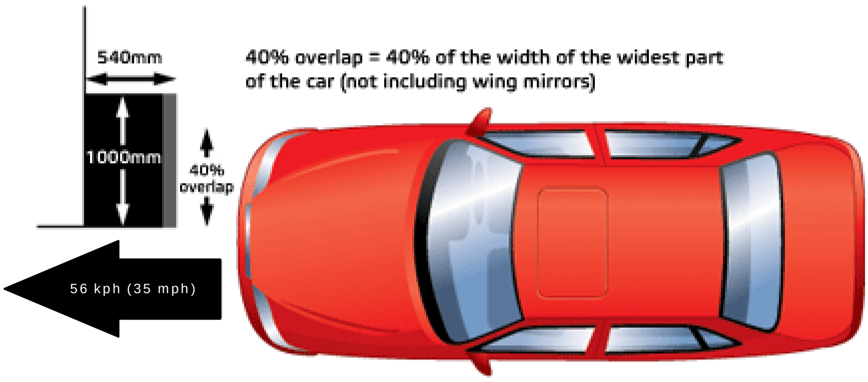

Figure 2.1: Test procedure in EC Directive 96/79/EC and UNECE Regulation 94

A car that represents the ‘worst case’ for the particular model is selected for the test. Hybrid III 50th percentile (male) dummies are restrained in each of the front outboard seats, with instrumentation in the head, neck, chest, femurs, knees and tibias. The dummy requirements comprise a series of performance limits, which are set out in Table 2.1. In addition, the following vehicle performance requirements are applied:

- Residual steering wheel displacement, measured at the centre of the steering wheel hub, must not exceed 80 mm in the upwards vertical direction and 100 mm in the rearward horizontal direction.
- No door may open during the test.
- After the impact, it must be possible, without the use of tools, except for those necessary to support the weight of the dummy to:
    - Open at least one door, if there is one, per row of seats and, where there is no such door, to move the seats or tilt their backrests as necessary to allow the evacuation of all the occupants; this is, however, only applicable to vehicles having a roof of rigid construction;

    - o Release the dummies from their restraint system which, if locked, must be capable of being released by a maximum force of 60 N on the centre of the release control;
    - o Remove the dummies from the vehicle without adjustment of the seats;

- In the case of a vehicle propelled by liquid fuel, no more than slight leakage of liquid from the entire fuel system may occur during or after the impact. If after the impact there is a continuous leakage of liquid from any part of the fuel system, the rate of leakage must not exceed $5x10^{-4}$ kg/s; if the liquid from the fuel-feed system mixes with liquids from other systems and the various liquids cannot easily be separated and identified, all the liquids collected are taken into account in evaluating the continuous leakage.

Table 2.1: Dummy performance requirements in EC Directive 96/79/EC and UNECE Regulation 94

Dummy performance limit	Value
Head performance criterion (HIC_{36})	• 1000
Head resultant acceleration (3ms exceedence)	80 g
Neck tensile force (presented as a chart of axial tensile neck force against duration of loading over given tension)	3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ • 80 ms
Neck shear force (presented as a chart of fore/aft neck shear force against duration of loading over given shear force)	3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ • 45 ms
Neck extension moment	57 Nm
Thorax compression	•50 mm
Viscous criterion (V*C)	•1 m/s
Femur force (presented as a chart of axial femur force against duration of loading over given force)	9.07 kN @ 0 ms 7.58 kN @ • 10 ms
Tibia compression force	• 8 kN
Tibia index	• 1.3 (top and bottom)
Sliding knee joint movement	• 15 mm

2.2.2 Test Procedures in Other Secondary Safety Regulations

While EC Directive 96/79/EC and UNECE Regulation 94 are now the main legislative tests for frontal impact, a number of Directives and Regulations also exist that apply to other aspects of the secondary safety of vehicles. These are summarised in Table 2.2. UNECE Regulation 44 (child restraint systems) is included in the Table, although it is recognised that this regulation is not related to the performance of the vehicle directly.

Table 2.2: EC Directives and UNECE Regulations on impact performance

EC Directive	UNECE Regulation	Subject
74/297/EEC	12	Steering assemblies
76/115/EEC	14	Seat belt anchorages
77/541/EEC	16	Seat belts and restraint systems
74/408/EEC	17	Seats and their anchorages
74/408/EEC	21	Interior fittings
78/932/EEC	25	Head restraints
-	44	Child restraint systems

The ‘component’ regulations in Table 2.2 were, in fact, the main European Legislation on impact performance, prior to the introduction of EC Directive 96/79/EC and UNECE Regulation 94 (in the 1990s). A full-scale crash test was required by UNECE Regulation 33 (structural behaviour in a head-on collision), but this was intended to control intrusion of the steering column only: no test dummies were used. The car was propelled into a rigid block extending across its full width.

The new Directive and Regulation were developed because it was thought that modifications to the component regulations would be unlikely to produce a large effect on the safety performance of vehicles. Nevertheless, these regulations are important for evaluating cars at the component level. Four of the regulations are particularly relevant for this study:

- EC Directive 76/115/EEC (UNECE Regulation 14);
- 77/541/EEC (UNECE Regulation 16);
- 74/408/EEC (UNECE Regulation 17);
- UNECE Regulation 44.

These are important because they include static or dynamic tests that are representative of the conditions of a frontal impact. If changes are made to the frontal impact legislation in the future, it may be necessary to review these component regulations.

EC Directive 76/115/EEC (as amended) and UNECE Regulation 14 relate to seat belt anchorages. In each case, the anchorages must meet a series of installation and technical requirements. In addition, a quasi-static load test is carried out to assess their strength. The test load (13.5 ± 0.2 kN) is applied through the belt in the direction the seat is facing. The anchorages must withstand the load for at least 0.2 seconds. While vehicles are becoming stiffer, and may continue to do so in the future, seat belt loads are unlikely to increase beyond the current test load level: particularly as more vehicles are being fitted with load limiters. The test load is, therefore, likely to remain appropriate irrespective of any changes to the test conditions in the frontal impact legislation.

EC Directive 77/541/EEC (as amended) and UNECE Regulation 16 apply to seat belts and restraint systems. The requirements cover each of the main components as well as the assembly as a whole. For the purposes of this study, the dynamic sled test of the seat belt assembly is the most relevant test in the Directive and the Regulation. This comprises a 50 ± 1 km/h impact with a stopping distance of 400 ± 50 mm. The deceleration curve of the sled, weighted with an inert mass, must remain within prescribed limits during a calibration test. At the highest level, the deceleration must fall between 26g and 32g. The requirements of the dynamic test are met if no part of the seat belt assembly breaks or unlocks during the test. In addition, limits are prescribed to the forward displacement of a TNO-10 dummy (representing a 50^{th} percentile male adult). In the case of three point seat belts, the dummy displacement must fall between 80mm and 200 mm at pelvic level and between 100mm and 300 mm at torso level. However, if the seat belt is intended for an outboard seat with an air bag in front of it, the displacement of the chest may exceed the limit value, if the speed at this value does not exceed 24 km/h.

The dynamic sled test in EC Directive 77/541/EEC (as amended) and UNECE Regulation 16 is a test of the integrity of the seat belt assembly under relatively high deceleration. The full-scale crash test in EC Directive 96/79/EC and UNECE Regulation 94 does not assess the seat belt in a car to this level. This is because the car is offset against the barrier face, which is a severe test of the vehicle structure, but results in lower overall deceleration. The sled test and the full-scale crash test are therefore complementary: the sled test is demanding of the restraint system and the full-scale test is demanding of the vehicle structure.

If changes were made to the full-scale test conditions, the European Commission may wish to examine how the deceleration pulse of a car subjected to the test would compare with the sled deceleration from EC Directive 77/541/EEC (as amended) and UNECE Regulation 16. For instance, if a full-width test was introduced, a separate integrity test at the component level may be unnecessary.

EC Directive 74/408/EEC (as amended) and UNECE Regulation 17 set out requirements for all forward facing seats, their anchorages and head restraints. A series of static and dynamic tests are prescribed. These comprise:

- A test of the strength of the seat back and its adjustment systems;
    - A force producing a moment of 530 Nm in relation to the R point is applied longitudinally and rearwards to the upper part of the seat back frame. The force is applied through a component that simulates the back of a dummy. If the supporting frame of a seat is common to more than one seating position, the test is carried out on each position simultaneously. No failure is permitted during or after the test but permanent deformations, including ruptures may be accepted provided that they do not increase the risk of injury in the event of a collision and the load was sustained.
- A test of the strength of the seat anchorages and the adjustment, locking and displacement systems;
    - A deceleration of at least 20 g is applied to the whole shell, or a representative part of the shell, of the vehicle. Both forward and rearward deceleration tests are carried out. These are intended to assess the resistance to inertia only and hence no dummies are used. Once again, no failure is permitted during or after the test but permanent deformations that do not increase the risk of injury may be accepted.
- A test of the performance of the head restraint;
    - An initial force producing a rearward moment of 373 Nm about the R point is applied by means of a spherical headform 165 mm in diameter. The initial force is then increased to 890 N (unless the seat or the seat back fails). The head restraint and its anchorage must bear this load and the maximum rearward displacement of the headform must be less than 102 mm.
- A test of the energy dissipation of the seat back and the head restraint;
    - A 165 mm headform fitted to a pendulum strikes either the seat back or the head restraint at 24 km/h. The deceleration of the headform must not exceed 80 g continuously for more than 3 ms in each test.

As vehicles become stiffer, the deceleration for a given impact speed increases. If changes were made to the frontal impact legislation that encourage stiffer vehicle designs, the seat strength requirements in EC Directive 74/408/EEC (as amended) and UNECE Regulation 17 may no longer be adequate. It would be necessary, therefore, to consider changes to the Directive (and Regulation) that ensure the same level of seat safety is maintained.

UNECE Regulation 44 contains design and performance requirements for child restraint systems. The performance of the child restraint in a collision is evaluated by means of a frontal and a rear impact test. The frontal impact test is carried out with an impact speed of 50 km/h and a stopping distance of 650 ± 50 mm. The deceleration curve of the sled, weighted with an inert mass, must remain within prescribed limits during a calibration test. At the highest level, the deceleration must fall between 20 and 28 g. Limits are applied to the head excursion and chest acceleration of the child dummy during the test.

Measures to improve protection for adults seated in the rear of a car could have unintended effects on the protection afforded to children. For example, a seat belt load limiter would reduce the forces on the clavicle of an adult, but would increase the head excursion of a child in a child restraint system (and consequently their risk of head contact with the vehicle interior). This could be relevant if changes to the frontal impact legislation were considered that required or encouraged car manufacturers to fit advanced adult restraint systems in the rear.

UNECE Regulation 44 was introduced before the legislative frontal impact test in EC Directive 96/79/EC and UNECE Regulation 94. It is not, therefore, intended specifically to reproduce the same deceleration profile and conditions. Nevertheless, it would be worthwhile to consider whether changes to the legislative test would need to be reflected in UNECE Regulation 44 in the future.

2.2.3 Test Procedures for Consumer Information

The frontal impact legislation (i.e. EC Directive 96/79/EC or UNECE Regulation 94) provides a minimum standard of safety for new cars. However, most new models are also tested by the European New Car Assessment Programme (Euro NCAP). Euro NCAP is a consumer information programme that encourages car manufacturers to exceed the legislative requirements. The Euro NCAP frontal impact test is based on that in EC Directive 96/79/EC and UNECE Regulation 94, but the impact speed has been increased (by 8 km/h) to 64 km/h. This represents a car to car collision with each car travelling at around 55 km/h. A schematic diagram of the test procedure is shown in Figure 2.2.

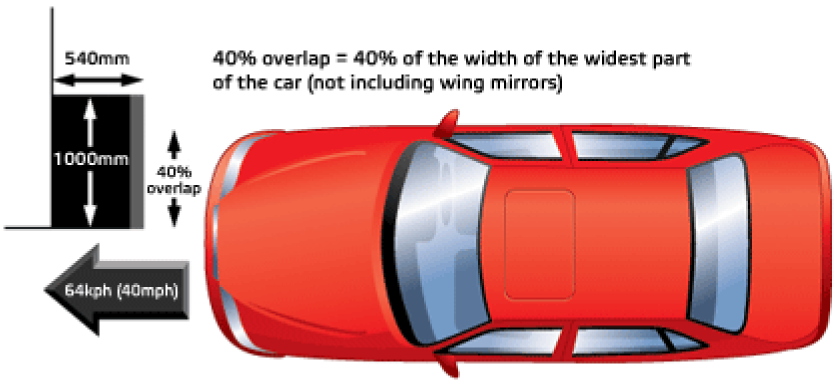

Figure 2.2: Frontal impact test procedure in Euro NCAP

The best-selling version of the model is selected for the test. Hybrid III 50th percentile (male) dummies are restrained in each of the front outboard seats, with instrumentation in the head, neck, chest, pelvis, femurs, knees and tibias. P1½ and P3 child dummies are restrained in suitable child restraint systems in the rear: the P1½ is placed in the rear passenger-side seat and the P3 in the rear driver-side seat. Both child dummies are fitted with instrumentation in the head and the chest, while the P1½ is also fitted with instrumentation in the neck.

Response data from the child dummies are used to assess the child occupant protection for the car. The adult occupant protection assessment for the car relates primarily to the driver response, unless a body region of the passenger fares less well. The structural performance of the car is also considered by taking account of the steering wheel displacement, pedal movement, footwell distortion and 'A' Pillar displacement.

Two performance limits are used for each assessment parameter: a more demanding limit, beyond which a maximum score is obtained and a less demanding limit, below which no points are scored. The least demanding boundaries are generally equivalent to the limits in the legislative test. The more demanding boundaries were set to identify aspects of a car's performance which offer significantly greater protection (Euro NCAP, 2008). In addition, a series of modifiers may be applied to the score if it is considered that the outcome would have been worse for different sized occupants in different seating positions, or accidents of slightly different severity.

It should be noted that having a similar test in both legislative and Euro NCAP testing helps to reduce the testing burden on manufacturers. Hence, if changes were made to the legislative test, an equivalent change to Euro NCAP test would be necessary to maintain the current relationship and help ensure that the testing burden on manufacturers was not increased.

2.3 Frontal Impact Legislation in the Rest of the World

This section examines the frontal impact legislation in the rest of the world. The main focus is on the test procedures used and how these differ from Europe. Some comment is also made on the test procedures used by consumer information programmes. Four regions were examined:

- the United States;
- Canada;
- Australia;
- Japan.

Table 2.3 summarises the frontal impact legislation in these regions along with Europe.

Table 2.3: Frontal impact legislation in Europe and selected other regions

	Europe	United States	Canada	Australia		Japan	
	96/79/EC and UNECE R94	FMVSS 208	CMVSS 208	ADR 69/00	ADR 73/00 (UNECE R94)	Article 18, Safety Regulation	
						Full width	Offset (UNECE R94)
SCOPE							
Vehicle type	M1 vehicles	Passenger cars, MPVs, trucks and buses	Passenger cars, MPVs, trucks and buses	M1 and N1 vehicles	M1 vehicles[3]	M(• riding capacity of 10) and N vehicles	M1 and N vehicles
Vehicle mass	• 2.5 tonnes	• 2,495 kg	• 2,495 kg	-	• 2.5 tonnes	N• 2.8 tonnes	• 2.5 tonnes
TEST CONFIGURATION							
Test speed	56 -0/+1 km/h	32 – 40 km/h 48 km/h 56 km/h[1] 40 km/h[2]	48 km/h	48 km/h	56 -0/+1 km/h	50 ± 2 km/h	56 -0/+1 km/h
Barrier type	Deformable	Rigid Deformable[1, 2]	Rigid	Rigid	Deformable	Rigid	Deformable
Barrier alignment	Offset (40%)	Full width (100%) Offset (40%)[1, 2]	Full width (100%)	Full width (100%)	Offset (40%)	Full width (100%)	Offset (40%)
DUMMIES AND INSTRUMENTATION							
Driver	Hybrid III 50th%	Hybrid III 50th% Hybrid III 5th%[1]	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%
Passenger	Hybrid III 50th%	Hybrid III 50th% Hybrid III 5th%[1]	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%	Hybrid III 50th%

	Europe	United States	Canada	Australia		Japan	
	96/79/EC and UNECE R94	FMVSS 208	CMVSS 208	ADR 69/00	ADR 73/00 (UNECE R94)	Article 18, Safety Regulation Full width	Offset (UNECE R94)
PERFORMANCE CRITERIA AND LIMITS							
Head performance criterion	HIC_{36} • 1000	HIC_{15} • 700	HIC_{15} • 700 (if air bag fitted)	HIC_{36} • 1000 or HIC_{15} • 700 (if no head contact)	HIC_{36} • 1000	HIC_{36} • 1000	HIC_{36} • 1000
Head res. acceleration (3ms exceedence)	80 g	-	80 g	-	80 g	-	80 g
Neck tensile force	3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ • 80 ms	Hybrid III 50th%: • 4,170 N Hybrid III 5th%: • 2,620 N	-	• 3,300 N (if no head contact)	3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ • 80 ms	-	3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ • 80 ms
Neck compressive force	-	Hybrid III 50th%: • 4,000 N Hybrid III 5th%: • 2,520 N	-	-	-	-	-

	Europe	United States	Canada	Australia		Japan	
	96/79/EC and UNECE R94	FMVSS 208	CMVSS 208	ADR 69/00	ADR 73/00 (UNECE R94)	Article 18, Safety Regulation	
						Full width	Offset (UNECE R94)
Neck shear force	3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ • 45 ms	-	-	-	3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ • 45 ms	-	3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ • 45 ms
Neck extension moment	57 Nm	-	-	-	57 Nm	-	57 Nm
N_{ij}	-	• 1 Critical values Hybrid III 50th%: Tens. – 6,806 N Comp. – 6,160 N Flex. – 310 Nm Ext. – 135 Nm Hybrid III 5th%: Tens. – 4,287 N Comp. – 3,880 N Flex. – 155 Nm Ext. – 67 Nm				-	-

	Europe	United States	Canada	Australia		Japan	
	96/79/EC and UNECE R94	FMVSS 208	CMVSS 208	ADR 69/00	ADR 73/00 (UNECE R94)	Article 18, Safety Regulation	
						Full width	Offset (UNECE R94)
Thorax res. acceleration (3ms exceedence)	-	60 g	-	60 g	-	60 g	-
Thorax compression	• 50 mm	Hybrid III 50th%: • 63 mm Hybrid III 5th%: • 52 mm	• 50 mm • 60 mm (GVWR > 2,722kg)	• 76.2 mm	• 50 mm	-	• 50 mm
Viscous criterion (V*C)	•1 m/s	-	-	-	• 1 m/s	-	•1 m/s
Femur force	9.07 kN @ 0 ms 7.58 kN @ • 10 ms	Hybrid III 50th%: •10 kN Hybrid III 5th%: • 6,805 N	• 10 kN	• 10 kN	9.07 kN @ 0 ms 7.58 kN @ • 10 ms	• 10 kN	9.07 kN @ 0 ms 7.58 kN @ • 10 m
Tibia compression force	• 8 kN	-	-	-	• 8 kN	-	• 8 kN
Tibia index	• 1.3 (top and bottom)	-	-	-	• 1.3 (top and bottom)	-	• 1.3 (top and bottom)
Sliding knee movement	• 15 mm	-	-	-	• 15 mm	-	• 15 mm

	Europe	United States	Canada	Australia		Japan	
	96/79/EC and UNECE R94	FMVSS 208	CMVSS 208	ADR 69/00	ADR 73/00 (UNECE R94)	Article 18, Safety Regulation	
						Full width	Offset (UNECE R94)
Steering wheel displacement	• 80 mm (vertical) • 100 mm (horizontal)	-	-	-	• 80 mm (vertical) • 100 mm (horizontal)	-	• 80 mm (vertical) • 100 mm (horizontal)
Restraint release force	• 60 N	-	-	-	• 60 N	-	• 60 N

1) New requirements being phased in; 2) Offset deformable barrier test conducted at 40 km/h; 3) Forward-control and off-road passenger vehicles exempt.

2.3.1 Test procedures in the Legislation

2.3.1.1 United States

The main standard in use for the frontal impact performance of vehicles in the United States is FMVSS 208. FMVSS 208 includes occupant crash protection requirements, which are assessed by means of a series of crash tests. This section describes the requirements specified for passenger cars. Tests are carried out with both belted and unbelted occupants. Traditionally, the vehicle was propelled into a rigid barrier at 48 km/h. The barrier extended across the full width of the vehicle and was perpendicular to the line of travel in most tests; however, some oblique tests were also carried out. In recent years, some significant changes to FMVSS 208 have been phased in by the United States. For example, the Standard now requires a 56 km/h test (with a rigid barrier extending across the full width of the vehicle). Another change has been the addition of tests with the Hybrid III 5th percentile (female) dummy, supplementing those already carried out with the 50th percentile (male) dummy. Finally, the Standard now requires a test to be carried out with an offset deformable barrier. This test is performed from 40 km/h with the Hybrid III 5th percentile (female) dummy. The rationale for this test and its conditions is not explained; however, TRL understands that it is intended as an airbag deployment test.

The Hybrid III dummies are instrumented in the head, neck, chest and femur during FMVSS 208 tests. The dummy requirements comprise a series of performance limits, which are included in Table 2.3. The Table highlights some differences between the dummy requirements in the United States compared with those in Europe. For instance, in some cases, different limits are applied to the same criteria (e.g. thorax compression: 63 mm in the United States and 50 mm in Europe). However, in other cases, altogether different performance criteria are used, as with the neck. Another notable difference is the lack of lower leg performance criteria in FMVSS 208.

In summary, the main differences from the European legislation are:

- Barrier type and alignment: The rigid barrier and full overlap in FMVSS 208 results in a higher vehicle deceleration level than that in EC Directive 96/79/EC and UNECE Regulation 94. The impact specified in FMVSS 208 is considered, therefore, a more severe test of the restraint systems, but a less severe test of the vehicle structure.
- Performance criteria and limits: These differ in a number of ways, which may reflect the differences in the test set up and conditions.

2.3.1.2 Canada

In Canada, CMVSS 208 describes a range of design and performance requirements. These include crash protection requirements that are assessed by means of a full-scale crash test. The test conditions are set out in Test Method 208 – Occupant Restraint Systems in Front Impact (1996). During the test, the vehicle is propelled into a rigid barrier at 48 km/h. The barrier is perpendicular to the line of travel of the vehicle and extends across its full width. Hybrid III 50th percentile (male) dummies are restrained in each of the front outboard seats, with instrumentation in the head, chest and femur. While some elements of the Canadian Standard are similar to the United States FMVSS 208, it would appear that the most recent amendments to FMVSS 208 have not been adopted in Canada to date.

The dummy performance requirements in CMVSS 208 are included in Table 2.3. It would appear that CMVSS 208 prescribes fewer requirements of the dummy performance than the European and the United States legislative tests. It is particularly surprising that there are no performance criteria for the neck.

In summary, the main differences from the European legislation are:

- Barrier type and alignment: The rigid barrier and full overlap in CMVSS 208 results in a higher vehicle deceleration level than that in EC Directive 96/79/EC and UNECE Regulation 94. It is considered, therefore, a more severe test of the restraint systems, but a less severe test of the vehicle structure.
- Performance criteria and limits: These differ in a number of ways, which may reflect the differences in the test set up and conditions. Most notably, only head, chest and femur performance criteria are included. There are no neck performance criteria in CMVSS 208.

2.3.1.3 Australia

Australian Design Rule 69/00 describes a 48 km/h crash test in which the vehicle is propelled into a rigid barrier. The barrier is perpendicular to the line of travel of the vehicle and extends across its full width. Hybrid III 50th percentile (male) dummies are restrained in each of the front outboard seats, with instrumentation in the head, chest and femur. Australian Design Rule 73/00 implements UNECE Regulation 94.

Regarding the interaction between these two standards, Australian Design Rule 69/00 states that vehicles demonstrating compliance with Rule 73/00, using dual front air bags, will be deemed to comply with the technical requirements of Rule 69/00, provided that the manufacturer can demonstrate this at a Conformity of Production assessment. The Design Rule provides no further information regarding the possible ways that this compliance must be demonstrated.

The dummy performance requirements in Australian Design Rules 69/00 and 73/00 are included in Table 2.3. Australian Design Rule 69/00 sets out performance criteria and limits for the head, neck, chest and femur of the Hybrid III 50th percentile dummies. These criteria and limits tend to be different from the European legislative test and more in line with those in FMVSS 208. Australian Design Rule 73/00 is harmonised with UNECE Regulation 94 and applies the same performance criteria and limits.

In summary, the main differences from the European legislation are:

- Barrier type and alignment: Australian legislation prescribes a full width test into a rigid barrier in addition to an offset, deformable barrier test. The offset test is harmonised with UNECE Regulation 94 and there is provision for manufacturers to conduct this test only, provided that they can demonstrate compliance with the rigid barrier test by some other means.
- Performance criteria and limits: Different performance criteria and limits are used in the full width test, reflecting the differences in the test set up and conditions.

2.3.1.4 Japan

Attachment 23 (Technical Standard for Occupant Protection in Frontal Collision) describes a 50 km/h crash test into a rigid barrier. The barrier is perpendicular to the line of travel of the vehicle and extends across its full width. Hybrid III 50th percentile (male) dummies are restrained in each of the front outboard seats, with instrumentation in the head, chest, and femur. The dummy performance requirements are included in Table 2.3. The Japanese full-width test is very similar to that in CMVSS 208 and hence prescribes fewer requirements of the dummy performance than the European and the United States legislative tests. However, in Japan, a 56 km/h crash test into an offset, deformable barrier is also required. UNECE Regulation 94 is used with the same performance criteria and limits as set out in the Regulation.

In summary, the main differences from the European legislation are:

- Barrier type and alignment: Japanese legislation describes a full width test into a rigid barrier in addition to an offset, deformable barrier test. The offset test is harmonised with UNECE Regulation 94. TRL understands that both tests must be carried out.

- Performance criteria and limits: Different performance criteria and limits are used in the full width test, reflecting the differences in the test set up and conditions.

2.3.2 Test Procedures for Consumer Information

The United States New Car Assessment Programme (US NCAP) has rated the crashworthiness of cars since the late 1970s. The frontal impact test procedure, a 56 km/h full-width test into a rigid barrier, is based on the legislative test in FMVSS 208. When US NCAP was introduced, FMVSS 208 comprised 48 km/h impacts only: hence the consumer test was conducted at a higher speed than the legislative test. Since that time, NHTSA has started to phase 56 km/h impacts into FMVSS 208. Nevertheless, US NCAP remains significant because it highlights to the consumer where there are differences in performance among new vehicles.

NHTSA selects cars for the programme on the basis of predicted sales volumes, or if they have been redesigned with structural changes or improved safety equipment. The vehicles are purchased from dealerships and hence not from the manufacturer directly. The tests are performed at one of several contracted locations throughout the United States.

Hybrid III 50th percentile dummies are restrained in the front outboard seats during each test. Instrumentation is fitted in the head, neck, chest, pelvis, femurs, tibias and feet of the dummies. The frontal star ratings indicate the risk of receiving a serious head and chest injury only; however, this is currently under review and changes will be made for model year 2010.

A second consumer information programme in the United States is operated by the Insurance Institute for Highway Safety (IIHS). The frontal impact test procedure is basically the same as the Euro NCAP test (see Figure 2.2), but without a passenger dummy. Three factors affect the rating the car will receive: the structural performance; dummy injury measures; restraints/dummy kinematics. A four-level evaluation is awarded from poor to good (with marginal and acceptable in between).

Manufacturers perform the tests themselves but provide the results, including all the vehicle and test parameters, to the IIHS. This information is reviewed and a rating awarded according to the Institute's protocols. In addition, the IIHS carries out audit tests to ensure the manufacturers' good faith.

A Hybrid III 50th percentile dummy is used in the tests with instrumentation in the head, neck, chest, femurs, tibias and feet. The dummy performance criteria are the same as those in FMVSS 208 with several additions: sternum deflection rate; tibia-femur displacement; tibia index; tibia axial force and foot acceleration. The dummy measurements associated with each performance criterion are compared with three cut-off values that determine the injury protection rating for the car. With some exceptions (e.g., chest acceleration), the borders between acceptable and marginal ratings for a given performance criterion correspond to published injury assessment values.

The Australian New Car Assessment Programme (ANCAP) followed identical procedures to US NCAP when it was introduced in the 1990s. However, since that time, ANCAP signed a memorandum of understanding with Euro NCAP and aligned its protocols with those of European programme. The test and assessment evaluation and the presentation of results now follow the same form as Euro NCAP.

The Japanese New Car Assessment Programme (JNCAP) includes both full-width and offset frontal impact tests. The full-width test is based on US NCAP (a 55 km/h collision with a concrete barrier) while the offset test is based on Euro NCAP (a 64 km/h collision with a deformable barrier). A Hybrid III 50th percentile dummy is restrained in the front outboard seats in each test. The dummies are fitted with instrumentation in the head, neck, chest, femurs and tibias. The dummy measurements in each of these body regions are used, with vehicle deformation measurements, to determine a score for each ‘seat’ in each test. These are also combined to determine an overall star-rating and score for the driver’s seat and for the passenger’s seat.

2.4 Summary

The summary is divided into three parts. The first part summarises the differences between European legislation and that in the rest of the world; the second part summarises the relationship between UNECE Regulation 94 and other secondary safety legislation and identifies which legislation may be effected if changes are made to Regulation 94; and the third part summarises the relationship of legislation with consumer testing.

A diagram presented by the VDA (Verband der Automobilindustrie; German association of the automotive industry, 2008) to the GRSP informal group on frontal impact gives a good summary of the relationship between the different legislative and consumer tests from region to region (Figure 2.3).

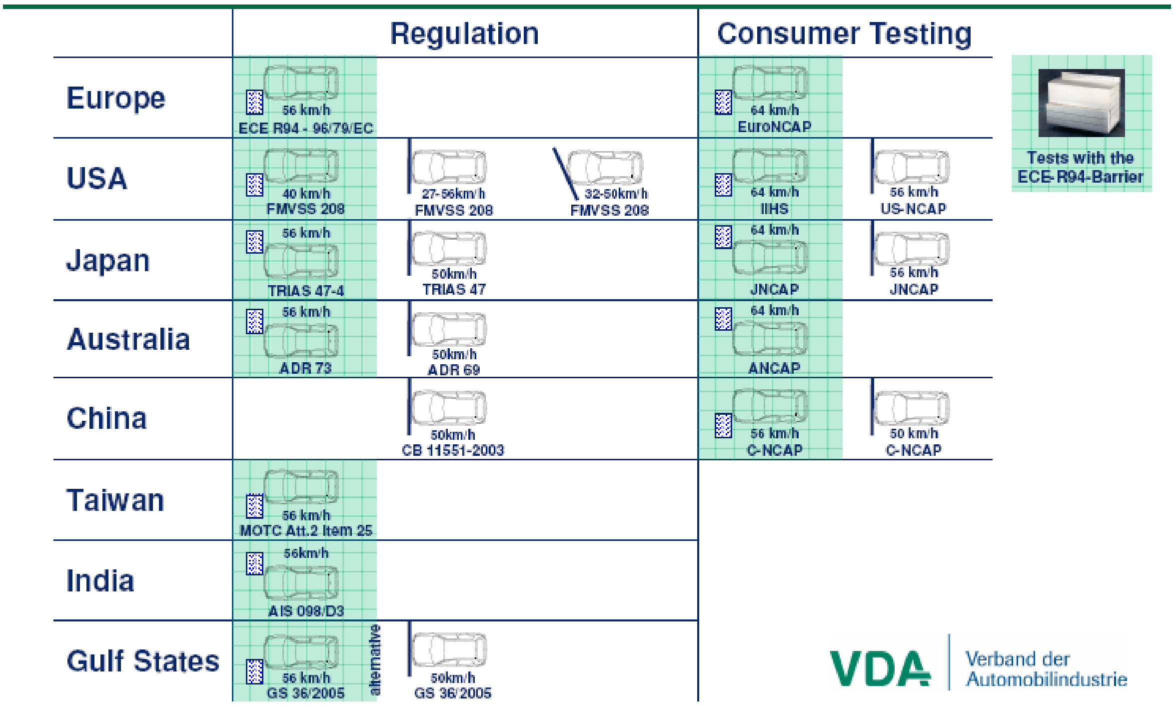

Figure 2.3: Frontal impact testing procedures used in regulation and consumer information programmes throughout the world (VDA, 2008)

2.4.1 Relationship between European legislation and the rest of the world

The expansion of the 1958 Agreement to include countries outside the UNECE region has contributed to greater harmonisation of vehicle legislation around the world. A number of key industrialised countries have joined, including Australia and Japan. The Agreement is based around the principle of type approval and the mutual recognition of approvals from the territory of another signatory. The United States and Canada have not joined the 1958 Agreement and do not, therefore, recognise UNECE approvals. Instead, they operate systems of self-certification whereby car manufacturers certify that their products comply with their own national safety standards.

Around the world, standards for the frontal impact performance of vehicles are based on full-scale crash testing with instrumented, 50th percentile (male) dummies. While important steps have been taken to harmonise these standards, a number of key differences remain. These differences can be found in the test procedures that are used, in the performance criteria and in the performance limits.

The European legislation describes a 56 km/h collision with a deformable barrier. The car is offset such that the barrier extends across 40 percent of its width. Restrained dummies are placed in the front (outboard) seats. Outside Europe, frontal impact legislation in the United States (and Canada) has developed differently. The most notable differences from Europe are the type of barrier used and its alignment with respect to the car. In the United States, the vehicle is propelled into a rigid barrier that extends across its full width. Traditionally, the impact speed was 48 km/h; however, this has been increased to 56 km/h for new vehicles. In fact, a number of tests are performed in the United States. These include tests with unbelted dummies, oblique impacts and a low speed test (40 km/h) into an offset deformable barrier with a 5th percentile (female) dummy. In Canada, a 48 km/h collision is carried out into a rigid barrier that extends across the full width of the car. The dummies are restrained and no further tests are performed such as unbelted or oblique tests.

Australia and Japan differ from Europe and North America in that both full width and offset tests are required. In each case, the full width test comprises a 48 km/h collision with a rigid barrier. Fiftieth percentile (male) dummies are restrained in the front (outboard) seats. The offset test is basically the UNECE Regulation 94 test (in both Australia and Japan). The Australian legislation states that vehicles that meet the requirements of the offset test (i.e. UNECE Regulation 94), and are equipped with dual frontal air bags, may also be considered complaint with the full width test. However, this is dependent on this compliance being demonstrated somehow. It would appear that Japan is the only country in this review where both full-scale offset and full width tests are mandatory.

Offset tests are more demanding of the car’s structure than full-width tests because the energy is absorbed over a smaller area. However, full-width tests result in higher passenger compartment deceleration and are therefore more demanding of the restraint systems. In many ways, offset tests and full width tests are complementary. In Europe, however, only offset tests are required by the legislation. While the strength of the passenger compartment is the key factor in these tests, the dummies are instrumented in all the key body regions and limits are applied to their response values. Hence the restraint system does play a role in the performance of the vehicle. In addition, the car’s restraint system is also subject to a high deceleration sled test of its integrity.

The differences in the way the frontal impact tests are carried out is probably one of the key reasons for the differences in the dummy performance criteria and limits used. For instance, the dummy performance criteria tend to be lower for the full width tests, while lower leg performance criteria tend to be applied in the offset tests only (where footwell intrusion is more likely).

2.4.2 Relationship between Regulation 94 and other safety legislation

Should changes be made to UNECE Regulation 94, depending on what those changes are, consideration should be given to the need to update the related regulations listed below:

- EC Directive 76/115/EEC and UNECE Regulation 16 relate to seat belts and restraint systems. The integrity of the seat belt is assessed by means of a high deceleration sled test. In this case, the Commission may wish to examine whether a separate component test of the restraint system is necessary if changes to the frontal impact legislation are made (that affect the deceleration of the passenger compartment during the full-scale test).

- EC Directive 74/408/EEC and UNECE Regulation 17 relate to seats, their anchorages and head restraints. As vehicles are becoming stiffer and deceleration levels are increasing, the European Commission may wish to review some of the test conditions within this Regulation, In particular, the Commission may wish to examine the deceleration level applied for the test of the strength of the seat anchorages.
- UNECE Regulation 44 relates to child restraint systems and assesses their performance in a sled test. While the impact test is not intended to reproduce the same deceleration profile and conditions as the frontal impact legislation, the Commission may wish to consider how changes made to the full-scale test conditions would affect the relationship with UNECE Regulation 44.

2.4.3 Relationship between legislation and consumer testing

Frontal impact (and other secondary safety) legislation provides for a minimum level of safety. However, many vehicles are now assessed by consumer test programmes also. These differ from legislative tests in that they grade the car’s performance rather than just giving a pass / fail mark. Another way in which they differ is that the particular car selected for consumer testing usually represents the best selling version, whereas for legislative testing in Europe a car representing the worst performing version, usually the heaviest one with the largest engine size, is selected.

Euro NCAP is the main consumer test programme in Europe. The frontal impact test is based on that in EC Directive 96/79/EC and UNECE Regulation 94, but the impact speed is increased (by 8 km/h) to 64 km/h. If changes are made to the legislative test, the European Commission may wish to propose that an equivalent change is made within Euro NCAP. This would help to maintain the current relationship between Euro NCAP and the legislative test, which helps to reduce the testing burden on manufacturers.

In the United States, there are two important consumer tests: US NCAP and the Insurance Institute for Highway Safety tests. US NCAP is a full width test very similar to the legislative test; however, the Institute test is an offset test similar to Euro NCAP. The results from these tests can be used together to gauge the overall frontal impact performance of a car, in terms of the passenger compartment strength and the effectiveness of the restraint systems. However, different rating systems are used and different models may have been tested.

In Australia, ANCAP signed a memorandum of understanding with Euro NCAP and aligned its protocols with those of the European programme. In Japan, JNCAP includes both full-width and offset frontal impact tests. The full-width test is based on US NCAP (a 55 km/h collision with a concrete barrier) while the offset test is based on Euro NCAP (a 64 km/h collision with a deformable barrier).

3 Definition of the Problem – Accident Issues

3.1 Introduction

Any regulatory test procedure that seeks a cost-effective reduction in the risk of injury in road accidents must have a foundation in real-world accident and injury data. To determine the current frontal impact accident situation in Europe, existing published accident analyses from the literature and information from other sources have been reviewed. This review will form the basis for prioritising frontal impact accident scenarios for injury reduction. In addition, appropriate literature from non-European countries has been reviewed to identify any significant differences in accident scenarios between European and non-European countries, that may be relevant for consideration of the harmonisation of international standards, for example Global Technical Regulations.

In particular it is the objective of the review to identify information which can help to:

- Determine which accident configurations are the most relevant and the injuries that are a priority for prevention in each accident configuration.
- Provide the answer to questions such as the need for a full width frontal impact test in Europe, as currently only an offset test is legislated.
- Quantify the importance of vehicle to vehicle crash compatibility.
- Provide information to help determine other aspects of test procedure configuration such as the test speed and the appropriate dummies to use with respect to size, gender and injury prediction capability.

The review of accident analyses has been separated into three broad groups:

- Firstly, information related to the European accident situation is considered, along with information from individual countries within Europe
- Secondly, information from the rest of the world is included
- Finally, where reported, information concerning approaches towards worldwide harmonisation of frontal impact test procedures is also summarised

It should be noted that the recent accident analyses in the literature cover only a small number of European countries and are typically focused on only a part of the above questions.

3.2 Background

3.2.1 Introduction of UNECE Regulation 94

In support of the introduction of UNECE Regulation 94 (and, by extension, EC Directive 96/79/EC), Lowne (1994) reported, on behalf of EEVC WG11, on the accident situation at the time. Several of the key points summarised by Lowne are repeated here as a basis against which the changing accident situation can be considered.

In general European data suggested that frontal impacts accounted for between 40% and 66% of impacts causing severe or fatal injuries. The car-to-car impact was the most frequent configuration in frontal impacts, varying from 45% to 66% in the references cited by Lowne. At the time impacts where both longitudinal members played a significant part in absorbing energy probably accounted for less than 25% of accidents with severe or fatal injuries. In the majority of frontal impacts only one longitudinal member was involved, with some additional loading via the engine and bulkhead load path in a proportion of these impacts. Consideration of the nature of loading and load paths suggested strongly that the partial overlap deformable barrier would provide a more realistic simulation of a typical car-to-car collision than was possible with any rigid faced barrier impact. A frontal impact test with a small overlap (where only one longitudinal member is involved) was also thought to be of potential help to control intrusion in accidents with greater overlap; whereas a test with greater overlap would not necessarily guarantee good control of intrusion in accidents with smaller overlaps.

When injuries of AIS • 2 were considered, the head (including the face) was the most frequently injured area particularly for drivers. Head and facial injuries caused by contact with the steering wheel were probably the single most important issue in frontal impact protection, according to Lowne, even for belted drivers. The use of a head injury criterion on instrumented dummies in a full scale crash test was therefore deemed to be necessary. Leg injuries were also particularly important among belted drivers surviving frontal impacts, when injuries of AIS • 3 were considered. This was said to imply that particular attention must be paid to the lower fascia and footwell areas, and also to interaction with the steering assembly. Chest and abdominal injuries were generally of lesser importance to belted drivers, though for fatally injured occupants they were still important. Also chest and abdominal injuries became relatively more important for belted passengers. Several of the accident studies presented to EEVC WG11 had information regarding the distribution of the change in velocity (•v) experienced by the vehicles involved in accidents. The data indicated that, to cover around one third of all fatals and about one half of those injured at severity AIS • 3, an impact equivalent to an accident ‘Crash 3’ •v of 55 km/h would be required (see Glossary for description of change in velocity). Based on field assessment information, as reported by Wykes (1998 - see Section 3.4.1), typically a laboratory based test speed needs to be 5 to 10 km/h higher than the equivalent estimated accident speed (e.g. EES) to recreate the same amount of deformation to the vehicle. Thus a car tested at a speed of 60 km/h would be assessed as having an EES of 50 to 55 km/h.

3.2.2 Background to Current Accident Issues

The basis of the decision that the frontal crash test regulation in Europe would use a deformable barrier offset to the driver’s side was to examine the vehicle’s structural performance. It was developed by the EEVC to address the accident situation at the time which suggested that two thirds of fatal and serious injuries were found to occur with passenger compartment intrusion.

Many authors have commented on the successful implementation of the European frontal impact directive EC Directive 96/79/EC (and UNECE Regulation 94):

> ETSC (2001): For car occupants, contact with the car’s interior, exacerbated by the presence of intrusion is the greatest source of serious and fatal injury. Consequently, the historical priority in improving frontal impact protection has been able to improve the car structure to endure severe offset impacts with little or no intrusion. In the absence of intrusion, the seat belts and airbags are provided with the space to decelerate the occupant with minimum injury risk (a ‘survival space’). Since the mid-nineties there have been significant improvements in the protection available to the occupants of cars. The frontal and side impact Directives and consumer information from the European New Car Assessment Programme (Euro NCAP) have led to the most rapid developments in car occupant protection that Europe has experienced.

> Cuerden et al. (2007a): Over the past ten years frontal impact crashworthiness has significantly improved with the advancement of car structures and restraint systems. The European frontal impact directive and Euro NCAP tests continue to promote the enhancement of crash energy management structures, aimed at reducing the amount of loading occupants experience. The test requirements have resulted in an increase in compartment strength and, as a consequence, intrusion is less common in real-life frontal impacts.

However, car occupant casualties remain the largest single group in the EU road casualty totals. Accident research continues to show that current measures do not adequately control performance in many real-life situations. A crash test can only ever deal with a limited number of crash scenarios and at present occupant protection is focussed on the average-sized (mid-aged) male occupant. Therefore the engineering countermeasures employed are dependent on the nature of the crash configuration and occupant characteristics. Other accident configurations and occupants of different sizes also need consideration.

Although much can be done to stop some accidents from happening, it is clear that for the short and possibly medium term the majority will continue to occur. Reducing the risk of injury in accidents is and will remain a priority. The single most effective way of achieving this is by improving the safety of cars. As such, there are still many opportunities for further casualty reductions using passive safety measures (ETSC, 2001).

Although many new cars are capable of absorbing their own kinetic energy in their frontal structures, so avoiding significant passenger compartment intrusion, there is currently no control of the relative stiffness of the fronts of different models of car. Consequently, when cars of different stiffness collide, the stiffer car overloads and crushes the weaker car. Historically, larger cars have tended to be stiffer than small cars, resulting in over-crushing problems for the small car. However, before the stiffness of car fronts can be matched, to provide greater compatibility, it is necessary to overcome the problems of poor structural interaction between cars when they impact (ETSC, 2001).

In a review of the British STATS19 accident data, Broughton (2008) suggested that changes to the design of new cars over the past 15 years have provided modern cars with better secondary safety features than older cars. According to Broughton, these improvements have come at a price, however; in car to car collisions, modern cars tend to impose greater risk of fatal injury on the occupants of the other car than do older cars. A modern car tends to be more aggressive than an older car when in a collision with another car. There are indications, however, that this trend has been reversed more recently, as cars registered in 2004 to 2005 appear to be safer in this respect than those registered in 2000 to 2003.

3.3 Overview of European Road Casualty Statistics

Car (including taxi) occupants made up 51.2% of EC road traffic fatalities in 2006 (see Figure 3.1, from the SafetyNet Annual Statistical Report (SafetyNet, 2008)). There were a total of 41,247 road traffic fatalities in the EU-25 region in 2005 (CARE, Feb 2008), so it can be estimated that approximately 20,000 car occupants were killed. Approximately one-third of fatalities were passengers and two-thirds were drivers (CARE, Feb 2008).

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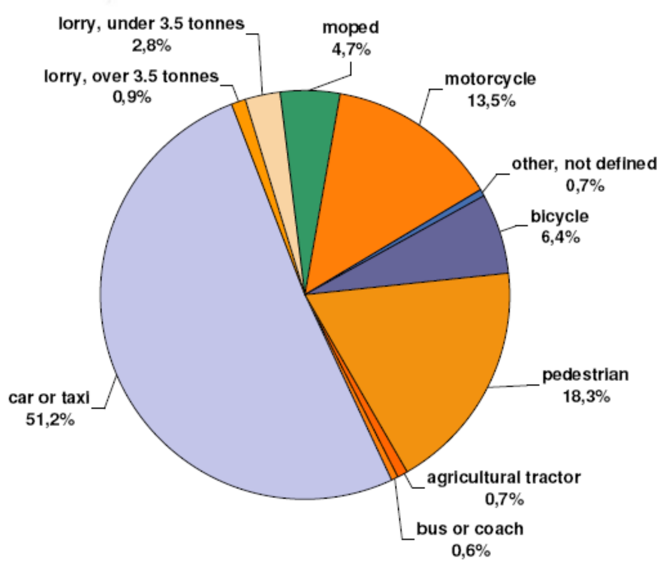


Figure 3.1: Distribution of fatalities by mode of transport, EU-25 2006 (SafetyNet, 2008)

In general, the numbers of injured persons and those killed in road traffic accidents have been decreasing in recent years (see Figure 3.2).

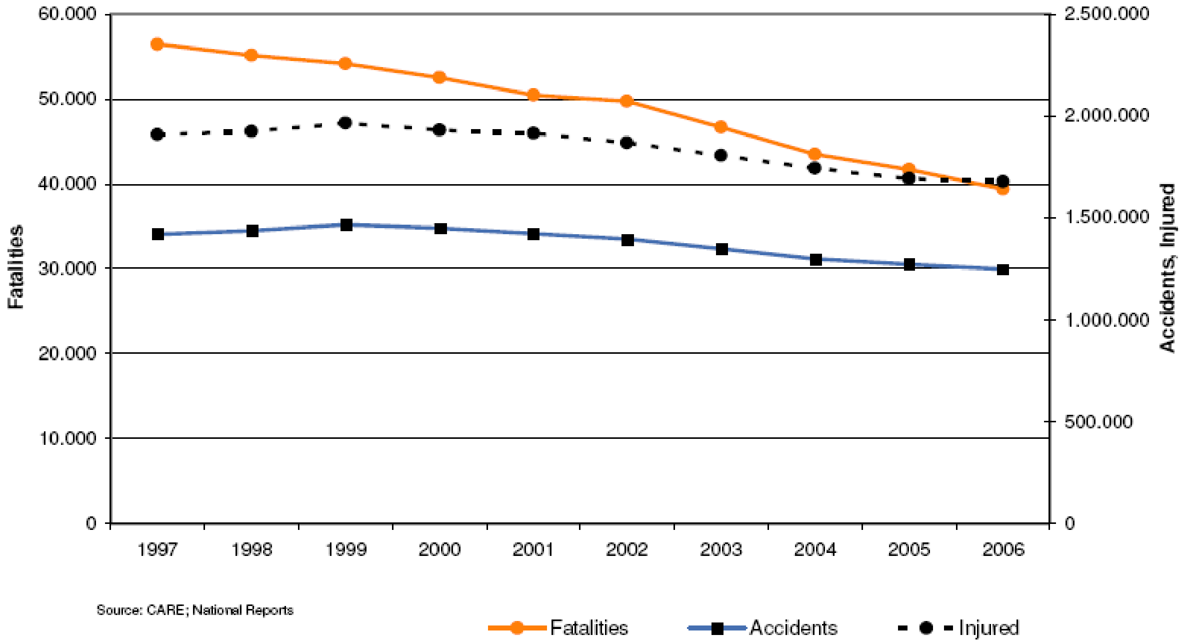


Figure 3.2: Annual number of fatalities, injury accidents and injured people, EU-25, 1997-2006 (SafetyNet, 2008)

Many factors may be contributing to the decreasing numbers of people killed in road traffic accidents. However, Broughton (2003) used car accident data from GB between 1980 and 1998 to estimate the effect on the number of driver casualties of the gradual improvement in the secondary safety features of the national car fleet. Statistical models were used to confirm that the proportion of car drivers who were killed or seriously injured (KSI) was lower among more modern cars. Broughton also argued that this reduction could be used to assess the casualty reductions brought about by improved secondary safety. He estimated that, of the casualties that would have occurred in 1998, if all cars had the level of secondary safety found in cars first registered in 1980, improved secondary safety reduced the number of drivers who were KSI by at least 19.7 %. This figure relates to all cars on the road in 1998, but when confined to the most modern vehicles (those first registered in 1998) rises to 33 %.

No pan-European data were available regarding the distribution of front, side, rear and other impact configurations for car occupant fatalities. Based on GB national statistics, Cuerden et al. (2007a) reported that the front was described as the first point of contact for 50% of fatal casualties and 58% of KSI casualties in Great Britain; not all of these impacts would be classified as frontal if investigated in depth, but the majority are likely to be frontal impacts.

ETSC (2001) reported that 36% of car occupant fatalities in the UK and 48% in Germany were attributable to frontal impacts. The main difference was that 16% of UK cases were classified as 'other'. If the more recent Cuerden GB figure and the ETSC German figure are assumed to be representative of frontal impacts for the EU-25 region, approximately 10,000 fatalities would be expected to occur annually in car frontal impacts.

In summary, Broughton's analysis suggests that the Directive and UNECE Regulation 94 have contributed strongly to the observed reduction in car occupant fatalities in Europe since 1998.

3.4 Review of European Accident Analyses

The following sections review the literature firstly for multi-country European studies, followed by studies specific to single countries.

3.4.1 Multi-national European Studies

When the EC Frontal and Side Impact Directives were published, they included the requirement to review certain technical aspects, within two years of their implementation date (1 October 1998). The technical content of these Directives was based on proposals put forward by the EEVC (European Enhanced Vehicle-safety Committee). These EEVC recommendations were the culmination of many years of accident investigation, research and dummy testing by a number of European institutions. However, since full scale testing using dummies was new for Europe, the reviews were built into the first edition of the Directives to allow benefit to be taken of the latest research and experience with the tests when used within a legislative framework. The EC invited the EEVC to propose a research programme to assist with the review process. The report by the EEVC (2000) was prepared at the conclusion of that research programme. It is based on EEVC research together with an accident analysis study. The accident analysis is summarised briefly below (Wykes, 1998); whilst the EEVC recommendations are reported at the start of the Proposed Test Procedures and Identification of Potential Options to Change Legislation task, Section 5.2.

The accident analyses reported by Wykes (1998) used data samples taken from the UK Co-operative Crash Injury Study (CCIS), a database of Swedish accident cases, held by the Volvo Car Corporation, and the German BASt/Medical University of Hannover database. This report seems to have formed the main substance for the review of the frontal and side impact directives as reported by the EEVC (2000, see above). In addition to the general conclusions drawn by the EEVC, some further detail is documented below.

In the samples from each country, more than two thirds of the MAIS • 3 occupants in the frontal impact sample experienced a Principle Direction of Force (PDF) within approximately ± 15 degrees of the vehicle's longitudinal axis. Of those with a PDF outside this range (but still within the ± 45 degree range specified in the selection criteria used by Wykes), about 60% saw a force from their side of approaching traffic. That is, from the right in the UK and from the left in Sweden and Germany.

Wykes commented that care must be taken when deciding upon the impact severity level up to which the test is attempting to protect. If the severity is too low then an unnecessarily high proportion of accident victims will not be offered adequate protection. If the chosen severity is too high there exists the risk that vehicle design will be sub-optimised for the most severe of accidents. This design sub optimisation may unnecessarily increase the risk of injury in the more frequent, but less severe accidents. A vehicle design which becomes tuned to offer good protection at a specific impact severity, such as the test speed, may not offer the best overall occupant protection to the range of accidents in which the vehicle may be involved.

The quartile ETS and EES values for accidents in which an occupant received an MAIS • 3 injury, from the three databases reviewed by Wykes are shown in Table 3.1. These figures were based on 148 restrained occupants who received an MAIS • 3 injury in the UK sample and 192 from the Swedish sample. The German data were weighted to represent the German national population, but the original numbers were not recorded. As such, the German values are subject to weighting errors.

Table 3.1: Impact severity assessment which encompass 25, 50, and 75% of the restrained MAIS • 3 occupants (Wykes, 1998)

Severity percentile	UK (n=148)	Sweden (n=192)	Germany
10^{th}%ile severity	27 km/h ETS	21 km/h EES	29 km/h EES
25^{th}%ile severity	37 km/h ETS	28 km/h EES	37 km/h EES
50^{th}%ile severity	47 km/h ETS	39 km/h EES	58 km/h EES
75^{th}%ile severity	56 km/h ETS	54 km/h EES	72 km/h EES
90^{th}%ile severity	74 km/h ETS	67 km/h EES	82 km/h EES

Wykes also showed how test speeds chosen in relation to MAIS • 3 injuries would relate to the distribution of impact speeds associated with fatal injuries to occupants. This is reproduced in Table 3.2. The different rows in Table 3.2 correspond to levels of protection that could be selected to represent either 25%, 50%, or 75% of occupants who would otherwise sustain an MAIS • 3 injury. The first column under each country then shows the ODB test speed required to be in excess of, or match, the accident speeds for that proportion of the MAIS • 3 injured occupants. The second column indicates the approximate percentage of fatally injured occupants for whom that test speed would be in excess of, or match, their accident speed.

No estimate was made for the ODB test speeds that would correspond to the impact severities associated with 25% and 75% of the MAIS • 3 casualties in the UK. This was because it was thought that the estimates would have been beyond the bounds of reasonable extrapolation, based on the data used.

Table 3.2: Proportion of restrained occupant fatalities which would be addressed by a test established by consideration of the percentage of restrained MAIS • 3 occupants in each sample (Wykes, 1998)

	UK		Sweden		Germany	
	ODB test speed estimate (km/h)	Fatalities addressed at this test severity	ODB test speed estimate (km/h)	Fatalities addressed at this test severity	ODB test speed estimate (km/h)	Fatalities addressed at this test severity
Test severity to address 25% MAIS • 3	-	Approx. 14%	33 to 38	Approx. 12%	42 to 47	None
Test severity to address 50% MAIS • 3	64	Approx. 30%	45 to 50	Approx. 33%	63 to 68	None
Test severity to address 75% MAIS • 3	-	Approx. 53%	59 to 64	Approx. 58%	77 to 82	Approx. 20%

On review of this information, Wykes makes the remark that relative to the injuries attributed to restraint systems, it was a feature common to all of the three samples that contact induced injuries were much more frequent overall. Additionally, in the UK and German samples, contact injuries were;

- distributed more widely across the range of impact severity bands
- distributed about a slightly higher median impact severity

Wykes concluded that there is still considerable scope for reducing serious injuries from contact, with or without intrusion. Increasing the test speed should help to achieve this, by improving the structural integrity of the vehicle for higher severity impacts. Wykes comments that it was difficult to quantify the actual benefits of increasing the test speed, but it would appear that the scope for reducing contact injuries was considerably greater than any likely increase in restraint system injuries.

It was observed from the Swedish data, that some injuries occur in very low severity impacts. This fact was attributed to the vulnerability of the occupant and not necessarily the level of protection offered by the vehicle. However, it was said to emphasise the high vulnerability that a small percentage of occupants have to injury.

Since the implementation of the R94 test, airbags have been widely adopted by vehicle manufacturers in their restraint systems for drivers and later for front seat passengers. The effectiveness of airbags in frontal collisions has been demonstrated repeatedly in the literature. For instance, in their review of airbag effectiveness, Lenard et al. (1998) concluded that compared with injured drivers from non-airbag-equipped vehicles, injured drivers from vehicles where an airbag deployed incurred proportionately fewer head injuries and more arm injuries. At the higher injury severity levels (MAIS 3 to 6), the incidence of the head being the most severely injured region was less than half (10 percent for drivers in frontal impacts where an airbag deployed, compared with 23 percent in impacts with no bag). Conversely, for the arms, the incidence was 23 percent in airbag deployed cases, compared with 15 percent for drivers with no air bag deployment. The favourable head injury result arose most directly from a reduction in fractures.

Frampton et al. (2000) used UK data from the CCIS and German data from the Medical University of Hannover to draw the following conclusions regarding frontal crashes:

- For drivers with MAIS • 2 injury, European airbags reduce AIS • 2 injury to the cranium and face by 32% and 55% respectively
- The maximum benefit of airbags can be seen in crashes exceeding 30 km/h
- European airbags do not provide any benefits in terms of chest injury reduction
- Drivers in airbag equipped vehicles sustain proportionately more AIS • 2 upper extremity injuries (particularly to the shoulder) than those in non-airbag equipped vehicles
- Airbag deployment thresholds do not appear to be set above the threshold of head injury
- There is evidence to suggest that some deployments occur unnecessarily in low severity crashes

For the EC-Project Aprosys (Advanced PROtection Systems), Cuerden et al. (2007b) conducted an accident analysis based on both UK data, from the CCIS, and German data, from the GIDAS. The purpose of this accident analysis work was to help answer open questions relating to the specification of an Advanced European Full Width (AE-FW) test, specifically:

- What should the test speed be?
- What should be the dummy specification and injury criteria?
- Should rear occupants be included and if so what should be the dummy specification and injury criteria?

A synopsis of the answers (regarding the AE-FW test) was provided in the summary to the report and is reproduced below:

- Test Speed – The proposed test speed of 56 km/h was found to cover an appropriate proportion of the serious injuries (greater than two thirds of MAIS • 3).
- Dummy Specification – The analysis found that the injured (MAIS • 3) driver is predominately male and the injured front seat passenger female. Based on the GIDAS data, the mass and height of the front seat occupants (driver and passenger) were found to match the Hybrid III 50th%ile dummy closely.
- Dummy Injury – It was found that the body regions to focus on for reducing severe life threatening injuries were the head and thorax. Leg injuries were also found to occur relatively frequently at a high severity, but are generally not life threatening.
- Rear seating positions – The analysis of the GIDAS accident statistics showed that rear seat occupancy in collisions was very low. In addition, the German data indicated that protection for rear seated occupants in frontal impacts was found to be intrinsically higher than for front seated occupants. An assessment of rear occupant anthropometry was inconclusive as the most commonly injured age group varies considerably in mass and height. Definitive conclusions on the rear occupant injury could not be drawn due to the low number of injured occupants in the selected sample.

3.4.2 National Studies

3.4.2.1 UK

Once the frontal impact directive had been in place for several years, authors began to consider the effectiveness of vehicles designed either side of the implementation date.

Based on STATS19 data, Thomas and Frampton (2001) reported that cars manufactured in the period 1996 to 2000 showed a rate of driver serious or fatal injuries that was 11% below that of cars built in the first part of the decade. The number of fatal injuries from frontal impacts dropped in the new cars to 34 per year, compared with 39 per year in the older cars. However, this was also associated with a lower rate of frontal impacts in the newer car group than the older car group, therefore one might expect a reduction in the number of fatal injuries from frontal impacts. Accounting for this, the proportion killed in frontal impacts decreased by 5% in the newer vehicles; indicating some improvement in the risk of fatal injury in newer vehicles.

The median ages of drivers and front passengers, included in the sample of all CCIS occupants selected by Thomas and Frampton were similar at 36 and 31 years although front passengers exhibited a wider range of ages than drivers. Rear seat passengers were substantially younger with a median age of 17 years. Fatally injured occupants showed little difference in age distribution from occupants with all severities of injury except for front passengers, when fatally injured, that had a median age of 52 years and an upper quartile of 64 years.

Car-to-car collisions were the most common group of collisions when all casualty severities were examined accounting for more than 50% of casualties in the group of newer cars. In comparison, impacts with roadside objects caused 25% of injuries and impacts with trucks or buses caused 15%. The group of fatally injured occupants in newer cars showed a different pattern. 35% were killed in impacts with cars while 33% were killed following a collision with a roadside object, usually a tree. Collisions with trucks or buses accounted for a further 27% of fatalities in newer cars.

The median •v for all casualty severities was 33 km/h in older vehicles compared with 30 km/h in newer vehicles. Amongst fatalities it was 60 km/h in older vehicles against 53 km/h in newer cars. There are several factors which may have contributed to this finding, for instance: changes in vehicle mass with year of manufacture and the demographic of the drivers and other occupants. When comparing effects of different ages of vehicles it is important to compare like for like and account for other changes going on in the environment in which the new vehicles operate. As an example, one should limit the relative ages of collision partners so that equivalent new-car to new-car or old-car to old-car impacts are evaluated. It is also possible that changes in the stiffness of vehicles have affected the accuracy of •v predictions.

Thomas and Frampton note that the Euro NCAP severity at 64 km/h was above the 75th%ile for the group of fatalities. Only 15% of fatal casualties in frontal impacts experienced a •v above 64 km/h in new cars compared with 44% in older cars. The GB accident database, STATS19, was used by Frampton et al. (2002) to examine gross changes in casualty patterns between newer and older cars. Crashes occurring in the calendar years 1997 and 1998 were used to estimate trends in crashes. They found that there was a general reduction in injury rates for drivers of newer cars and those reductions were greatest for serious and fatal injuries. In addition to the Stats19 analysis, Frampton et al. also reviewed data from the CCIS for calendar years 1992 to 2001 to examine injury outcome for specific body regions of belted drivers in frontal crashes. As with the work from 2000, Frampton et al. reported a substantial reduction in the predicted incidence of AIS • 2 head injury for belted drivers in newer cars. However, no major reductions in AIS • 2 chest, thigh and below knee injury were demonstrable in newer cars. The comparative head and chest injury frequencies are shown in Table 3.3.

Table 3.3: Head and chest injury severity (Frampton et al., 2002)

	Head injury severity		Chest injury severity	
	Older	Newer	Older	Newer
AIS 0	61 %	72 %	54 %	55 %
AIS • 1	39 %	28 %	46 %	45 %
AIS • 2	13 %	6 %	12 %	10 %
AIS • 3	5 %	2 %	6 %	4 %
Number	2,704	1,194	2,706	1,193

The conclusions of Frampton et al. (2000) (see Section 3.4.1 were re-iterated by Kirk et al. (2002) based on a further review of CCIS cases from 1996 to 2001. For example:

- The MAIS • 2 rate for belted drivers in frontal crashes was reduced from 32% in non-airbag equipped vehicles to 24% in airbag equipped vehicles
- There was a strong improvement in the severity of head injuries for belted and unbelted drivers. The effectiveness for belted drivers at the AIS • 2 level was 58%.
- Controlling for ETS or overall driver injury severity, no significant benefit was apparent for thoracic injury
- There were situations in which frontal airbags were less effective for head injury reduction such as one o'clock impacts and pole impacts.[1]

The research question that Frampton et al. (2004) attempted to answer was:

"What are the conditions where serious injury now occurs in modern cars and does a single point test, with one size of dummy, accurately predict the risk outcome?"

Frampton et al. (2004) selected cases from the CCIS database where the vehicle had been involved in a frontal impact and that vehicle model had also been subject to a Euro NCAP frontal crash test previously. There were 653 drivers in the CCIS database which met the study criteria at the time.

In the sample studied by Frampton et al. (2004) the AIS • 3 head injury rate was just 1%, compared with a 4% rate for the chest. The upper leg (AIS • 2) rate was 6%, the lower leg rate was less than 1% and the rate for the ankle/foot was 6%.

Frampton et al. (2004) reported that this indicated, in modern vehicles, protection for the head is good. Therefore, in light of improved protection for the head and regarding life-threatening injury, chest protection should now take priority. However, Frampton et al. (2004) noted that the chest protection scores for Euro NCAP did not show a clear trend with the occurrence of AIS • 3 injury in the real crashes, even though the groups of real crashes were comparable for crash severity, overlap and driver age. A study of the factors related to serious chest injury showed a mean Equivalent Test Speed (ETS) of 41 km/h, with more than half of the injuries occurring in full overlap configurations.

In terms of injuries which cause impairment, protection for the upper leg and ankle/foot should be considered. By comparison, lower leg protection appears to be good in the Frampton et al. sample of crashes. The mean ETS for AIS • 2 upper leg injuries was 45 km/h, almost half occurring with full overlap. The mean age of drivers with these injuries was 40 years. Frampton et al. noted that nearly 40% of drivers with these

[1] For one o'clock impacts it is not stated whether or not this result is statistically significant. For pole impacts it is stated that this result is not statiscally significant.

injuries experienced fascia intrusion less than 6 cm. However, a high proportion of drivers sustaining those injuries were female (62%); suggesting the scope for injury assessment based on a small female dummy. The mean ETS for AIS • 2 ankle/foot injuries was 39 km/h, 50% occurring with full overlap. The mean age for drivers with those injuries was 42 years. As with upper leg injuries these injuries occurred with full overlap crashes, 45% of occupants with those injuries experiencing less than 6 cm of footwell intrusion.

From their review of Stats19 data, Welsh et al. (2006) found that car-to-car accidents account for 35% of fatalities (in all impact directions). A further 20% of fatalities involved car-to-pole/tree impacts. Then, in a more detailed review of CCIS frontal impact cases, Welsh et al. were able to deduce that 75% of fatally injured belted drivers in frontal impacts sustained an AIS • 3 chest injury and 60% sustained an AIS • 3 head injury. MAIS • 3 injuries to drivers who survived were relatively rare, although in contrast, AIS • 2 injuries (fractures to the arms and legs were comparatively common.

For fatally injured front seat passengers, around 50% sustained an AIS • 3 injury to the chest and approximately 50% sustained an AIS • 3 injury to the head.

Welsh et al. concluded that, in frontal impacts lower extremity and chest injuries are the most frequently occurring whilst head injuries remain the most costly. Lower extremity injuries were the most frequent and the most costly injuries sustained by front seat occupants who survived a frontal or side impact accident. Foot/ankle injuries were reported by Welsh et al. as comprising 8.2% of all AIS • 2 injuries received in frontal impacts. On this basis they were considered to be an important sub-set of injuries; particularly because, although they are not especially life-threatening, some are invariably associated with long-term disability and impairment (for example calcaneous, pilon, Lisfrancs and talus fractures) and for this reason are expensive in nature.

When investigating injuries sustained by rear seat occupants in older and newer vehicles, the Stats19 part of the analysis by Welsh et al. identified that occupants of newer cars were disadvantaged when compared with those occupants in the rear seats of older cars. The explanation offered by Welsh et al. is that as a consequence of strengthening the occupant compartment to reduce intrusion and improve protection for front seat occupants, vehicles have become stiffer across their frontal structure. This in turn has had the effect of increasing the severity of the crash pulse and resultant forces experienced by the occupants at a given crash speed. Whilst secondary safety measures have been introduced for front occupants (load limiters, pre-tensioners, and airbags) this is not the case for those seated in the rear. It is possible therefore that the increased rate of KSI outcome for rear occupants is a result of design changes aimed at improved frontal impact protection.

It is likely that to improve substantially protection for rear seat occupants in frontal impacts some assessment of restraint efficacy is needed. However, it is important to note that, as with front seat passengers, some restraint system interventions may not be advantageous to all classes of occupants. For example, airbag and seat belt load limiters are unlikely to be beneficial for children in Child Restraint Systems (CRS). There is also the chance of injurious interactions between a CRS and an airbag, which may require deactivation of such technologies, when rear seats are used by children in CRSs.

In order to overcome some of these concerns, ETSC (2001) recommended (as one of their top three priorities for large reductions in casualties in the short to medium term) that universal ISOFix child restraint anchorages with an effective third anchor point should be standard equipment. Whilst ISOFix anchorages and CRS are becoming more common, not all CRS Groups are universal: e.g. Group 0+ CRS are only semi-universal; some Group 1 seats are vehicle-specific, some are semi-universal (with a foot prop that may only be used in specified vehicles), and some are universal (and may be used as universal provided that the vehicle also has universal approval, which requires that the vehicle seat has an anchorage point for a top tether).

It should be noted that top-tethers are used as a mandatory third anchor point in some regions, and that alternative fixing systems that would deliver universal ISOFix are currently being investigated at GRSP.

Welsh et al. (2006) also noted that the chest injury rates, in frontal impacts, in new cars have improved for front seat occupants. The improvements were largest at the maximum AIS • 2 and maximum AIS • 3 severity levels. This finding conflicts with other research (see Cuerden et al., 2007a) and may indicate the effect of not accounting adequately for changes in vehicle and occupant characteristics between old and new vehicle sub-sets. However, the rates of vessel and organ injuries had more than halved between the two car samples. This was not the case for skeletal injuries, which remained a large proportion of all AIS • 2 injuries received in frontal impacts. According to Welsh et al. over half (54%) of the AIS • 2 injuries were fractures to the sternum which are ranked as AIS 2 injuries and despite being painful, are usually uncomplicated in nature and generally lead to a full recovery in a short space of time.

From a review of the GB national accident data (Stats19), Edwards et al. (2007) reported that for the years 1999 to 2003 about 60% of the car occupant casualties occurred in frontal impacts. Of these casualties, about 70% occurred in collisions with another vehicle.

In the sample of CCIS cases investigated by Cuerden et al. (2007a), there were 1,652 MAIS • 2 seat belted casualties, who were occupants of cars registered in 1996 or later. Of the selected casualties, 806 experienced a frontal impact, and of these casualties, 75% experienced a Principal Direction of Force (PDF) that was head-on (0° ± 15°). About 80% of the fatalities (drivers and passengers) were encompassed at the Euro NCAP frontal test speed (64 kmh^{-1}) rising to 95% of MAIS • 3 seriously injured survivors.

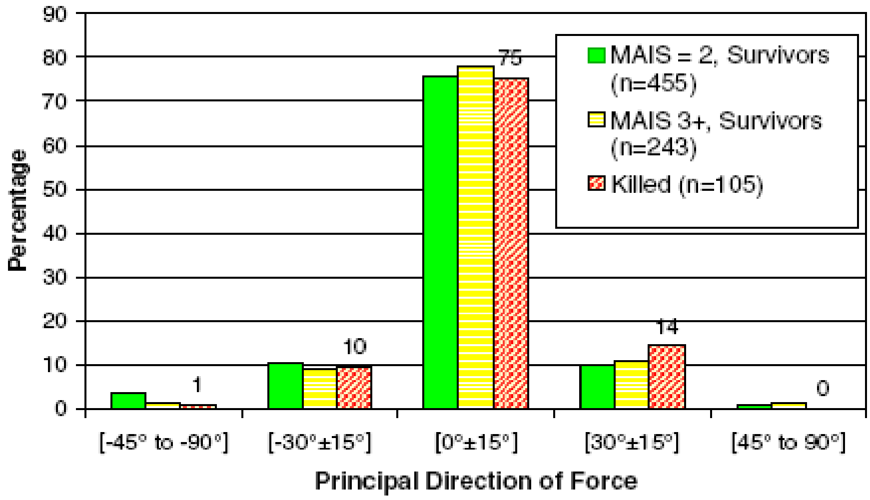


Figure 3.3: Principal direction of force by car occupant injury severity (Cuerden et al., 2007a)

The most common loading location for MAIS • 2 casualties involved more than 66% direct contact (Code D from the Collision Damage Classification, CDC, system – 66% to 100% of car's width). However, Cuerden et al. commented that it is not possible to compare this directly with the 40% offset configuration used in legislative and consumer tests. The position and the percentage overlap of the direct loading with respect to the side the occupant is seated (and position of frontal vehicle structures) can be an important factor, in terms of the amount of intrusion and/or rotational acceleration experienced.

There were 310 drivers classified as MAIS 2; of these 115 drivers had an AIS 2 thorax injury or 37%. For MAIS 2 and MAIS • 3 survivors, abdomen injury was relatively uncommon for drivers and front passengers. However, 28% of the MAIS • 3 rear passengers sustained an AIS 3 or greater abdomen injury.

For MAIS 2 casualties, the most commonly injured body regions at AIS 2, for drivers were the thorax (37%), lower (35%) and upper (34%) extremities. For front seat passengers the order changed and the rate of injury observed was different with injuries to the thorax (44%), upper (43%) and lower (15%) extremities. The largest difference was observed for the rear seat passengers, with the upper extremities (59%), the head (23%) and the thorax (18%) being most commonly injured.

For MAIS • 3 survivor casualties, the most commonly AIS • 3 injured body regions, for drivers were the lower extremities (60%), the thorax (37%) and the upper extremities (23%). For front seat passengers the order changed and the rate of injury observed was different with injuries to the thorax (45%), upper (29%) and lower (24%) extremities. The largest difference was observed for the rear seat passengers, with the thorax (28%), the abdomen (28%), the lower extremity (22%) and the head (17%) being most commonly injured.

For those casualties who were killed, the most common body regions injured at AIS • 3 were the thorax and head for the drivers and front seat passengers and the thorax and abdomen for rear seat passengers.

The direct impact loading to the front structural components of the cars were evaluated by Cuerden et al. with respect to the drivers' injury outcome. Each car's front structure was simplified to consist of an offside (right or UK driver's side) longitudinal, a nearside longitudinal and an engine. The CCIS vehicle investigators record if these components were directly loaded in the crash and outline the extent of the crush and/or bending. The amount of car frontal direct contact damage by the percentage of overlap was similar to that reported from the investigation of the structural component loading.

The offside longitudinal and the engine were the areas which were directly loaded together most commonly. The second most common configuration involved both longitudinals and the engine (All) being directly loaded. Of the drivers, 31% experienced loading to the offside and nearside longitudinals only or to 'All' three components. It was interesting to Cuerden et al. to note that for the more seriously injured or killed drivers, the relative frequency of loading to the offside and engine or all three components increased. Only about 36% of the killed and 40% of the MAIS • 3 survivors had an impact that was less than 60% offset.

The accuracy of the percentage overlap measured in the field is important to consider. Experienced examiners record the damage they find as accurately as is practicable, but it is possible for some small measurement errors to occur. Also of concern is the potential for retrospective studies to overestimate the amount of direct contact damage for cars that have rotated during the impact due to their angular momentum. When a car collides, an extra degree of deformation may take place compared with the initial contact area due to rotation. This additional damage is sometimes difficult to differentiate from that caused at the initial point of contact.

The potential overestimation may affect the results of the degree of overlap and underestimate the number of cars that are involved in impacts below 60% overlap. However, it is still believed that the most frequent type of impact has a greater overlap than the 40% used in either of the tests.

Compartment intrusion of • 10 cm was common for frontal crashes resulting in driver death, but more than 80% of moderate injury (MAIS 2) and approximately 50% of serious injury (MAIS • 3) was sustained with little or no intrusion to the compartment (< 10 cm). Approximately a third of driver fatalities also occurred in the absence of major intrusion.

3.4.2.2 Germany

The investigation by Eichberger et al. (2007) included the newest available data from the German In-Depth Accident Database (GIDAS), the University of Technology, Graz database (VSI, Lethal Accident Database from Austria), and a database of Austrian court cases.

The data sample from the GIDAS contained 39,706 vehicles, 56,584 persons and 30,601 injured persons. On analysis of the data, Eichberger et al. observed that there was a comparatively low risk of injury in vehicle-to-vehicle collisions, although the rate of occurrence was still high. For vehicle-to-vehicle collisions, hitting the front of a collision partner posed the greatest risk for the occupants.

The proportion of car-to-car frontal collisions was about 7% to 9% of all traffic accidents. In the investigated databases, the proportion of small lateral offset scenarios (where the main load path is located outside of the longitudinal beams; less than 30% overlap) was about one-third of the frontal car-to-car crash cases.

3.4.2.3 Austria

To investigate the influence of the angle of impact, Eichberger et al. (2007) had to use the data from the VSI and court case databases. Altogether Eichberger et al. reconstructed 20 cases with PC-crash accident reconstruction software. From the arithmetic average value, an impact angle of 8.9° was derived. Based on this, the authors concluded that an impact angle for a test configuration of 0° would be more appropriate. This was based on three factors:

1. It was not possible to decide upon a positive or a negative angle of impact since it depends on the vehicle that is considered
2. For 50% of the cases considered, the angle was smaller than five degrees
3. Tests become more complicated if any angle other than zero degrees is specified

3.4.2.4 Sweden

In the opinion of Kullgren et al. (1998), the 40% overlap tests do not address impacts with an overlap below 30%, in which the main energy absorbing structure of most car models is not engaged. This type of impact, if severe, is characterised by a high closing velocity, but with a relatively low change of velocity and high intrusion velocity. Most often this impact mode results in the two vehicles glancing off one another.

The study by Kullgren et al. includes data from 245 frontal collisions and crash recorder information from 177 frontal impacts. Of the 245 frontal impacts 22% had an overlap below 30% and of those with a recorded crash pulse in the accident data, 13% had an overlap below 30%. There was a 24% ratio (13/55) between MAIS • 2 injuries and the number of restrained drivers for accidents with an overlap below 30%, whereas there was a 14% ratio (26/190) with an overlap exceeding 30%. The corresponding ratio numbers for MAIS • 3 injuries with restrained drivers were 9% (5/55) and 4% (7/190) for lower than 30% overlap and for 30% and above overlap respectively. Therefore the risk of sustaining either an MAIS • 2 or MAIS • 3 injury was greater in impacts with an overlap of less than 30% than in impacts with an overlap of greater than 30%.

Of all moderately (MAIS 2) or severely injured (MAIS • 3) drivers, 33% and 42% of the drivers injured at these levels sustained their injuries in impacts with an overlap below 30%. The dominating AIS • 2 injuries in these impacts were head, leg and chest injuries. At a peak acceleration of 30 g there was a 50% risk of a severe injury in high overlap impacts while it was almost 100% in impacts with low overlap.

The aim of the paper by Lie et al. (2000) was to find to what extent there is an overall correlation between successful application of best practice as shown by Euro NCAP front and side protection scores, and benefits in real life impacts. They found that there was a strong and consistent overall correlation between Euro NCAP scoring and risk of serious and fatal injury. High ranked vehicles, as a group, had a lower risk of serious and fatal injury across 90% to 110% of average impact severity. There was insufficient data to extend this observation beyond the small range of impact severity for severe and fatal injuries. However, the cars with a greater Euro NCAP score rating had a lower risk of injury (all severities) at about 80% of the average impact severity. For impact severities above this level, there was no difference in the risk (for all severities) of injury between the two groups of cars.

In 2004, Lindquist et al. reported on a new method for the collection of vehicle deformation data. Data was collected from frontal car crashes from an area covering approximately 40% of Swedish inhabitants. In a single year (forming the study sample) 259 fatalities occurred in the sample area out of 534 recorded in Sweden as a whole. The project focussed on examining the 61 belted fatalities which occurred in 53 fatal frontal crashes.

The initial view of the results, made by Lindquist et al. indicated a trend for the structural interaction to be biased towards the driver’s side of the vehicle. It was noted that the drive-train (engine block) provided a component of the resistive load path in only 27 (44%) of the investigated fatalities, occurring in 20 (38%) of the fatal crashes. The involvement of either the left or right main longitudinal was even smaller, occurring in 16 (32%) and 11 (20%) respectively of the fatal car crashes. The results indicated that neither the drive train nor the main longitudinal beams were the most frequently involved load paths during the crash event. The resistive load paths with the highest frequency of use during the crashes were the side structural components (the hinge pillar, front wheel, and the upper longitudinal rail), on the driver’s side. Each of these resistive load paths was found to have been used in approximately 57% of the fatal car crashes.

The measured longitudinal deformations were divided into three groups with respect to deformation quantity and quality. The longitudinal deformation group with over 40 cm represented more than 50% of the fatal car crashes with longitudinal loading. The dominant collision partners for fatal crashes where main longitudinal loading existed were other cars in 14 out of 24 (58%) crashes. In contrast to these crashes, those crashed cars with an effective longitudinal deformation of 20 to 40 cm had a crash interaction which occurred with a relatively large degree of vehicle overlap, resulting in drive-train to dash panel loading in the subject vehicle.

Lindquist et al. concluded that small overlap crashes where load paths of less than 30% of car width are used represented 48% of the belted fatalities in frontal crashes within their study sample. According to Lindquist et al. crashes where the load paths used were comparable to current barrier crash test procedures (i.e. the drive-train and at least one longitudinal was involved) represented 23% of the belted fatalities. Therefore they suggest that there is a need to address better small overlap crashes.

3.4.3 M1 and N1 vehicles not Covered by the Current Legislation

As reported in Section 5.2 the EEVC (2000) reviewed the accident analyses for N1 and M1 vehicles. They reported that both vehicles were involved in similar accidents, but were concerned about the aggressivity of the heavier N1 vehicles. They therefore recommended that the Directive should not be applied to vehicles greater than 2.5 tonnes total permissible mass until there was a better understand of the influence that this would have on the compatibility of these vehicles. A similar recommendation was made for M1 vehicles of greater than 2.5 tonnes maximum permissible mass.

Most N1 vehicles below 2.5 tonnes were found to be car-derived and few problems with including these vehicles in the scope of the Directive were found and this was recommended.

Smith and Knight [2005] reviewed Light Commercial Vehicle (LCV - N1 vehicles not including car-derived N1 vehicles) accidents in the UK. The reported that between 1993 and 2003 there was approximately a 43% reduction in the accident rate for accidents involving LCVs. Over the same period, the accident rate for all vehicles was reduced by 21%. The casualty rates have reduced for both fatal and Killed or Seriously Injured (KSI) casualties in all accidents by 23% and 36% respectively. For casualties caused in accidents involving LCVs, the casualty rates have also reduced. The fatality rate reduced by 37% and the KSI rate reduced by 48% over the ten year period. However, since 1999 the fatality rate for accidents involving LCVs has risen or stayed constant contrary to other trends.

The authors reported that there is currently no European Directive on the frontal impact protection for LCVs. Improving the frontal crashworthiness of the LCV alone was not considered to be one of the most beneficial countermeasures. However when combined with other countermeasures such as wearing the seatbelt and fitting an airbag, the predicted benefits were substantially increased.

3.4.4 Summary

3.4.4.1 Scale of the Frontal Impact Problem

- Of 41,247 road traffic fatalities in EU-25 in 2005, approximately 10,000 car occupants were killed in frontal impacts in EU-25 in 2005.
- The numbers of persons killed in road traffic accidents in Europe has consistently decreased year on year since 1998. Broughton’s analysis suggests that the Frontal Impact Directive and UNECE Regulation 94 have contributed strongly to this reduction.

3.4.4.2 Impact Configuration

- Impact Partner:
    - In the UK, approximately 50% (Thomas and Frampton, 2001) of front impact casualties occurred in car-to-car impacts.
    - Approximately 70% of frontal impact fatal and seriously injured casualties occur in an impact with another vehicle (Edwards et al., 2007).
    - The relative importance of pole-like (road-side) object impacts and collisions with heavy vehicles increases when considering more severe or fatal injuries. For fatalities, the proportions were 35% car-to-car, 33% roadside object (usually a tree) and 27% trucks or buses (Thomas and Frampton, 2001).
    - However, from the literature reviewed here, the order of importance (in terms of number of casualties caused as a result of such impacts) still appears to remain car-to-car, then pole/tree, then heavy vehicle collisions.
- Speed: For the UK and Germany, a full-width test speed of 56 km/h would cover more than two-thirds of the MAIS • 3 injuries (Cuerden et al., 2007b). For UK and Germany an ODB test speed at about 64 km/h would cover half of the MAIS • 3 injuries (Wykes 1998). However, it should be noted that the Wykes analysis is ten years old and so may not be representative of the current vehicle fleet.
- Overlap: The proportion of fatal and serious injuries in different overlap frontal impacts varied between countries. Inconsistencies also exist in the method of classifying and reporting the extent to which the vehicle front is involved in a frontal impact:

- In the UK, 64% of those killed and 60% of MAIS • 3 survivors had an impact that was at least 60% overlap (Cuerden et al., 2007a).
- In Germany, about one-third of the frontal car-to-car crash cases had less than 30% overlap (Eichberger et al., 2007).
- In Sweden, Kullgren et al. (1998) found that the 40% overlap test does not address impacts with an overlap of less than 30%, where the main energy absorbing structure of most car models is not engaged. The risk of serious injury was almost double in impacts with less than 30% overlap, compared with impacts with greater overlap. 42% of MAIS • 3 drivers were injured in impacts with less than 30% overlap. In a study of fatal accidents, Lindquist et al. (2004) found that 48% of belted fatalities occurred in small overlap crashes; only 23% were involved in crashes were the engine and at least one longitudinal was involved.

- Intrusion: Approximately 50% of driver serious MAIS • 3 injury and one third of driver fatalities occurred with little or no intrusion (< 10 cm) (Cuerden et al., 2007a).
- Collision Angle: The literature reviewed suggests a configuration of 0° would be most appropriate.

3.4.4.3 Population Injured

- Driver and FSP - Gender: The analysis of the UK CCIS and German GIDAS datasets identified that the driver should be male (accounts for upwards of 72% of the MAIS 3+ drivers) and the front seat passenger female (accounts for upwards of 60% of the MAIS 3+ front seat passengers). Based on data from Germany, the mass and height of both the driver (male) and front seat passenger (female) were found to closely match the Hybrid III 50th percentile male dummy (Cuerden et al., 2007b). Analysis of the UK CCIS dataset by Frampton for Euro NCAP tested cars found that a high proportion of drivers sustaining upper leg and ankle/foot injuries were female (62%); suggesting the scope for injury assessment based on a small female dummy.
- Driver and FSP - Age: Wykes (1998) noted that in Swedish accident data some injuries occurred in very low severity impacts, and this was attributed to the vulnerability of the occupant. Care should be taken to ensure that improved protection in high severity accidents is not delivered at the cost of reduced protection for the most vulnerable occupants (predominantly the elderly) in more frequent low-severity impacts. Wykes noted that improvements in restraint system design should be able to mitigate the effects of more vulnerable occupants, but a second, low-severity test may be required to encourage such designs (Digges and Dalmotas, 2007).
- Rear Seat Occupants:
  - Rear seating positions were found to be better protected than front seating positions for GIDAS data (Cuerden et al., 2007b), although the number of rear seat occupants was very low. By contrast, Welsh et al. (2006) reported that rear seat occupants in newer cars were disadvantaged compared to those in older cars. It was hypothesised that the increased rate of KSI for rear seat occupants in newer cars was a result of design changes aimed at improved frontal impact protection. No conclusive statements regarding the size and sex of belted rear seat casualties could be made (Cuerden et al., 2007b), but the most common age range was 12 to 22 years for UK data. A median age of 17 was found for all CCIS rear seat occupants (Thomas and Frampton, 2001), with a similar median age for fatally injured rear seat occupants.

  - Consideration of improvements to the efficacy of rear seat restraint systems should consider all rear seat occupants, including children in CRSs. Currently, many CRSs are installed using the adult seat-belt. Updates to the regulation regarding rear seat occupants should be considered in parallel with updates to deliver universal three-point CRS anchorages (such as an updated universal ISOFix) that would ensure that restraint of the CRS was independent of the seat-belt. This would ensure that improvements to the seat-belt for adult occupants would not have negative effective effects for child occupants.

3.4.4.4 Frequency and Severity of Injuries

- Overall: The overall serious injury and fatality risk has reduced in new cars that are compliant with UN ECE Regulation 94 (e.g. Kirk et al., 2002).
- Head: Head injury protection in frontal impacts has improved markedly, although a large proportion of fatally injured drivers still have an AIS • 3 head injury (e.g. Welsh et al., 2006). Due to the nature of the injuries, head injuries were found to be the most costly in frontal impacts.
- Thorax:
  - Frampton et al. (2002) reported newer cars did not provide any major reductions in chest injuries. Recent data (Cuerden et al., 2007b) showed that the thorax was the highest priority for AIS 3+ injury (UK and German data) and that the thorax was also very important when considering fatal accidents. Organ injuries (non-skeletal) were particularly important at the thorax. A study of the factors related to serious thorax injury showed a mean Equivalent Test Speed (ETS) of 41 km/h, with more than half of the injuries occurring in full overlap configurations (Frampton et al., 2004).
  - It is also possible that the ODB test as currently regulated in Europe, is not being effective in reducing thoracic injuries because it is primarily designed to control intrusion-related injuries. Thorax injuries are primarily related to interaction between the occupant and the restraint system. (It should be noted that thorax, and other, injuries would be expected to be more severe in the absence of the restraint system, but that some injuries remain despite the overall effectiveness of the restraint system.) For this reason it may be that a full-width test would be better suited to drive improvements in restraint technology and therefore reductions in thorax injury risk. However, as with the lack of lower leg improvements in vehicles manufactured after the implementation of the ODB test, thorax protection needs to be assessed with a test tool of sufficient biofidelity and injury assessment capability, and with injury criteria that are relevant to the population at risk of sustaining these injuries.
- Abdomen: Abdomen injury was relatively uncommon for drivers and front seat passengers, but 28% of the MAIS • 3 rear passengers sustained an AIS 3 or greater abdomen injury (Cuerden et al., 2007a).
- Upper and lower leg:
  - Protection of these body regions remains a priority, both in frequency and impairment terms. Approximately half of these injuries occur in full-overlap impacts (e.g. Frampton et al., 2004), which implies that improved dummy lower extremities, injury criteria and injury risk functions are required for both the current ODB test procedure and in any future full-width test procedure. The priorities are thigh, knee and foot/ankle protection. Foot and ankle injuries comprised 8.2% of all AIS • 2 injuries in frontal impacts and were costly because some invariably lead to long-

    term disability and impairment (Welsh et al., 2006). Lower extremity injuries were the second highest AIS 3+ priority identified for UK and German data (Cuerden et al., 2007b).

  - An improved dummy lower extremity may be necessary in order to deliver significant reductions in foot-and-ankle, knee and thigh injuries. The National Highway Traffic Safety Administration (NHTSA) is incorporating the THOR-Lx (Test device for Human Occupant Restraint – Lower extremity) lower leg in to the Hybrid III dummy for its ODB test procedure. Improved thigh biofidelity may also lead to more realistic interaction of the torso of the dummy with the restraint system, enabling improved estimates of torso injury risk. An improved dummy lower extremity, injury criteria and injury risk functions should be used in both the current ODB and any future full-width test procedure.
  - Lower extremity injuries (thigh and foot/ankle) occur even without significant footwell intrusion (e.g. Frampton et al., 2004), so intrusion is not a sufficient measure of lower extremity injury risk. The mean ETS for AIS • 2 upper leg injuries was 45 km/h and for AIS • 2 ankle/foot injuries it was 39 km/h (Frampton et al., 2004).

- Rear Seat Occupants: Based on a limited number of UK cases, the most frequently AIS • 3 injured body regions for survivors were the thorax (28%), the abdomen (28%), the lower extremity (22%) and the head (17%) (Cuerden et al., 2007a). For fatally injured rear seat passengers, the most commonly injured AIS • 3 injuries were to the thorax and abdomen.

3.4.4.5 N1 and M1 Vehicles not Covered by the Current Legislation

- Little new data was available in the literature for M1 and N1 vehicles not covered by the current legislation.
- Improving the frontal crashworthiness of the LCV alone was not considered to be one of the most beneficial countermeasures, at least partly because of low belt wearing rates amongst LCV occupants. When combined with other countermeasures such as wearing the seat-belt and fitting an airbag, the benefits of LCV self-protection were substantially increased.
- No information was found that directly addressed the EEVC concerns (EEVC, 2000) that the compatibility of heavier vehicles should be better understood before these vehicles are included in the Directive. Despite this, the European Transport Safety Council (ETSC, 2001) recommended that M1 vehicles above 2.5 tonnes should be included in the Directive.

3.5 Other Regions

3.5.1 United States of America

At ESV in 2003, NHTSA published a comparison of the likely injury saving due to the three frontal impact crash test types that were most commonly used or discussed at the time (Ragland, 2003). The crash test types considered were the offset deformable barrier (ODB), moving deformable barrier (MDB), and fixed rigid barrier (FRB). These three crash test types were characterised in the following ways:

- ODB - low accelerations, long duration crash pulses, and moderately high intrusions for the subject vehicles
- MDB - short duration crash pulses, high accelerations, and high intrusions for subject vehicles

- FRB - short duration crash pulses, high accelerations, and relatively low intrusions for the subject vehicles

Full-width fixed deformable barrier and progressive deformable barrier tests were not considered; however, in terms of the definitions used in this paper, they would be very similar to the FRB and ODB tests respectively. Ragland reported that the majority of injuries were attributable to the MDB configuration (more than twice as many as either full-width FRB or ODB). When broken down by injury type, the biggest differences were for extremity injuries and, in particular, lower extremity injuries.

Ragland noted that the ODB test was 'designed primarily to address lower extremity injuries'. It is the understanding of the authors of this report that the ODB test was developed primarily to encourage improved stability of the occupant compartment, thereby providing a survival space in which the restraint systems can operate to reduce injury risk. Ragland concluded that the MDB test was the most relevant to the US accident population, and best placed to address the largest number of injuries, particularly lower extremity injuries. Comparison of belted and unbelted injuries was used to infer that lower extremity injuries are caused primarily by intrusion, and not by inertial loading from the occupant.

Saunders et al. (2004) contains updated accident data, 40% ODB test results, and a review of test data relating to vehicle compatibility. The accident analysis compares injury risks to each body region for full frontal (25%), left offset (37%) and right offset (38%) frontal crashes. Oblique impacts (see Ragland (2003) above) are no longer classified, and the Ragland accident analysis is not mentioned. The risk of thorax, upper extremity, knee-thigh-hip, and below knee injuries was highest in full-width frontal impacts, but the total number of lower limb injuries was highest in left offset impacts because these impacts are more numerous. Half of below knee injuries were to the ankle, with 25% to the tibia/fibula shafts. The risk of AIS 2+ knee-thigh-hip injuries was higher in SUVs and minivans than cars, whilst the risk of AIS 2+ below knee injuries was highest in cars. The risk of lower limb injury was found to be significantly higher in SUVs than any other vehicle body type. The risk of knee-thigh-hip injuries increased markedly for newer vehicle models, while little change was apparent for below knee injuries.

The authors reported that comparison of the real-world accident data with ODB test data suggested that the ODB test may underestimate the risk of thorax injury and knee-thigh-hip injury, but correctly estimate the risk of below knee injury. Lower extremity injury assessment values showed no relationship with toe-board intrusion, which was held to indicate that intrusion is not the only factor related to lower extremity injury. This is consistent with Post Mortem Human Subject (PMHS) tests that have generated serious (disabling) ankle injuries with only modest intrusion (e.g. Hynd et al. (2003)).

The most recent update of the NHTSA ODB test procedure was from Saunders et al. (2007). This included presentation of the seating procedure for the driver dummy (50^{th}%ile male Hybrid III with THOR-Lx lower leg), ODB crash test results, and discussion of possible changes to vehicle stiffness and compatibility resulting from the test procedure. Vehicle compatibility was assessed using the amount of energy absorbed in the first 25 to 400 mm of crush in a 35 mph rigid wall test. No further accident data was presented.

Eigen and Martin (2005) present the first results from a National Highway Traffic Safety Administration (NHTSA) study to use US NASS CDS accident data to determine injury prevention priorities for crash test dummy development. The data approach attempted to explore the following questions:

- What types of injuries should NHTSA strive to prevent?
- What measurements are required of a crash dummy to ascertain whether such injuries are sustainable in a crash test?

- How many lives are likely to be saved under a given performance requirement to prevent such injuries?

The paper disaggregates the injury data by front impact, near and far side impact, child rear seat occupant in a CRS etc., because these are directly relevant to the development of crash test dummies. Detailed frequency and cost of injury information is given for near side and all impacts, but not for front impacts separately - although it is implied that this data will become available.

From the analysis, a ranking of the top ten injuries of concern will be available, along with information on the mechanism of injury and, therefore, the relevant dummy measurements that are required. It may also be possible to value injury countermeasures based on the injury severity and cost information, although it is noted that this method is not currently used in NHTSA rulemaking.

At ESV 2007, NHTSA presented an initial analysis of the target population for improvements in advanced restraint systems (Eigen et al., 2007). The study incorporated only belted drivers and passengers, and used NASS CDS data. Frontal ‘offset’ (defined as having a direction of force of 11 or 1 o’clock, so equivalent to the oblique terminology used elsewhere) were the most prevalent for MAIS 3+ head and thorax injuries. Further case review of the head and thorax injuries was planned. The authors indicated that European data would also be considered if available, in the same way that US CIREN or SCI data would be used to help understand different accident scenarios.

Sullivan et al. (2008) developed a new taxonomy for frontal impact accidents based on weighted US NASS/CDS data. In addition to the CDC classifications, the authors included consideration of the height of damage, engagement of the longitudinal rails, and obliquity of impact. This resulted in a taxonomy of eight categories for all frontal impacts. Whilst there were a number of assumptions in the automated classification system used to allocate each case to a taxonomy, cases were selected at random and checked for inconsistencies.

The authors found that the full-engagement (CDC group D - greater than two-thirds engagement - with both rails engaged) and offset (CDC group D, Y or Z, with exactly one rail engaged) groups each contributed approximately 33% to the total number of frontal impacts. The remaining 34% were distributed across six other classifications of impact. However, when the relative risk of an injury occurring in an involved vehicle was considered, the group ‘D, Y, Z No Rail’ (CDC groups D, Y and Z with no rail involvement) had the highest relative risk of injury. For this group, a relative injury rate of 2.9 and 3.6 times for AIS 3+ and fatal injuries respectively was reported, although this group comprised only 2.6% of crash-involved vehicles.

Injury severity, occupant population, and injury type were not considered in this study.

Sullivan et al. require greater than 45° obliquity in frontal crashes before the crash is classified as oblique. In terms of allocating cases to full-engagement and offset crash types, this is almost the opposite extreme of the Ragland classification.

In a paper expected to be presented at ESV 2009 (but already available from the Insurance Institute for Highway Safety; IIHS), Brumbelow and Zuby (2009) also reviewed the impact and injury patterns in frontal crashes of vehicles with ‘Good’ consumer information ratings for frontal crash protection. They analysed frontal crashes from the US NASS/CDS that produced fatal or serious injuries to belted front-seat occupants. Frontal crashes were defined as those coded with a primary general area of deformation value of ‘F’ by the NASS/CDS investigators. All such cases were included when a belted outboard front-seat occupant sustained an injury with an AIS severity of 3 or greater (AIS • 3), unless the only such injury was to the upper or lower extremities.

Study vehicles were assigned a crash configuration based on photographs of damaged vehicle components and the struck object. The configurations were defined in reference to the longitudinal structures involved in frontal crashes.

- Centre impact – major load path was between the two main longitudinal
- Small overlap – major load path was outboard of all major longitudinal structure
- Moderate overlap – major load path was along one longitudinal member and associated structures; off-side member may have been loaded, but this was either less substantial, was induced by cross beams connecting the two members, or occurred after initial engagement with the struck object or partner vehicle
- Full width – major load paths were along both longitudinal structural members
- Under-ride – major load paths were along components vertically above the bumper bar and longitudinals
- Override – major load paths were along components vertically below bar and longitudinals
- Low severity – minor loading to all structural components; insignificant longitudinal crush, if any
- Non-frontal/irreproducible – miscoded primary deformation location or extreme crash scenario with limited relevance to general crashworthiness. Cases categorised as non-frontal or irreproducible were not analysed further

After categorisation and removal of the non-frontal/irreproducible cases, 96 occupants were left for further analysis. For cases involving these occupants, centre impact, small overlap, and moderate overlap configurations represented similar numbers of crashes and together compromised two-thirds of the cases. Under-ride and low-severity configurations were the next largest categories, together making up one-quarter of the total. Full-width and override configurations comprised the remaining eight percent of crashes.

Intrusion and restraint factors were each judged to have contributed to the injuries for more than one-third of the occupants. Occupant factors made up ten percent of the injured occupant cases. For the remaining 16 percent of cases, it was not possible to determine whether occupant or restraint factors were predominant in causing injury. Intrusion was most commonly related to injury in small overlap and under-ride crashes. For centre, full-width, override, and low severity crashes, restraint and occupant factors were predominant. Moderate overlap crashes had the most even mix among the various injury factors.

Occupants in under-ride and over-ride crashes had the highest median Injury Severity Score (ISS), although the override value was based on only two observations. Occupants in low-severity and moderate overlap crashes had the lowest median ISS. For injury categories, median ISS was higher for occupants with injuries attributed to intrusion than for other occupants. The chest was the most commonly injured body region at the AIS • 3 level. This was true for the entire sample as well as for the subsamples of occupants in centre, small overlap, moderate overlap, and full-width crashes. When injuries were attributed to intrusion or restraint factors, more occupants had serious chest injuries than any other injury type. Head injuries were the most common type of AIS • 3 injury for occupants in under-ride crashes and the second most common in centre, small overlap, and moderate overlap crashes, as well as in crashes where injury was attributed to intrusion or restraint factors.

According to Brumbelow and Zuby, analysing CDC (Collision Damage Classification) codes alone could lead to an overestimation of the number of real-world crashes represented by the full-width US NCAP test. Only six percent of occupants in their sample were in full-width crashes. No occupants were killed, and all vehicles had very little intrusion or none at all. Based on that sample of cases, Brumbelow and Zuby state that relatively few restrained occupants seriously injured in frontal crashes were in impacts that resembled the US NCAP test configuration. Moderate overlap is the other crash configuration currently used to evaluate the frontal crashworthiness of the fleet. This configuration was one of the two largest categories of crashes in the sample analysed by Brumbelow and Zuby, even though good performance in the IIHS offset test was an inclusion requirement. Among occupants seated on the same side as the impact, about half (8 of 15) were in crashes where substantial intrusion occurred, likely contributing to injury. However, the moderate crashes with substantial intrusion were all likely to have had higher speed impacts than the IIHS frontal offset test.

The small overlap configuration was the most common among crashes where intrusion contributed to injury and the second most common in the entire sample when considering the side of the vehicle being loaded. Currently there are no regulatory or consumer test programmes evaluating protection in small overlap crashes. Such a programme could result in vehicle design changes that expand the structural protection across the full width of the vehicle. As such, some occupants in moderate overlap and full-width crashes could also benefit from any increased load sharing brought about by the design changes.

3.5.1.1 LTV Compatiblity

Gabler and Hollowell (1998) reported that Light Trucks and Vans (LTVs) currently account for over one-third of registered U.S. passenger vehicles, yet collisions between cars and LTVs account for over one half of all fatalities in light vehicle-to-vehicle crashes. In these crashes 81% of the fatally-injured were occupants of the car. These statistics show that LTVs and passenger cars are incompatible and that LTVs are the more aggressive of the two vehicle classes.

Verma et al. (2005) reported on an analysis of 1997-2003 US NASS CDS front impact crashes between Light Truck based Vehicles (LTVs) and passenger cars. 14.9% of the harm arising from these crashes occurred in ‘Front Distributed’ crash types, with the next largest group ‘Front-Left Angled’ impacts at 4.7% of the harm.

Verma (2007) reported the progress of the Enhanced Vehicle Compatibility technical workgroup of the Alliance of Automobile Manufacturers on their voluntary agreement to improve the compatibility between light truck based vehicles and passenger cars. The workgroup’s charter is to develop compatibility improvements that do not cause significant reductions in the self-protection in these vehicles. The paper does not give specific information on the number of accidents, injuries or fatalities for LTVs, but it does quote an IIHS study of US FARS data for 2001 to 2004, which included car-to-SUV and car-to-pickup truck collisions. The relative risk of fatal injury was 16% lower in the SUV and 20% lower in the pickups than for the struck car. This illustrates the compatibility problem between LTVs and cars in the US.

The paper includes the workgroup’s early research results on the three approaches to test procedures that they consider could be used to encourage better car to LTV compatibility: full-width fixed deformable barrier with load cell wall; CAE-based simulations; and mobile deformable front impact barrier. No conclusions from this work were included in the paper.

3.5.1.2 Seat-belt Load Limiters

The IIHS reviewed the effect of seat-belt load limiters on driver fatalities in frontal crashes of passenger cars (Brumbelow et al., 2007). The authors compared the fatality rates for vehicles before and after the introduction of seat-belt load limiters, depowered airbags, or both. Only vehicles with no structural changes or other restraint system changes were included. Changes in the vehicle environment (such as average travel speed, vehicle fleet mix and so forth) were controlled for by normalising for the fatality rate in control vehicles with no change in the vehicle structure or seat-belt over the same time period. All data was extracted from the US Fatality Analysis Reporting System (FARS).

Brumbelow et al. found that the fatality rate tended to increase following the introduction of load limiters, or load limiters combined with depowered airbags. This was attributed to be likely to be due to increased head excursion allowing contact with interior structures such as the steering wheel or the A-pillar. A small review of NASS-CDS cases was presented in support of the statistical data. The authors acknowledge the importance of managing belt-induced thoracic loads during crashes. However, they caution that optimising the performance of airbags and load limiters for full-width rigid barrier tests (as used in the US regulation) without regard for the risks from increased occupant excursion may not produce the most effective restraint systems for real-world crashes. They recommend that alternative methods for reducing the localised loading from seat-belts, such as four point or inflatable seat-belts, should be sought.

Whilst not directly relevant to the accident conditions that should be targeted in a regulatory front impact test procedure, this paper does highlight the possible disadvantage of requiring compliance to just one test condition - systems can be optimised to that condition and may not perform optimally in other conditions, including those in real-world accidents.

3.5.1.3 Rear Seat Occupants

The protection of rear seat occupants in frontal crashes was examined by Kuppa et al. (2005). They used NASS CDS and FARS data, along with full-scale car crash tests with a full-width rigid barrier crash configuration. The FARS data suggested that occupants younger than 50 years of age benefited from sitting in rear seats in frontal crashes, but restrained adult occupants older than 50 years were found to be significantly better off in the front seats than the rear seats. Crash test results indicated that restrained rear seat occupants generally sustained higher injury measures than dummies of the same size in the driver’s and front seat passenger’s seating positions. The authors concluded that rear seat restraints could be further optimised to mitigate injury in frontal crashes for older rear seat occupants. Thorax injury was the most frequent AIS 3+ injury for belted occupants.

3.5.1.4 Pole Impacts

Arbelaez et al. (2006), from the Insurance Institute for Highway Safety (IIHS) in the US, used weighted data from NASS and FARS to determine the crash and occupant injury characteristics for real-world frontal collisions with narrow objects such as trees and poles. Narrow objects were defined as trees greater than 10 cm in diameter and non-breakaway posts 10-30 cm in diameter. It was acknowledged that trees greater than 10 cm in diameter could be very large and impacts with these objects may not be representative of narrow impacts, but that the exact diameter could not be determined from the database.

The authors compared the driver death rate per 10 million registered passenger vehicles. They reported that driver death rates had reduced by 56% between 1988 and 2004 for non-narrow frontal crashes, but that narrow crashes had reduced by only 44%. Approximately one quarter of fatal and serious (MAIS 3+) injury crashes involved collisions with posts, poles and trees. The authors concluded that narrow object frontal impacts contributed significantly to car occupant fatalities and injuries and that the fatality rate per registered vehicle was not falling as quickly for this category as for other front impact types.

Further to this, the IIHS recommended in public evidence to NHTSA that a frontal impact pole test should be incorporated in US NCAP (Lund, 2007).

Padmanaban and Okabe (2008) reviewed NASS CDS, NASS GES and FARS data to examine the frequency and severity of frontal crashes with narrow objects. In particular, the study compared results with those of Arbelaez et al. (2006). Padmanaban and Okabe reported that Arbelaez et al. defined narrow impacts as trees plus poles less than 30 cm wide, but that they used poles greater than 30 cm in their analysis. Both sets of authors acknowledged that trees may be wider than 30 cm, but noted that the actual diameter is not recorded in NASS CDS. Padmanaban and Okabe contend that the IIHS metric of fatality rate per million registered vehicle years was not relevant, because it does not take in to account changes in traffic patterns or other factors contributing to crashes. Instead, Padmanaban and Okabe recommended using the fatal rate based on the number of belted drivers exposed to different types of frontal crashes.

They found that if a frontal crash occurs, the risk of fatal injury to belted drivers in collisions with narrow objects was much lower than in other frontal crash types, and the risk of serious head/face/neck and torso injuries to belted drivers was the same for 'narrow' and other objects, although lower extremity injury risk was higher for 'narrow' object frontal crashes. The authors also undertook a case-by-case review of 402 NASS cases (of all injury levels), which is to be reported in detail in a future paper. However, some of the results were highlighted in the current paper. They found that relatively few of the impacts defined as narrow had a vehicle damage pattern that would be expected from such an impact. Of the 402 cases, 321 (82% of the weighted total) of the 'narrow' object impacts had a damage pattern similar to those in the IIHS frontal offset crash test, 71 had multiple impacts, and only 10 had damage patterns markedly different from the IIHS test. Sixty-nine of the 402 cases involved serious (MAIS 3+) to fatal injuries. Of these, 91% of the weighted serious and fatal injuries involved collisions with trees wider than 30 cm, or multiple trees, or involved both frontal and side impacts. These findings appear not to support the IIHS assertion that a pole impact test should be incorporated in US NCAP (Lund, 2007).

Hong et al. (2008) undertook a review of IIHS pole impact development test results, based on data made available by the IIHS. The authors compared the pole test results with the standard IIHS 40% offset frontal test results and found that toe-pan intrusions in the IIHS pole tests were markedly more severe than in the IIHS 40% frontal offset test procedure for the same vehicles. The dummy lower extremity measurements were also much higher. Thorax measurements were only slightly worse, which Hong et al. considered to be better than expected based on the real-world data presented by the IIHS. Further to this, Hong et al. presented FE simulation results evaluating the energy absorption patterns for a typical car (based on a NHTSA model) and another model with different energy absorbing structures. This led to recommendations for how to improve crash performance in the proposed IIHS test procedure.

The data from both Padmanaban and Okabe (2008) and Hong et al. (2008) imply that lower extremity injuries may benefit most from a frontal pole test procedure. Lower extremity injuries were also the primary focus for the NHTSA oblique MDB frontal impact test procedure that was proposed by, for example, Ragland et al. (2003). It is not clear from the information reviewed whether the two test types would target different lower extremity injury mechanisms or whether only one test type would be necessary.

3.5.1.5 CIREN

The University of Michigan reviewed 442 cases from their part of the CIREN database to compare the cases with crash configurations used in current regulatory or consumer crash tests, or crash test configurations under development by various organisations [University of Michigan, 2008]. All frontal impact cases were required to have been restrained by an appropriate seat-belt to be included in the database.

48.9% of cases had crash configurations and CDC (Collision Damage Classification) extents similar to current regulatory, consumer or development crash tests; 31.7% had similar configurations, but greater CDC extents; and 19.5% of cases had configurations that differed from current crash tests. For frontal impacts, the majority of those cases not matching current crash test types were small overlap, predominantly on the driver's side (5.5% of the total dataset, including side and other impacts), followed by small overlap on the passenger's side (just over 1% of the total dataset). For comparison, the largest three categories were: full-width frontal impacts with similar CDC extent were 14.5%; left offset impacts with similar CDC extent were 11.5%; and full-width impacts with greater CDC extent were 9.5%.

Small overlaps comprised 10.7% of frontal cases in the University of Michigan CIREN database. Head injuries attributed to A-pillar contact were frequent in this accident configuration, and were considered to be due to lateral occupant motion and rearward displacement of the A-pillar.

The Medical College of Wisconsin [Pintar et al., 2008] undertook a study of CIREN data, motivated by the Lindquist et al. [2004] study. The Lindquist study found that in Sweden, corner impacts (with very small overlap and little structural interaction between energy absorbing structures) are a significant contributor to fatal and serious injuries.

Seventy-one CIREN cases of corner impacts were analysed, covering a wide range of vehicle types and ages, as well as occupant ages. Lower extremity, head and chest injuries were the most frequent at the AIS 2+ level, while lower extremity, chest and pelvis were the most frequent at the AIS 3+ level. Impacts with trees or poles, or vehicles of similar size typically caused severe injuries, with an average Injury Severity Score (ISS) of 18; impacts with vehicles of a mismatched size were even more, severe with an average ISS of 24. It was also reported that delta-v and crush measures were not reliable indicators of trauma severity in low overlap crashes.

3.5.2 Australia

The effectiveness of ADR 69 was first assessed by Morris et al. (2001), later updated by Fitzharris et al. (2004) with more stringent statistical methods, and most recently by Fitzharris et al. (2006). The comments below are taken from the latter source.

ADR 69 produced no observable injury reduction benefit for the thorax (controlling for the average airbag / non-airbag injury effect). However, it should be noted that ADR 69 uses the Hybrid III dummy and requires a maximum thorax compression of 76.2 mm. This is considerably greater than the threshold for UN ECE Regulation 94, which requires a maximum thorax compression of 50 mm. This represents a 50% risk of AIS 3+ thorax injury, compared with a risk of injury at 76.2 mm of over 90% (estimated from Mertz et al., 2001). Airbags, independent of whether the vehicle met ADR 69, were found to have a significant protective effect for thorax injuries. The report recommended investigating the likely benefit of requiring front airbags for all front seat passengers, and of the feasibility of including the 5th%ile female in ADR 69. The thorax injury risk for elderly drivers was much higher than for younger drivers. The report noted that thorax injuries carry a high degree of morbidity and mortality for older adults in particular, such that older patients with rib fractures have twice the mortality and morbidity of younger patients with similar injuries, and for every additional rib fracture mortality increases by 19% and the risk of pneumonia increases by 27%. This suggests that thorax injury risk functions relevant to elderly occupants would be most beneficial in reducing thorax injury risk.

The authors noted a continuing high risk of debilitating lower extremity injury. They recommended examining the risk of lower extremity injury in ADR 73/00 compliant vehicles and, if still high, considering the use of new dummy parts and injury criteria to address these injuries.

In-depth data from the Australian National Crash In-Depth Study (ANCIS) were analysed by Logan et al. (2007). They investigated a dataset of seriously-injured drivers in frontal crashes to determine the incidence and severity of AIS • 2 injuries by body region in narrow offset (direct damage width less than 410 mm), wide offset, and fully distributed crashes. They found little difference in the collision partners across the frontal crash configurations, although 60 percent of fully distributed crashes occurred with another vehicle compared with 42 percent of narrow offset crashes and 43 percent of wide offset crashes, respectively. Logan et al. also reported that the median Injury Severity Scores (ISS) were similar across the crash types (fully distributed: 9 %, narrow offset: 10 %, and wide offset: 10 %); with major trauma, indicated by an ISS greater than 15 constituting 22.6 %, 19.4 %, and 31.4 % of cases respectively.

Regarding lower extremity injuries, MAIS • 2 injuries were 2.6 times more likely to occur in narrow offset crashes and 2.9 times more likely to occur in wide offset crashes relative to fully distributed crashes. The Odds Ratio of femur or bony pelvis injuries in narrow versus wide offset crashes was 0.28, indicating a greater risk of sustaining such an injury in wide offset crashes. Logan et al. concluded that; despite the significant improvements realised in recent years to full and offset frontal crash performance, their results showed a need for further gains, particularly with regard to the lower extremities, with 31 percent of HARM (~A$ 64,000 per crash) associated with injuries to that body region.

3.5.3 Japan

Several papers from Japan were reviewed, but all used US NASS data and were relevant to the US market only, not Japan.

3.5.4 Summary

3.5.4.1 Impact configuration

- Overlap:
    - Among all US frontal crashes, 25% were full frontal, 37% were left offset and 38% were right offset frontal crashes (Saunders et al., 2004). The risk of AIS 2+ thorax and below-knee injury was twice as high in full frontal compared with offset frontal collisions. Oblique frontal impacts were the most important for MAIS 3+ head and thorax injuries (Eigen et al., 2007), with a more detailed review planned, possibly including European data.
    - Sullivan et al. (2008) found that approximately 33% of US frontal impacts were full-width (with both rails engaged) and 33% offset (with one rail engaged). Impacts with no rail engagement had the highest risk of serious and fatal injury, although this group comprised only 2.6% of crash involved vehicles.
    - In Australia, Logan et al. (2007) reported that 45% of frontal impacts were full-width, 29% were associated with wide offset damage, and 26 % were narrow offset impacts (damage width less than 410 mm); although they found no significant differences in median Injury Severity Score between the crash overlap groups.
    - Brumbelow et al. (2007) found an increased rate of fatal injury following the introduction of load limiters, or load limiters combined with depowered airbags. They cautioned that optimising the performance of restraint systems only to a full width test procedure may not deliver the most effective restraint system for real-world crashes.
    - Two CIREN hospital-based studies in the US found that small corner overlap accidents had a high risk of injury. In one study, such impacts comprised approximately 10% of the frontal impact sample. Lower extremity, head and thorax injuries were prominent in these impacts.

- Compatibility:
    - Collisions between cars and LTVs account for over one half of all fatalities in light vehicle-to-vehicle crashes and in these crashes 81% of the fatally-injured were occupants of the car (Gabler and Hollowell 1998).
    - Small overlap crashes with vehicles of a mismatched size were reported to be the most severe (Pintar et al., 2008), indicating a need for improved vehicle compatibility even at small overlaps.
    - Verma (2007) quotes an IIHS study of US fatal accident data that showed that the relative risk of fatal injury was 16% lower in the SUV and 20% lower in the pickups than for the struck car.
- Pole Impacts:
    - Pole impacts were targeted by the IIHS as a possible additional front impact test procedure for the car safety consumer information programme (Lund, 2007).
    - In contrast, Padmanaban and Okabe (2008) found that the risk of serious head, face, neck and torso injury was equal in narrow object impacts and other frontal impacts. Lower extremity injury risk was reported to be higher in narrow impacts than other impact types.

3.5.4.2 Frequency and severity of injuries

- US: NHTSA has presented initial findings from an on-going detailed review of injury prevention priorities for crash test dummy development, including front impact dummies (Eigen and Martin, 2005). When this review has been completed, it is expected that priorities based on frequency and cost will be available, along with information on the mechanism of injury and therefore the relevant dummy measurements that are required.
- Head: Serious MAIS 3+ head injuries in the US were most prominent in oblique frontal impacts (Eigen et al., 2007) and were associated with an increased risk of fatal injury when load limiters and depowered airbags were fitted (Brumbelow et al., 2007), although the authors acknowledged the need to control thorax injury risk from restraint loading.
- Thorax:
    - o Serious MAIS 3+ thorax injuries in the US were most prominent in oblique frontal impacts (Eigen et al., 2007).
    - o The thorax injury risk for elderly drivers in Australia was much higher than for younger drivers (Fitzharris et al., 2006). The authors noted that thorax injuries carry a high degree of morbidity and mortality for older adults in particular and recommended that thorax injury risk functions relevant to elderly occupants would be most beneficial in reducing thorax injury risk.
- Abdomen: In contrast to the European data, abdomen injuries were not identified as a particular problem for rear seat occupants, compared to other injuries.
- Upper and lower leg:
    - o The primary benefit of the ODB test procedure under development in the US is reported to be an expected reduction in lower limb injuries. These are both very numerous in offset crashes (Saunders et al., 2004) and costly (Eigen and Martin, 2005; Logan et al., 2007).
    - o In the US, the risk of AIS 2+ knee-thigh-hip injuries was higher in SUVs and minivans than cars, whilst the risk of AIS 2+ below knee injuries was

highest in cars. The risk of lower limb injury was found to be significantly higher in SUVs than any other vehicle body type. The risk of knee-thigh-hip injuries increased markedly for newer vehicle models, while little change was apparent for below knee injuries (Saunders et al., 2004).

  - Real-world accident data with ODB test data suggested that the ODB test may underestimate the risk of thorax injury and knee-thigh-hip injury, but correctly estimate the risk of below knee injury. Lower extremity injury assessment values showed no relationship with toe-board intrusion, which was held to indicate that intrusion is not the only factor related to lower extremity injury (Saunders et al., 2004). This finding is consistent with biomechanical data and the European accident data reviewed in this report.
  - A high risk of lower extremity injuries was also reported for pole impacts (e.g. Padmanaban and Okabe, 2008).
  - Fitzharris et al. (2006) noted a continuing high risk of debilitating lower extremity injury. Improved dummy parts and injury criteria may be necessary to address these injuries.

- Rear Seat Occupants:
  - US FARS data suggested that occupants younger than 50 years of age benefited from sitting in rear seats in frontal crashes, but restrained adult occupants older than 50 years were found to be significantly better off in the front seats than the rear seats (Kuppa et al., 2005). The authors recommended that rear seat restraints could be further optimised to mitigate injury in frontal crashes for older rear seat occupants. Thorax injury was the most frequent AIS 3+ injury for belted occupants.

3.5.4.3 Regional Variation in Accident Patterns'

From the accident data analyses available it is very difficult to make any comparison of the nature of the accidents in Europe with the rest of the world because the information available is mostly not directly comparable. This is because the analyses have been targeted to answer specific questions and do not provide overall data, such as the number of casualties in frontal impacts and the proportion of them in different types of frontal impacts. Most of the information available for the rest of the world is for the US. The only major difference noted between Europe and the US was that in the US a specific compatibility problem between LTVs (i.e. SUVs and pickups) and cars has been highlighted, whereas in Europe no such issue has been highlighted The reason for this difference is the large proportion of LTVs in the US vehicle fleet compared with Europe, and the large size of some US LTVs which are not as common in Europe. Some other small differences were also noted, such as abdomen injuries were not identified as a particular problem for rear seat occupants compared to other injuries in the US, whereas they were in Europe.

3.6 Conclusions

The scale of the frontal impact problem in Europe is illustrated by the following:

- Of 41,247 road traffic fatalities in EU-25 in 2005, approximately 10,000 car occupants were killed in frontal impacts.
- The numbers of persons killed in road traffic accidents in Europe has consistently decreased year on year since 1998. Broughton's analysis suggests that the Directive and UNECE Regulation 94 have contributed strongly to this reduction.

Examination of literature found that the accident data available to review the current frontal impact situation in Europe was limited. The last comprehensive and co-ordinated

European accident analysis study to be performed was by Wykes in 1998. Since then, the accident analyses performed have been mostly for specific countries, in particular the UK, and to answer specific questions. It was not possible to extract similar information from these analyses for direct comparison because each analysis used different data sets and broke the data down in different ways. So the approach taken was to highlight the key information from each analysis and wherever possible sort it into categories. The categories chosen were impact configuration, population injured and frequency and severity of injury. This information was then interpreted to give guidance for improvement of future legislation.

<u>Impact Configuration</u>

- Regarding collision partners in frontal impacts, the largest proportion of front impact casualties were in car-to-car crashes, which highlights the importance of compatibility.
- The three options regarding principal types of loading to the vehicle front structure are:
    - Loading to one longitudinal beam and the engine (given by current ODB test)
    - Loading to both longitudinal beams and the engine (given by full width test)
    - Loading to either one longitudinal and side structures or side structures only (given by small overlap test)

  The relative importance of these three options varies within the literature reviewed and by region; therefore a precise recommendation for priorities for replication through testing cannot be given on the basis of that information. However, the order given above would appear to be the most appropriate, indicating a potential need for a full width test in Europe, followed by a small overlap test to complement the current offset test.
- For the UK and Germany, a full-width test speed of 56 km/h would cover more than two-thirds of the MAIS • 3 injuries (Cuerden et al., 2007b).

<u>Population Injured</u>

- Driver and FSP - Gender: The analysis of the UK CCIS and German GIDAS datasets identified that the driver should be male (accounts for upwards of 72% of the MAIS 3+ drivers) and the front seat passenger female (accounts for upwards of 60% of the MAIS 3+ front seat passengers). Based on data from Germany, the mass and height of both the driver (male) and front seat passenger (female) were found to closely match the Hybrid III 50th percentile male dummy (Cuerden et al., 2007). However, UK data showed that a high proportion of drivers sustaining upper leg and ankle/foot injuries in Euro NCAP tested cars were female (62%); suggesting the scope for injury assessment based on a small female dummy.
- Rear seat occupant: Rear seating positions were found to be better protected than front seating positions using German GIDAS data (Cuerden et al., 2007b), although the number of rear seat occupants was very low. By contrast, Welsh et al. (2006) reported that rear seat occupants in newer cars were disadvantaged compared to those in older cars using GB data. This indicates that it may be necessary to test the rear seated position if it is decided that similar levels of crash protection should be maintained or improved for rear seated occupants.

<u>Frequency and severity of injury</u>

- Head: Head injury protection in frontal impacts has improved markedly, although a large proportion of fatally injured drivers still have an AIS • 3 head injury.

- Thorax: Recent data (Cuerden et al., 2007b) showed that the thorax was the highest priority for AIS 3+ injury (UK and German data) and that the thorax was also very important when considering fatal accidents. A study of the factors related to serious thorax injury showed more than half of the injuries occurring in full overlap configurations (Frampton et al., 2004). Thorax injuries are primarily related to interaction between the occupant and the restraint system. For this reason it may be that a full-width test would be better suited to drive improvements in restraint technology and therefore reductions in thorax injury risk. However, thorax protection needs to be assessed with a test tool of sufficient biofidelity and injury assessment capability, and with injury criteria that are relevant to the population at risk of sustaining these injuries, although some benefit may accrue from the use of the current Hybrid III frontal impact dummy provided that the injury risk functions and thresholds are relevant to elderly occupants.
- Abdomen: Abdomen injury was relatively uncommon for drivers and front seat passengers, but 28% of the MAIS • 3 rear passengers sustained an AIS 3 or greater abdomen injury (Cuerden et al., 2007a).
- Upper and lower leg: Protection of these body regions remains a priority, both in frequency and impairment terms. The priorities are thigh, knee and foot/ankle protection. Lower extremity injuries (thigh and foot/ankle) occur even without significant footwell intrusion, so intrusion is not a sufficient measure of lower extremity injury risk. Consideration should be given to an improved dummy lower extremity in order to deliver significant reductions in foot-and-ankle, knee and thigh injuries. An improved dummy lower extremity could be used in both the current ODB and any future full-width test procedure. It may be beneficial to implement the THOR-Lx advanced lower extremity as a retrofit to the Hybrid III dummy in the existing ODB test procedure, and this should also be considered for any full-width test procedure.
- Rear Seat Occupants: Based on a limited number of UK cases, the most frequently AIS • 3 injured body regions for survivors were the thorax (28%), the abdomen (28%), the lower extremity (22%) and the head (17%) (Cuerden et al., 2007a).

Limited information was found related to N1 and M1 vehicles not within the scope of the current legislation. A study by Smith and Knight (2005) which reviewed Light Commercial Vehicle (LCV - N1 vehicles not including car-derived N1 vehicles) accidents in the UK concluded that improving the frontal crashworthiness of the LCV alone was not that beneficial compared to other measures. However, when combined with other countermeasures such as wearing a seatbelt it became one of the more beneficial countermeasures.

Most of the accident analyses information available for the rest of the world was for the US. The only major difference noted between Europe and the US was that in the US a specific compatibility problem between LTVs and cars has been identified, whereas in Europe no such issue has been identified. The reason for this difference is the large proportion of LTVs in the US vehicle fleet compared with Europe, and their greater size.

4 Dummies

4.1 Introduction

A single family of adult frontal impact dummies is in global use for regulatory and consumer information frontal impact crash testing: the Hybrid III. Use of two 50th percentile Hybrid III dummies, installed in the two front (outboard) seating positions, is currently specified in the UNECE frontal impact regulation (Regulation 94). The Hybrid III family is also specified for frontal impact testing in U.S. FMVSSs and in consumer testing around the world. This has led to widespread acceptance and harmonisation of testing with the Hybrid III 50th percentile male dummy throughout the world.

Limitations in the biofidelity and injury prediction capability of the Hybrid III dummies, particularly with modern restraint systems, led NHTSA (National Highway Traffic Safety Administration) to initiate the development of a new front impact dummy, the THOR (Test device for Human Occupant Restraint). Initially the 50th percentile male THOR dummy was designed and made by GESAC Inc. More recently, FTSS (First Technology Safety Systems) have developed a version of the THOR dummy based on recommendations from the EC 5th Framework FID project. This has led to there being two, very similar, dummies being available: the THOR-NT and THOR-FT.

At this time the Hybrid III and the THOR are the only two dummies designed and available for use in frontal impact testing. It is acknowledged that the Hybrid II (the predecessor to the Hybrid III) is still made. However, this is not considered to be a viable alternative following the widespread acceptance and use of the Hybrid III around the world and the documented limitations of the Hybrid II in interacting with adult belt restraints (Beusenberg et al., 1996).

This study does not include any consideration of Child Restraint Systems (CRS) in the full-scale test procedures; therefore, child dummies have not been included in the review.

4.1.1 Overview of Front Impact Dummy Requirements

The Hybrid III dummy is a standard dummy used in legislative and consumer testing worldwide. It is envisaged that the THOR dummy will be the next frontal impact dummy used worldwide. However, the dummy requirements specified by groups in different regions of the world are not identical. As the Hybrid III design has remained unchanged in recent years, the performance of the Hybrid III dummy is already known with respect to the requirements. In contrast, whilst still in development, it is possible that design changes to the THOR may take place in order to improve the performance of the dummy. As such, the differing frontal dummy requirements in different regions may cause conflicts when making any alterations to the THOR design. Improving performance with respect to one set of requirements may not be as beneficial with regard to another set of requirements.

The EEVC published recommendations for the development and design of an advanced frontal impact dummy in 1996 (EEVC WG12, 1996). This covered all aspects of the requirements, from the capability identified from accident analysis, through overall dummy requirements such as handling, injury assessment and sensitivity, to the factors that should be considered in defining biofidelity requirements for each body region. Detailed biofidelity requirements were subsequently published in 2003 (van Don et al., 2003b - also available as EEVC WG12, 2003). The EEVC recommendations were based on work from the ADRIA and FID EC Framework projects, as well as other EEVC work. Since the EEVC recommendations were published (EEVC WG12, 1996), the requirements for a frontal impact dummy as identified in the accident analysis have changed. In particular, head injury protection has improved considerably in newer vehicles and facial fractures have reduced the most (see Section 2 ‘Definition of the problem – accident issues’). Therefore one might expect stringent requirements regarding dummy head performance to be less important with respect to the assessment of newer vehicles. However, those head injuries that do still occur in the real world can be severe and hence monitoring of head injury protection in car crash tests is still required. As such the requirements for the head of a dummy remain relevant.

The NHTSA have also published biofidelity requirements for a frontal impact dummy as part of their THOR development programme (GESAC, 2001) and updated in 2005 (GESAC, 2005). EEVC WG12 compared the EEVC and NHTSA biofidelity requirements and found them to be almost identical except for some additional WG12 requirements in some regions and substantial differences in the neck and lower leg requirements (see Appendix A of EEVC WG12, 2006). The EEVC report recommended that:

'at least Europe, North America, Australia and Japan [should] agree on a harmonised set of biofidelity requirements for a frontal impact dummy that takes the needs of all parties into account'.

To date such harmonisation has not taken place, although this may occur within the SAE THOR Evaluation Task Force.

Many of the biofidelity comparisons between Hybrid III and THOR that are made in Section 4.3.2.1 are made to either EEVC or NHTSA requirements, while others are direct comparisons with PMHS or volunteer data that are not included in either set of biofidelity requirements.

4.2 Hybrid III

4.2.1 Introduction

The Hybrid III was developed in 1976 by General Motors for use in US FMVSS 208. It is the most widely used adult crash test dummy in the world. The dummy is a regulated test device in the USA Code of Federal Regulations (Part 572, Subpart E) and also in the UN ECE Regulations. These regulations not only require the use of Hybrid III dummies, but also specify the design features and performance which any Hybrid III must comply with to be suitable for use. However, whilst the dummy specification is controlled to a tight standard in regulations and consumer tests, the injury risk functions and criteria used with the dummy vary depending on the exact test procedure in which it is being used.

The Hybrid III allows assessment of more than 40 measurements of acceleration, deflection and load in various body areas. Since the advent of airbags and other deployable devices, restraint systems have become increasingly advanced and complex. These advances have decreased the overall frequency of serious injury in motor vehicle accidents and were successfully developed and certified using the Hybrid III. Notwithstanding such success, it remains a goal to advance test dummy biofidelity and thus have the potential to evaluate future designs better (Dibb et al., 2006)

Following the successful development of the 50th percentile male Hybrid III dummy, the US government directed further developments to produce a family of dummy sizes for automotive safety test work. This family now includes a series of child dummies as well as 5th percentile female (as regulated by CFR 49, Part 572) and a 95th percentile male adult occupant. In addition, the 5th percentile female has a special kit, which allows consideration of pregnant occupant behaviour, making a 5th percentile pregnant female dummy. These dummies represent the potential to assess risk of injury for occupant sizes other than the mid-sized male. Therefore, some details regarding their specification will be presented in the following section. However, the main focus of this review is to assess the relative merits of the different types of frontal impact dummies available. As introduced above, in practice that means comparison of the Hybrid III and THOR dummies. On that basis detailed discussions will be limited to the 50th percentile male Hybrid III and THOR, so that equal dummy sizes are considered. This is also the most frequently used of the dummy sizes and hence has the greatest amount of published information on which to base the comparison.

4.2.2 Basic Performance

To work towards reducing deficiencies with predecessors, General Motors undertook the development of the Hybrid III in 1975. The primary objective was to design and build a dummy whose component response characteristics were consistent with available biomechanical data, while retaining or improving upon the best features and assets of the Hybrid II and ATD 502 designs (Foster et al., 1977).

4.2.2.1 Head

The Hybrid III head was designed to meet a 376 mm isolated drop test biofidelity requirement. The procedure and limits were based on similar tests conducted with PMHS (Foster et al., 1977).

In the paper by Ward (1985), the dynamic responses of the Hybrid III head and the Part 572 dummy head (the predecessor to the Hybrid III) were compared with the responses of PMHS heads. Frontal, mandible, and lateral impacts to the heads were carried out and the resultant head accelerations compared. Ward found that the Hybrid III head accelerations were closer to those of the human heads than the Part 572 head. However, the Hybrid III accelerations were low in the frontal impacts, approximately the same in the lateral blows, and higher than the human head in the mandible impacts.

In 2004, Denton ATD released a technical bulletin in response to comments from several customers that the head skin of the Hybrid III was different between dummy manufacturers (Denton ATD, Inc., 2004). Denton found that their head skin mould was the same as the original drawing produced by NHTSA. However, this was different from that produced by FTSS. For example, the FTSS and Denton head skins had different forehead thickness, nose filling, and chin. FTSS responded by stating that their design met updated drawings held by NHTSA. These moulding differences would obviously have some effect on the reproducibility of the dummy from different manufacturers. However, the extent of that effect is not known, but is likely to be limited, assuming that the skin fits the head well. In particular, the effect is likely to be small with correct front airbag performance.

4.2.2.2 Neck

The Hybrid III neck is a one-piece flexible component with biomechanical bending and damping in both flexion and extension. The Hybrid III neck biofidelity requirements are based on flexion and extension performance in whole dummy sled tests (Culver et al., 1972; Mertz and Patrick, 1971), based on the responses of volunteers and PMHS. These biomechanical data are considered to be somewhat limited (EEVC WG12, 1996) and the neck biofidelity has been questioned, especially for frontal flexion.

4.2.2.3 Thorax and abdomen

The primary thoracic performance objective for the Hybrid III was to assess the efficiency of energy absorbing steering columns (Mertz et al., 1991). Compared with the Hybrid II, the Hybrid III has a slightly more profiled rib cage, a more compliant chest and more distinct clavicles. While an improvement over the Hybrid II (Horsch and Schneider, 1988), the clavicles do not articulate correctly and the chest is still not compliant in the same way as a human chest (Horsch et al., 1991). The Hybrid III thorax was not designed to reproduce human thoracic response to the type of asymmetric strip loading applied by the shoulder belt (EEVC WG12, 1996).

The biofidelity of the Hybrid III abdomen is limited (EEVC WG12, 1996) and the abdomen has no injury assessment capability. A number of prototype abdomen injury assessment systems have been developed, but none have been adopted for regulatory or consumer testing (see Section 6.2.5.10).

The specifications for the Hybrid III dummy were generated at a time when seat belt use was very low (less than ten percent) and airbag availability was almost zero. As such the Hybrid III was not designed to be used in the assessment of seat belt and airbag-based restraint systems. It is not clear that this dummy is appropriate for estimating injury risk from modern restraint system loading (Kent et al., 2003b). van Don et al. (2003) suggested that data of belt loading tests performed with PMHS/volunteers lying in a supine position should be used to define biofidelity requirements, because the loading pattern would be more representative of the real world than the historic blunt impacts.

4.2.2.4 Lumbar spine

The Hybrid III lumbar spine is a moulded, curved polyacrylate elastomer member. Two cables pass through the lumbar spine and attach to end plates, which connect to the thoracic spine and pelvis. The cables provide lateral stability while permitting fore and aft flexibility. The lumbar spine of the Hybrid III was carried over from the ATD 502 design and the biomechanical basis for that design is unknown. Its performance is specified in quasi-static conditions only.

4.2.2.5 Knee, thigh, and hip

The knee padding response for the Hybrid III was tuned to the PMHS data produced by Horsch and Patrick (1976). According to Foster et al. (1977), the peak impact force responses of the Hybrid III are within the range of the PMHS data. However, Donnelly and Roberts (1987) found that, in axial impacts to the knees, the Hybrid III dummy did not model the force response of a PMHS knee-thigh-hip complex very well. The dummy produced larger femoral forces and shorter pulse durations than the PMHS, impacted at the same conditions. Rupp et al. (2003) also developed knee/femur response corridors based on tests with 20 PMHS. They found that the Hybrid III knee and femur was more than twice as stiff as the PMHS response in the first 2 mm of deflection and then approximately 16 times as stiff thereafter.

A stiffer thigh is likely to provide a greater restraining force for the pelvis and to some extent for the torso of the dummy (via the lumbar spine). This may reduce the amount of work that the restraint system has to do in order to restrain the occupant and the abdomen, thorax, neck and head protection may therefore be overestimated. Correct thigh biofidelity may therefore be important for correct optimisation of the seat-belt and airbag restraint system.

4.2.2.6 Lower legs

Comparative Hybrid III and PMHS lower leg tests were conducted by Viano et al. (1978). They found that when the flexed (90°) lower leg was struck by a simulated bolster, the dummy contact force was significantly greater than in the PMHS tests. In impacts directed at the knee or at the knee and the lower leg, the contact force from the dummy tests was again significantly greater than from the PMHS tests.

Pairs of PMHS and Hybrid III lower limbs were impacted on the bottom of the foot, with a linear impactor, by Begeman and Prasad (1990). They found that approximately 45 degrees of ankle dorsiflexion (rotation of the foot such that the toes move towards the knee) corresponded with a threshold for ankle injuries. They concluded that the Hybrid III responses were not comparable with those from the PMHS because of the ankle design at the time. The increasing interest in assessing the injury risk of the lower legs resulted in design improvements of the Hybrid III ankle, compared with the design tested by Begeman and Prasad.

4.2.2.7 Other dummy sizes

The biofidelity requirements for the small female and large male Hybrid III dummies are scaled from the requirements for the mid-sized male. If one assumes that the dummies meet these requirements then the performance of the dummies should be related to that of the mid-sized male.

4.2.2.8 Overall repeatability and reproducibility

Repeatability and reproducibility are major considerations in the evaluation of a test dummy design. Repeatability is defined as the similarity of results expected to be obtained in repeated testing of a single dummy under identical conditions. Reproducibility is defined as the variability expected to be obtained between different dummies tested under identical conditions. Foster et al. (1977) tested three Hybrid III dummies a minimum of six times each in a special seat fixture on the GM Hyge sled. The data indicated that the Hybrid III had a repeatability of approximately four to six percent, with an improved reproducibility (of about one to seven percent) over the Hybrid II (although the Hybrid IIIs were prototype units with a very high degree of quality control). Saul et al. (1983) also found the repeatability of the Hybrid III to be better than that of the Hybrid II or Part 572 dummy in sled testing with a three-point belt restraint system. The coefficients of variation for the head, chest and pelvic acceleration and chest deflection measurements were four percent or less.

4.2.3 Handling

The Hybrid III is generally considered to be robust. The seated occupant version of the dummy has been used in many different applications. The Hybrid III (as had the Hybrid II) has also been modified to a standing posture for use in pedestrian tests. This shows a level of confidence in using the Hybrid III in more demanding, higher severity of loading situations than would be expected in a crash test representing typical accident types in which a vehicle occupant might be injured.

In use the Hybrid III is relatively easy to set-up and test engineers are familiar with the dummy. Equally users of the dummy are expected to be familiar with assembly and disassembly procedures, and the use of the instrumentation for the dummy.

4.2.4 Design issues

The options for Hybrid III instrumentation and measurement capabilities include the following:

- Head – Typically a three-axis accelerometer array; however fittings are present to install a nine- or twelve-axis accelerometer array, if required
- Neck – A six-axis upper neck load cell is used as standard although a lower neck load cell can also be used, if required
- Thorax – Thoracic spine acceleration (three-axis); mid-sternum thorax compression sensor (rotary potentiometer); and thoracic spine load cell (five-axis)
- Lumbar – Six-axis load cell
- Pelvis – Three-axis accelerometer array; pelvic load bolts (single-axis) – three mounted on each of the iliac crests
- Femur – Either a single- or three-axis upper load cell; the possibility exists to use a six-axis lower femur load cell as well
- Knees – Sliding knee potentiometers
- Lower legs - optionally, an upper tibia load cell measuring moments in two axes; and a five- or six-axis lower tibia load cell

Belt geometry was reported to be a problem for the Hybrid III chest deflection measurement by Horsch et al. (1991). They found that when the shoulder belt interacted with the Hybrid III neck during an impact, the chest deflection measurement could be reduced by up to a half compared with the a test under the same conditions only with the shoulder belt moved away from the neck of the Hybrid III.

Euro NCAP has been aware of Hybrid III dummy variability in the chest region for many years (Euro NCAP, 2008). On investigation they found that Hybrid III chest deformation characteristics under low speed test conditions were different to normal speed calibration test conditions and that the dummy response was not linear with respect to impact velocity (that is dummies that tend to be stiffer in normal calibration tests are not necessarily stiff at lower impact speeds). In order to control the variability of the thorax response more tightly, Euro NCAP specified that the Hybrid III dummy should meet both the low speed thorax test as prescribed by SAE J2779, as well as the full certification test in CFR572 for future Euro NCAP testing.

Submarining is an important example of a phenomenon highly affected by the response of the lumbar spine (EEVC WG12, 1996) and the shape of the pelvis. Concerns over the biofidelity of the lumbar spine of the Hybrid III are therefore important, in this respect, together with a lack of an accepted means of measuring abdominal injury risk with the Hybrid III. For instance, Couturier et al. (2007) reported that the Hybrid III was not as sensitive to submarining conditions as either the Hybrid II or Hybrid III FAA (as used in the aeronautic field). The pelvic load bolts are still an instrumentation option to detect the potential for submarining to occur (as described by Uriot et al., 1994). However, to date, little information has been published on their effectiveness in assessing submarining and hence abdominal injury risk.

In Japan, the US and Europe it was observed that the shape of the pelvis as well as the femur of the Hybrid III differs from that of the human body in such a manner that hard contact can occur, e.g. in airbag tests, between the iliacs and the femur, causing high vertical chest accelerations which are believed to be unrealistic (EEVC WG12, 1996).

4.2.5 Injury Prediction

The use of the Hybrid III dummy to rank vehicles or to evaluate design options contains the inherent assumption that the dummy’s measures are an objective indicator of injury risk (Kent et al., 2003b). The conditions of an experiment (or test), if they are appropriate and realistic, should not change the relationship between the measurements made by the dummy and injury risk for a human occupant subjected to the same conditions.

For the assessment of advanced airbags, NHTSA proposed a comprehensive set of injury criteria for evaluating the potential for injury to the head, neck, chest and lower extremities for the various Hybrid III dummy sizes, up to the 50th percentile male (Eppinger et al., 2000).

4.2.5.1 Head

Head injury assessment using the Hybrid III relies on the Head Injury Criterion (HIC), based on time histories of the linear accelerations of the centre of gravity of the head.

4.2.5.2 Face

In its standard form, the Hybrid III does not allow assessment of facial injuries, nor does it represent the human face deformation characteristics in direct contact. Some alternative designs for the Hybrid III facial structure have been proposed (for instance, the use of chamois on the face and observation of cuts in the leather; or a deformable element – Melvin and Shee, 1989; etc.), but have not gained worldwide acceptance (EEVC WG12, 1996)

4.2.5.3 Neck

Various criteria are used to assess the risk of neck injury in frontal impacts. UNECE Regulation 94 (UNECE, 1995) neck tension and shear injury assessments are based upon a ‘time at level’ evaluation. This describes the maximum continuous time at which the measured value of a signal exceeds a defined level. The Regulation also uses a limit of 57 Nm on the upper neck moment (M_y). Euro NCAP uses these criteria as a baseline.

In the upgrade to FMVSS 208, Eppinger et al. (1999) introduced the N_{ij} criterion as a replacement for conventional compression, tension, shear, and moment injury criteria. N_{ij} combines upper neck axial force (F_z) with the upper neck moment (M_y).

4.2.5.4 Chest

The chest acceleration criterion used in FMVSS 208 is that if the resultant thoracic spine acceleration is less than 60 g, using the 3 ms exceedence measure, then significant thoracic organ injury due to gross chest acceleration is considered to be unlikely.

Mertz et al. (1991) developed a relationship between the risk of significant thoracic injury (AIS • 3) and Hybrid III dummy sternal deflection for shoulder belt loading. This relationship was based on analysis of the occupants within APR (Association Peugeot-Renault) accident data who were restrained using force-limiting shoulder belts. Sled tests were then conducted with a Hybrid III dummy to reproduce the various degrees of force in the shoulder belt. From these results injury risk curves were developed.

The results of nineteen sled tests with the Hybrid III and THOR were analysed and reported by Kent et al. (2003a). The dummies were seated in both the right front passenger and driver positions of two contemporary mid-size vehicle bucks. They were restrained with either a three-point belt system with a buckle pretensioner and force-limiting retractor, and a de-powered airbag, or a standard three-point belt system (non-pretensioned, non-force-limiting) with an identical airbag. In addition to the standard sternum deflection slider, the Hybrid III was instrumented with four thorax compression string potentiometers. Kent et al. found that the maximum sternum slider deflections were significantly lower in the force-limiting restraint condition tests than in the tests with a standard belt. Furthermore, the shape of the time history of the slider deflection was representative of the time history of the maximum deflection (as measured with additional string potentiometers). However, the magnitude of the deflection from the sternum slider was lower over the entire time range, and the ratio varied across test conditions (i.e. standard Hybrid III thorax compression measurement did not detect the maximum compression and would therefore underestimate the injury risk in these tests). This difference between the maximum compression of the thorax and the deflection at the sternum had been reported previously by other authors (e.g.: Backaitis and St-Laurent, 1986; Yoganandan et al., 1991; Cesari and Bouquet, 1994).

Kent et al. recommended that future opportunities may lie in the use of multi-point deflection measurement and in an improved understanding of the relationship between externally mounted PMHS chest deflection, internally measured dummy chest deflection, and injury risk.

To account for differences in sternal deflection according to whether loading is localised or distributed, Petitjean et al. (2003) developed a relationship between seat belt load and sternal deflection. This was used to produce an updated chest deflection and Combined Thoracic Index injury risk curve for the Hybrid III (50 year old). However, Petitjean et al. comment that the relationship between central thorax deflection and shoulder belt load did not show a high correlation. They suggested that the use of real maximal deflection on the thorax and the consideration of the belt restraint geometry may improve the reliability of the relationship and hence the reliability of the equivalent criterion.

Eppinger et al. (1999) proposed the use of the Combined Thoracic Index (CTI) with the Hybrid III dummy because it “encompasses the effects of both airbag and belt systems”. The limits for intercept values for use with the 50th percentile male dummy were 102 mm for the deflection and 85 g for acceleration.

The viscous response describes the behaviour of soft tissue during an impact event (Lau and Viano, 1986). It is a product of the normalised compression and the rate of chest deflection. When used as a viscous tolerance criterion (or Viscous Criterion; V*C) the limit of 1.0 m.s^{-1} was set to correspond with a 25 percent chance of sustaining a severe thoracic injury (AIS • 4).

4.2.5.5 Overall evaluation of thorax injury prediction capability

The utility of the Hybrid III dummy for discriminating between injurious and non-injurious sled tests with diverse restraint conditions was evaluated by Kent et al. (2003b). Three dummy injury measures were considered in the analysis: the 3-ms clipped maximum resultant chest acceleration (A_{max}), the maximum mid-sternal chest deflection (C_{max}), and the combined thoracic index (CTI). Kent et al. considered 60 PMHS sled tests with 33 matched Hybrid III tests, taken from the literature. A_{max} was found to be a poor discriminator of injury outcome when the restraint condition, and hence the load distribution on the chest varied. Furthermore, the inclusion of A_{max} as a component of CTI degrades this criterion’s performance relative to C_{max}. C_{max} was a better predictor of rib fracture than A_{max} for diverse types of restraint loading (Kent et al., 2001)

Kent et al. found that the Hybrid III chest deflection level that corresponds to ‘injury’ is lower with belt loading than it is with distributed loading. The relationship between any of the three Hybrid III injury measures and actual injury risk was highly sensitive to experimental factors such as test speed, restraint condition, and seating position. This has been confirmed by other authors (Morgan et al., 1994). As a result, Kent et al. conclude that the use of Hybrid III measures to compare different design options may change with the experimental environment to the extent that the measured outputs are not comparable between the design options. Restraint-specific functions are therefore presented that quantify the relationship between injury and injury risk for belt loading, airbag loading, and combined loading. However, it is unclear how these functions could be implemented in the practical assessment of combined seat belt and airbag restraint systems without prior knowledge, for each test, of the contribution of the seat belt and airbag to the overall occupant restraint.

4.2.5.6 Abdomen

The Hybrid III dummy does not have any abdomen compression measurement capability and therefore there are no Hybrid III abdominal injury risk functions either. This is not to say that concepts for Hybrid III abdominal injury risk assessment do not exist. For instance, Rouhana et al. (1989) developed abdominal inserts for the Hybrid III family of dummies. These inserts deformed during testing and therefore gave a record of the peak abdominal intrusion caused by, for example, the lap belt. An alternative sensor system was developed by APR (Uriot et al., 1994), which consisted of assemblies attached to the lumbar column support intended to catch the lap belt when it slid up over the iliac wings. More recently instrumented inserts have been developed by Toyota (Ishiyama et al. 1994) and Rouhana et al. (2001). Both systems allowed measurement of abdominal compression and V*C. The Toyota Abdominal Deformation Analysing System (TADAS) used a metal band and strain gauge sensor, whilst the Rouhana et al. system used the electrical resistance between the front and rear of the abdomen to measure compression. Whilst these inserts showed good potential in terms of localised biofidelity, further work to validate the sensor design was reported as being necessary before it could be implemented in crash testing. Subsequently another sensor design was developed by Johannsen (2006), based on measurement of the surface force over the abdomen. However, this again requires further improvement before it could be considered for use in regulatory crash testing because it did not fulfil basic reliability and repeatability requirements.

A validated abdominal measurement system should have advantages over deformable elements. One of the key advantages with respect to regulatory use is the ability to certify the ‘instrumentation’. With a single-use deformable element there is no method of certifying the performance of the element before use. Instead batches of material would need to be certified. Depending on the reliability of this batch certification, it may be that this does not give sufficient assurance of performance for regulatory testing where the implications of such inaccuracy could be exceedingly onerous for a vehicle manufacturer (e.g. product recalls, redesign issues).

It is possible to retro-fit THOR abdominal instrumentation into the abdomen of the Hybrid III. An existing system for this requires replacement of the abdomen as well as the lumbar spine (Freeman and Matthews, 2005). Based on those changes it would be necessary to confirm the behaviour of the modified dummy before adopting it into regulatory use. With such structural alterations it is unlikely to be accepted without proof of consistency in performance with the unmodified Hybrid III, or detailed analysis of any performance modifications. This may require a reasonably large programme of test work.

From submarining sled testing using the THOR-alpha in the FID Project, van Don et al. (2003b) concluded that comparisons of the iliac crest force and lower abdomen compression results indicated that the iliac crest load cells could be used to determine whether or not submarining had occurred. Assuming that the Hybrid III iliac crest load cells were functionally similar, then it may be assumed that they could also be used to determine if submarining occurred. However, this would need to be validated before the iliac crest load cells were used in regulatory testing.

4.2.5.7 Femur and knee

Regulation 94 uses a Hybrid III axial force limit of 9.07 kN at 0 ms and 7.58 kN at
• 10 ms. Euro NCAP uses the Regulation 94 requirement as the lower performance limit for Hybrid III femur axial force and 3.8 kN as the higher performance limit. Neither of these are based on dummy-specific injury risk functions. Therefore, for these measurements to be appropriate and accurate, the assumption is made that the Hybrid III has a sufficient level of biofidelity. However, as reported in Section 4.2.2.5, the biofidelity of the Hybrid III is not perfect.

In the US, FMVSS 208 requires that the force transmitted axially through each upper leg shall not exceed 2,250 pound (~ 10 kN).

The injury Assessment Value for the knee is 15 mm of relative translation between the femur and tibia at the knee joint. This relates to a possible rupture of the posterior cruciate ligament of the knee joint, if the value is exceeded.

4.2.5.8 Lower leg, ankle and foot

A threshold of 4 kN of compressive load in the lower leg is used to indicate a risk of fracture. Also a combined bending and axial compressive loading criterion is used (the Tibia Index).

4.2.6 Other Issues Relating to Different Versions of Hybrid III

The thoracic biofidelity of the 5th percentile female Hybrid III dummy was evaluated in out-of-position tests with a driver’s airbag by Crandall et al. (1998). The dummy and seven small female PMHS were used in static out-of-position tests where the chest was placed in direct contact with the airbag module. Given the inherent variation in PMHS data, Crandall et al. concluded that the Hybrid III 5th percentile female provided a reasonable level of biofidelity in this loading condition.

According to Eppinger et al. (2000), DaimlerChrysler argued that the Hybrid III neck may be inadequate for accurately assessing the potential for flexion/extension neck injury due to airbag loading, based on test results with the 5th percentile female. NHTSA accepted that there may be some situations in which direct loading of the dummy's head causes the neck response to fall outside of the established moment-angle corridors. This can result in high neck extension and N_{ij} values.

Transport Canada compared the chest response biofidelity of the 5th percentile female Hybrid III between dummies produced by FTSS and Denton (Tylko et al., 2006). An initial finding was that the geometries of the torso jackets were different depending on which company had manufactured the dummy. Neither design met the drawing specifications of the intended jacket completely. Also the different jacket productions gave different chest responses when evaluated in component level and full-scale tests. In the crash tests the Denton and FTSS dummies exhibited differences in peak deflection of up to 11 mm. Prototype breast-less jackets were produced by Tylko et al. and were found to simplify the drawing specification, reduce confounding effects of the breasts and improve dimensional consistency.

The large (95th percentile) male Hybrid III dummy was evaluated by Shaw et al. (2007), using the proposed calibration and inspection tests for the dummy. Shaw et al. tested one dummy from each of the two manufacturers who produce large male Hybrid III dummies, subjecting each to six tests for each condition. Both dummies were found to have good to excellent repeatability and based on coefficients of variation the inter-dummy reproducibility was also excellent. However, Shaw et al. noticed differences in the timing of the responses from the two dummies with neck extension moment and knee impact measurements being significantly different. Shaw et al. also comment that the dummies did not meet the proposed certification requirements in all tests, but would comply if the requirements were changed slightly. Whilst this seems like a minor adjustment, it shows how the concept of scaling responses from one size of occupant to another is not a simple matter. It raises the question as to whether the dummy requirements (derived from scaling) or the dummy responses are the most suitable representation of a large human occupant.

The MAMA-2B (Maternal Anthropomorphic Measurement Apparatus, version 2B), the name given to the small female Hybrid III pregnant dummy as used to study the safety of a foetus and effects of seat belt and airbags, was evaluated and enhanced by Zhao et al. (2006). The testing by Zhao et al., with enhanced dummies, confirmed the same chest and abdominal performance as was seen with the dummy prototypes and provided the basis for thorax impact and hip range of motion test corridors.

4.2.7 Summary

In the past the Hybrid III has been applied successfully to improve car occupant protection. The Hybrid III is now the most widely used anthropometric test device for injury assessment. Currently it is used in the US regulation FMVSS 208, in Europe, and throughout many other regions of the world in the frontal impact test procedure (UNECE, R94). Nevertheless, both US and European regulatory bodies have recognised the need for further enhancements.

In frontal impacts there are several key aspects in the interaction between an occupant and the restraint system that a dummy should model. For instance: the interaction of the occupant knee-thigh-hip complex with the fascia, the engagement of the pelvis with the lap belt and seat base, and the interaction of the occupant's torso with the restraint system (in particular the diagonal part of the seat belt). The biofidelity of the dummy in these aspects is critical in representing living human occupants. In addition the dummy should be able to assess, through quantitative measurement, the risk of injury for the occupant. This requires both the correct interaction with the vehicle and appropriate instrumentation capabilities.

Particular areas of concern, which have already been highlighted, with the Hybrid III are:

- Head and face biofidelity and measurement capabilities
- Neck biofidelity
- Thorax biofidelity and measurement capability
- Abdomen biofidelity and measurement capability
- Lumbar spine biofidelity
- Pelvis anthropometry and sensitivity to submarining
- Leg biofidelity and measurement capabilities

Seemingly, of most importance are the insensitivity of the Hybrid III to abdominal loading, and thorax injury risk measurement, where the Hybrid III is very sensitive (in a non-humanlike manner) to differences in loading type. This is not surprising as the Hybrid III thorax was not designed to reproduce human thoracic response to the type of asymmetric strip loading applied by the shoulder belt.

These limitations in the biofidelity and injury prediction capability of the Hybrid III dummies, particularly with modern restraint systems, led NHTSA to initiate the development of a new front impact dummy. This brought about the development of the THOR.

It is possible that some design features from the THOR could be adopted in the Hybrid III (for example the abdominal instrumentation and the thoracic instrumentation) with some associated structural modifications to the dummy being required. By making changes of this magnitude, it may be considered that the dummy has been altered significantly from the already regulated form. Therefore, the new dummy performance would have to be proven experimentally. As such it is expected that substantial levels of performance testing would be required before such changes could be accepted into regulatory use. It is conceivable that this level of work may be similar to that required to approve the latest version of the THOR; therefore, it may be better to wait and make a whole dummy change to the THOR.

It is not known to exactly what extent the Hybrid III will be able or unable to deliver improved benefits in occupant protection in the future. This depends on a number of factors such as: the relative importance of general occupant loading and detailed restraint to occupant interactions, the injury risk functions and threshold levels set for use with the dummy, and the extent to which the dummy measurements are merely inaccurate or rather inappropriate for evaluating the performance of occupant restraint systems.

4.3 THOR

4.3.1 Introduction

The development of an advanced frontal impact dummy was initiated by the NHTSA in the early 1980s to address limitations in the performance of the Hybrid III, particularly with respect to the assessment of more advanced restraint systems (Haffner et al., 2001). The design of the dummy was informed by previous work on the OPAT dummy in the UK (by Ogle Design, TRL and MIRA), the ONSER dummy in France (EEVC WG12, 1996) and the TAD-50M (Trauma Assessment Device - 50th percentile Male) developed in the NHTSA Advanced Anthropomorphic Test Device (AATD) development programme

(Haffner et al., 2001), as well as new anthropometry information developed by UMTRI for the NHSTA (Robbins, 1983b; Schneider et al., 1985).

The TAD-50M developments were integrated with NHTSA-sponsored dummy neck and lower extremity developments to form the basis of a new advanced frontal impact dummy (Haffner et al., 1994) known as THOR (Test device for Human Occupant Restraint). The THOR dummy has been developed by GESAC Inc. under contract to the NHTSA, and has gone through a number of iterations, with the development and validation work currently on-going. A short summary of the development and evaluation process is given below.

The initial prototype THOR dummy was extensively assessed by groups from around the world, including NHTSA/VRTC in the US (Rangarajan et al., 1998), the EEVC co-ordinated ADRIA EC 4th Framework project (ADRIA, 1999), and JAMA/JARI in Japan. Information from more than 150 sled and 15 full-scale tests was used as input to a design update that became known as THOR-Alpha (Haffner, 2001). This included:

- Design issues (such as standardisation of fasteners, accelerometer noise in some channels, and lap belt entrapment in the pelvis-femur flesh interface);
- Durability issues (such as neck puck and spine articulation bonds, pelvis flesh and zipper)
- Handling issues (such as user manual, H-point tool and spine posture adjustment)
- Biofidelity issues (such as neck, shoulder and thoracic spine articulation)

The design updates to THOR-Alpha level are detailed in Haffner et al. (2001) and Artis et al. (2001) and version 1.1 of the THOR-Alpha dummy design was released in to the public domain in December 2001 (NHTSA, 2008). The THOR-Alpha dummy was again evaluated worldwide, including by the FID EC 5th Framework project (van Don et al., 2003a). Feedback from the many evaluation programmes, including that of the NHTSA, led the NHTSA and GESAC to update the dummy to THOR-NT status (NHTSA/GESAC, 2005; Shams et al., 2005; NHTSA, 2006) and this dummy was released in July 2005 (NHTSA, 2008).

In parallel with this development, as part of the FID EC project, FTSS produced a version of the THOR dummy specifically to meet the EEVC recommendations derived from the FID project (EEVC WG12, 2006), called THOR-FT. This has resulted in two different designs for THOR. In 2004, the Society of Automotive Engineers (SAE) in the USA set up a Task Force to assist in the development of a world harmonised THOR advanced front impact crash dummy. Many organisations, including the NHTSA and industry, academia and government organisations from around the world are contributing to developing a final version of the THOR dummy co-ordinated through the SAE Task Force.

The current THOR development status includes the following measurement capabilities:

- Head - Nine-axis accelerometer array; integrated head skin (no joints at the front of the head); five face load plates
- Neck - Upper and lower neck six-axis load cells; front and rear neck spring load cells; occipital condyle rotation potentiometer
- Mid-sternum, T1, T12 and pelvis accelerometers
- Four three-axis thorax compression sensors (CRUX units)
- One upper abdomen (single axis) and two lower abdomen (three-axis) compression sensors (Double Gimballed String Potentiometers - DGSPs)
- T12 five-axis load cell

- Two single axis iliac and two three-axis acetabular (femur neck) load cells
- Two six-axis femur load cells and two knee potentiometers
- THOR-Lx instrumentation (see below)
- Five two-axis tilt sensors in the head and spine

Further to the work on the 50th percentile male, a fifth percentile female version of the dummy was designed, developed and manufactured by GESAC funded by the NHTSA. The dummy anthropometry was derived from the UMTRI studies (Robbins, 1983a), the design requirements are given in Shams et al. (2003) and the dummy is described in McDonald et al. (2003). The THOR-5F dummy design is based on scaling the THOR-Alpha 50th percentile male dummy, with updates to the design including a new neck design, and new upper and lower abdomen designs. This dummy has not been released publicly at the time of writing (NHTSA, 2008).

Two advanced lower legs have also been developed by GESAC under contract to the NHTSA: the THOR-Lx 50th percentile male (Shams et al., 1999) and THOR-FLx 5th percentile female (Shams et al., 2002) lower legs. Both can be retrofitted to the relevant version of the Hybrid III dummy or used with the relevant THOR dummies. These parts include the following features and measurement capabilities:

- A spring-loaded representation of the Achilles tendon, designed to represent the passive resistance of the lower leg muscles to dorsiflexion
- A compliant tibia element designed to give the lower leg assembly the same axial force-compression characteristics as the human
- Three axes of rotation at the ankle, with offset axes for plantar-dorsiflexion and inversion-eversion similar to that found in the human ankle joint
- Upper and lower tibia load cells
- Achilles tension load cell
- Tibia and foot triaxial accelerometers
- Potentiometers for each ankle rotation axis

The discussion in the sections below focuses on the THOR-NT 50th percentile male dummy and THOR-Lx 50th percentile male lower leg where possible; however, the evaluation of the THOR-NT has been less extensive to date than previous evaluations of the THOR-Alpha so some comments relate to the Alpha version of the dummy. The performance of the THOR dummy is reviewed in absolute terms (e.g. relative to biofidelity or repeatability targets) and compared with the Hybrid III dummy.

Many published comparisons of the Hybrid III and THOR dummies compare the performance of the two and note differences, some also hypothesising why the performance differs, but they do not compare the dummies directly with baseline tests with a human. Direct comparisons between the dummies are useful for understanding the possible implications of changing from one dummy to the other within a legislative or other test procedure. At least, such comparisons confirm that the design of the car would be expected to change as a result of the change to the dummy, but do not directly identify whether the change would be beneficial to the safety performance of the car.

4.3.2 Basic Performance

4.3.2.1 Biofidelity

The biofidelity of the head, neck, thorax and abdomen of the THOR-NT was evaluated by Yaguchi et al. (2008) according to the biofidelity procedures of THOR. Only the head responses were within the PMHS corridors. However, Yaguchi et al. note that for the head, thorax and face, whilst the biofidelity and certification test procedures are quite similar the target response corridors do not overlap. Therefore it would not be possible to meet both sets of requirements at the same time.

As reported by van Don et al. (2003b), the biofidelity of the THOR-alpha neck was found to be close to, but not within, the requirements defined by van Don et al. (2003a). These are slightly different requirements to those derived for the Hybrid III (based on the work of Mertz and Patrick, and Partrick and Chou). Instead they use the biomechanical data from the NBDL (Naval BioDynamics Laboratory) in New Orleans. In relation to the NBDL-based requirements, the THOR neck performance has been shown to have greater biofidelity than the Hybrid III neck in frontal flexion (Hoofman et al., 1998). Comparison with a validated computational model of the living human head and neck was used by Dibb et al. (2006) to assess the performance of the Hybrid III and THOR-NT dummy necks in quasi-static tension-bending and pure bending. Dibb et al. found that the THOR was not as stiff as the Hybrid III but still substantially stiffer than the model. They commented that given the differences between the current THOR and the model, it is likely that some adjustment of the PMHS cervical spine tolerance values will be necessary before they can be used as THOR injury assessment reference values (IARVs).

Törnvall et al. (2005) found that the range of motion for the human shoulder complex during static loading was at least three times larger for the volunteers (at a maximum load of 200 N per arm) than that of the Hybrid III and the THOR-Alpha. Similar results were found with the THOR-NT, which led Törnvall et al. (2006) to develop a new shoulder design (THOR SD-1) which had the potential to function as a more human-like shoulder complex on the THOR dummy.

Vezin et al. (2002) reported on two series of sled tests with PMHS, the Hybrid III and the THOR-Alpha dummy. Each surrogate was tested three times at two conditions (50 km/h with 4 kN load limiter and airbag, and 30 km/h with a 4 kN load limiter, but no airbag), for a total of 18 tests. They found that the head, shoulder, thorax and pelvis response of the THOR was more similar to that of the PMHS than was the Hybrid III. By contrast, they reported that the improved T1 behaviour of THOR reported in the literature due to the flexible thorax joint was not obvious from their results.

Martinez et al. (2003) reported on the biofidelity and repeatability of the THOR-Alpha thorax, abdomen and femur, compared with the EEVC biofidelity requirements and NHTSA certification requirements. They found that the thorax was initially too soft compared with the PMHS corridor. Abdomen biofidelity was reasonable up to 70 mm of compression, after which the dummy abdomen bottomed-out against the spine and became far too stiff. The authors found the knee-femur impact response to be biofidelic with respect to the EEVC requirements.

The results of the EC fifth framework FID project’s review of the THOR-Alpha dummy were reported by Van Don et al. (2003a), which included the results from Vezin et al. (2002) and Maritnez et al. (2003). In addition to these results, the authors found the head response to be biofidelic, but the impact response of the face could be improved.

Petitjean et al. (2002) compared the chest responses of PMHS, Hybrid III, a modified Hybrid III with multi-point chest compression instrumentation, and the THOR-Alpha dummy. Each surrogate was tested in two restraint conditions: 4 kN seat-belt load limiter plus airbag; and 6 kN seat-belt load limiter only. The two restraint conditions were shown in a previous study to have a 16% and 55% risk of AIS 3+ injury for an 80 year-old driver, based on real-world accident data with both restraint configurations.

Existing legislative injury criteria (chest compression and V*C) did not discriminate between the restraint configurations and other proposed criteria (e.g. CTI) did not give a clear discrimination either. The Hybrid III with multi-point chest compression sensors and the THOR dummy both identified different loading patterns on the thorax from the two types of restraint system, and the THOR was found to be more sensitive in this respect.

THOR-Alpha abdomen stiffness was found to be too high and viscous response four times too low compared with PMHS (Trosseille et al., 2002). No comparative tests with Hybrid III were performed.

When compared against their knee/femur response corridor, Rupp et al. (2003) found the THOR knee and femur to be two to three times stiffer than the PMHS. However, this represented an improvement over the Hybrid III leg, which unlike the THOR or PMHS had a bilinear force-deflection response and was further from the stiffness shown by the PMHS response corridor than the THOR.

Petit and Trosseille [1999] commented on the limitations of dummy ankle designs which do not take muscle tension into account. The THOR-Lx addresses this limitation with a device to simulate the passive tension of dorsiflexion muscles. As a result the THOR responses to impacts directed to the ball of the foot were closer to PMHS responses than the Hybrid III, although it is not clear exactly what the design target should be for relaxed and tensed living human dorsiflexion.

Shaw et al. (2000; 2002a) undertook frontal impact sled tests with PMHS, THOR and a Hybrid III dummy with four-point chest compression instrumentation. The thorax of each surrogate was additionally instrumented with chestbands at the upper and lower thorax, which recorded the shape of the rib cage over time. The test configuration used a 1993 Ford Taurus buck, with energy absorbing steering column, adjustable knee bolster, three-point seat-belt with force limited retractor and buckle-side pretensioner, and a tethered airbag, appropriate to the vehicle model.

The Hybrid III recorded lap belt forces almost twice as high as the PMHS, while the THOR recorded slightly lower lap belt forces than the PMHS. The trajectory of the THOR upper spine (T1) was more similar to the PMHS than was the Hybrid III. THOR also showed a chest compression response that was much more like that of the PMHS than did the Hybrid III, based on both the external chest band measurements and the internal four-point compression measurements in each dummy. Both dummies exhibited lower head forward excursion than the PMHS. The authors hypothesised that because the THOR neck was designed to meet design targets that included volunteer neck responses, which include muscle tone and may therefore be stiffer than PMHS, the dummy response may be more biofidelic than indicated by the comparison with PMHS test results. Overall, the authors found that the THOR-Alpha was more biofidelic than the Hybrid III in the test conditions used. All dummy responses showed good repeatability for both dummies.

In agreement with the findings of Shaw et al., Kent et al. (2003c) also noted that the THOR chest displaced anteriorly at the lower right CRUx location in frontal and oblique sled tests. In contrast, the Hybrid III chest displaced posteriorly at all times and at all locations. Shaw et al. (2000) had reported that the bulging out of the lower portion of the THOR chest was also observed with PMHS and was therefore an improvement in biofidelity. In addition, Kent et al. observed that the Hybrid III chest displaced to the left (away from the shoulder belt anchorage) during testing, whereas the THOR chest motion was towards the right, where the greatest maximum deflection occurred. This was explained as being an artefact of the THOR having less thoracic coupling, while the Hybrid III sternum must move, essentially, as a single unit. It was not possible to say from comparison with PMHS test data which dummy response was more human-like. However, Kent et al. suggest that the flexible and geometrically more human-like THOR chest would be expected to show greater biofidelity than the Hybrid III.

In low-speed sled tests, Forman et al. (2006) noted that the degree of coupling between the upper and lower thorax of the Hybrid III deviated significantly from the PMHS response. The degree of coupling with the THOR was closer to that of the PMHS response.

Overall, the kinematics of THOR-Alpha are better than the Hybrid III (better rotation about the diagonal belt), but there is still scope for improvement compared with PMHS test results (Vezin, 2002).

Differences in the dynamic responses of the THOR-NT and FT dummies were investigated by Onda et al. [2006]. The comparisons between the dummies were based on a series of component tests and sled tests using an ordinary-size passenger body in white, at 56 km/h. Their study noted several differences in the THOR-NT and FT dummies. In particular, forward travel of the pelvis was significantly greater in the THOR-FT compared with the NT and Hybrid III. This was thought to have been due to differences in the shape of the dummy pelves. The design of the THOR-FT pelvis is shaped in a way that it encouraged compression of the abdomen by the seat-belt. According to Onda et al. this may have increased the displacement of the lower abdomen, affecting the dummy's behaviour.

4.3.2.2 Biofidelity of the THOR-Lx

The biofidelity of the standard Hybrid III lower leg, a modified Hybrid III with a foot and ankle developed by General Motors, and the prototype THOR-Lx was assessed by Wheeler et al. (2000). They compared the performance of the dummy parts with volunteer and PMHS test data, including impacts to the toe and heel. The prototype THOR-Lx was found to be more biofidelic and measured tibia axial force was more accurate than the other dummy parts, although further improvements were recommended for heel impacts. The fidelity of the measured forces would be important for accurate injury risk functions. The improved biofidelity and expanded injury assessment capability of the THOR-Lx was reported to make it a useful research tool for reducing the incidence of severely disabling injuries in frontal impacts.

Rudd et al. (1999, updated and revised in Rudd et al. 2000) reported on the biofidelity and response characteristics of the THOR-Lx prototype dummy lower extremity. They had performed several types of test on the THOR-Lx, including quasi-static ankle joint moment-angle determinations and dynamic dorsiflexion tests, and simulated toepan impacts (Rudd et al., 2000 only). The THOR-Lx results were compared with PMHS, the Hybrid III dummy lower extremity, and volunteer responses, where possible. Rudd et al. concluded that their results indicated that the THOR-Lx is an improvement over the Hybrid III dummy lower extremity. They report that design features that had limited the biofidelity of the Hybrid III lower extremity had been improved, and the THOR-Lx provided a more realistic representation of the human lower limb suitable for crash testing.

4.3.2.3 Repeatability and Reproducibility

Shaw (2000;2002a) found that both the THOR-Alpha and Hybrid III showed good repeatability for all dummy responses in sled tests with three-point seat belt, load limiter, pretensioner and airbag (see Section 4.3.2.1 for a description of the test configuration).

Rangarajan et al. (1998) reported various test series undertaken at Volvo Car Corporation, Sweden and Autoliv Research, Sweden using the Hybrid III and prototype THOR dummies in sled tests with various restraint conditions. In limited repeatability testing (three tests with each dummy), they found that the results indicated a better repeatability for the THOR prototype than the Hybrid III, with the exception of upper neck tension (Fz). However, Xu et al. (2000) found the THOR to be less repeatable in tests involving pendulum impacts to the chest than the Hybrid III, although the two dummies showed the same level of repeatability in rear impact tests.

Vezin et al. (2002) found good test-to-test repeatability for both the Hybrid III and THOR dummies (see Section 4.3.2.1 for a description of the test configuration). Both dummies also showed a reasonable level of repeatability (five to ten percent) in the HYGE sled tests reported by Masuda et al. (2008).

The global repeatability of the THOR-Lx was found to be acceptable by Petit and Trosseille (1999).

Shaw et al. (2002b) compared the response and repeatability of the THOR-Lx retrofitted to a Hybrid III with the response of the standard Hybrid III leg. Both dummy parts showed acceptable repeatability in sled tests, with a coefficient of variation generally less than 10% for both. Upper body movement and injury criteria values for the head and thorax also showed acceptable consistency with the THOR-Lx retrofit lower leg and were reported to be generally indistinguishable from those in tests with the standard Hybrid III lower leg.

4.3.3 Handling

Ten pendulum tests with the THOR head-neck system had been planned by Hoofman et al. (1998). During the sixth test, the neck was so badly damaged that further testing was impossible, therefore they could draw no conclusion about the repeatability of the THOR neck.

In impactor and belt component tests with the THOR-Alpha, Maritnez et al. (2003) had to reject six out of eight upper abdomen test results due to durability problems and had numerous thorax component failures. These made it impossible to assess the repeatability of the dummy.

Van Don et al. (2003a) reported that durability of the THOR-Alpha was too poor to allow repeatability and reproducibility to be assessed for most body regions. In particular, neck debonding in component and sled tests, thorax and abdomen component failures, and lumbar spine failures were reported. In addition, it was found that the chest compression measurement sensors (CRUX units) were easily damaged, but that such damage was difficult or impossible to detect without dismantling the dummy and removing the sensors. Similar problems were found with the lower abdomen compression sensors (DGSPs) and it was recommended that the thorax and abdomen compression sensors should be reviewed. The THOR-Lx was found to be generally robust if used in conditions similar to real frontal impacts.

Conversely Xu et al. (2000) found that ‘no major durability problems were identified in the THOR.’ However, in addition they commented that because the THOR is more complex than the Hybrid III it is harder to use and handle; although this was based on testing with an early version of the THOR. They reported that:

“In order for the THOR to be as easy to use as the Hybrid III, greater effort is needed to improve convenience in terms of data processing, documentation and handling (Xu et al., 2000).”

In 2006, handling had not been improved substantially. Onda et al. (2006) reported that due to improved biofidelity and measuring function the dummy structure has become more complex making it less easy to handle and maintain than the Hybrid III.

Rudd et al. (2003) reported on sled tests comparing the THOR-Lx and the Hybrid III lower leg responses with and without toepan intrusion. Both lower legs were attached to a standard Hybrid III 50th percentile male dummy. They reported that the increased biofidelity and measurement capabilities of the THOR-Lx did not lead to increased difficulty of use. Durability was not a concern for either dummy leg design, although recommendations for improvements were made. The THOR-Lx was found to provide a more thorough and conservative assessment of lower leg injury risk compared with the Hybrid III lower leg.

4.3.4 Design issues

The THOR neck was designed to be a more accurate representation of the human neck than had been seen in previous dummies. In addition to a traditional flexible rubber and metal neck column, the neck incorporates external cables running from the head to the torso both in anterior and posterior positions. Within the FID Project these cables were identified as an uninstrumented load path in the neck which has not been completely eliminated in the THOR-NT design. The two cables in the THOR neck allow load to be transmitted from the head to the torso without being measured at the neck load cells. In the revised THOR-NT design a load cell can be added to measure the force being transmitted through the neck cables. However, because of the neck cable installation, which involves a number of controlling pulleys, substantial underestimates of this force can occur.

Deguchi et al. (2007) found that the THOR-FT exhibited greater rotation about the seat-belt than the Hybrid III, and the shoulder belt tended to slip off the shoulder of the dummy in an oblique frontal impact. This has implications for seat-belt restraint design, although it should be noted that the paper did not compare the dummies directly with human performance data. This rotation about the diagonal belt has been reported by other authors to be an improvement in biofidelity (e.g. Vezin et al., 2002).

According to Kent et al. (2003c), based on their series of sled tests, the Hybrid III and THOR dummies were both insensitive to the change in collision angle (for 0° to 30°); although the two dummies exhibited different responses in the tests. Equivalent PMHS tests at up to 30° collision angle indicated very similar rib fracture patterns, which was used to support the assertion that the thoracic loading environment does not change substantially up to 30° for belted occupants in frontal oblique impacts.

Maritnez et al. (2003) found that the abdomen compression and force measurements were highly sensitive to the location of impact and the actual response may be underestimated if the impact is not aligned well with the sensors.

In the sled tests reported by Masuda et al. (2008) the sensitivities of the THOR-NT and Hybrid III to seating position were evaluated. Masuda et al. found that in general the kinematics and responses of the two dummies were similar in the UMTRI and standard seat positions (the UMTRI position put the seat 45 mm rearward and 18 mm higher than the standard, mid, position). However, they observed large differences in kinematics and responses for the lower legs. According to the authors these differences were caused by the differences in the stiffness (biofidelity) of the tibia and foot, the different shapes (anthropometry) of the femur and tibia and the differences in seating positions between the standard and the UMTRI positions.

When conducting comparative sled tests with PMHS, a Hybrid III and a THOR, Forman et al. (2006) noted that because of its greater hip-to-knee length, the knees of the THOR-NT were positioned closer to the instrument panel than either the PMHS or the Hybrid III (by about 30 to 40 mm). In contrast to the PMHS and Hybrid III, the THOR-NT knees experienced substantial interaction with the instrument panel, causing higher femur compression forces, and differences in the acceleration of the pelvis and lower thorax.

A hydraulic test set-up was developed by Uriot et al. (2006) to investigate belt-to-pelvis interaction of the THOR-NT, Hybrid III and PMHS. The pelves of the dummies and PMHS were rigidly fixed onto the test frame and lap belt tension was applied, and a dynamic rotation of the belt anchorages was then imposed. The pelvis angle at which submarining occurred was found to be smallest for the PMHS, then the Hybrid III (24° higher than the PMHS or 42° when transferred to a seated coordinate system) and largest for the THOR-NT (41° higher than the PMHS, or 44° after transformation to a seated coordinate system). The geometry of the pelvis was assumed to be responsible for this difference, at least in part. Uriot et al. also noted that the dummy pelves were stiffer than the PMHS.

Petit and Trosseille (1999) found the THOR-Lx to have a very low sensitivity to the foot dorsiflexion angular velocity. They suggested some amendments to the design (change in the moment arm of the Achilles tendon and modification of the ankle stop to have greater biofidelity) which may have helped resolve this to a certain extent.

More recently, Olson et al. (2007) conducted laboratory testing to compare the Hybrid III and THOR-Lx lower extremities. Linear impactor component tests and full-scale offset and full-width frontal barrier crashes comprised the testing. Whilst they found that the Hybrid III and THOR-Lx designs showed different results in the component tests, Olson et al. concluded that those differences were masked in full-scale tests. They found no statistical difference in the axial upper tibia force between the Hybrid III and THOR-Lx which was expected due to the compliant element in the THOR-Lx tibia. However, because the THOR-Lx ankle reaches its joint stop quicker than the Hybrid III ankle, greater axial force values were measured at the THOR-Lx lower tibia than with the Hybrid III lower extremity.

4.3.5 Injury Prediction

Within the APROSYS Project, the injury risk functions available for use with the THOR dummy were reviewed. (APROSYS 2008 Deliverable 1.2.1). It should be noted that all of these injury risk functions are preliminary and have no official sanction. Many are based on the performance of older versions of the dummy and are indicative only; they were used to compare the performance of the THOR-NT with the Hybrid III in full-scale car crash and sled tests.

In most cases, injury risk functions that were specific to the THOR-NT were not available. For the thorax and abdomen, NT-specific injury criteria are needed, but existing data (THOR-prototype and human data for the thorax and abdomen respectively) could be used as an interim measure for guidance. Table 4.1 shows a summary of the tentative injury criteria for use with the THOR-NT.

Table 4.1: Summary of tentative injury criteria for use with the THOR-NT

Body region	Injury criterion	Suggested injury risk function	Notes
Head	Resultant linear head acceleration	Existing Hybrid III thresholds for HIC and peak resultant acceleration	THOR-NT and Hybrid III head biofidelity response is equivalent
Neck	No THOR-NT specific injury risk functions	Not possible to compare THOR-NT and Hybrid III at this time - monitor all load cell channels and neck angle	Neck structures too different to compare THOR-NT and Hybrid III directly
Thorax	Thorax compression	Use ADRIA THOR-Prototype injury risk function AS A FIRST APPROXIMATION	Thorax response of THOR-NT somewhat different to THOR-Prototype
	Thorax V*C	Use ADRIA THOR-Prototype injury risk function AS A FIRST APPROXIMATION	Thorax response of THOR-NT somewhat different to THOR-Prototype
Abdomen	Upper abdomen compression	Monitor upper abdomen compression; < 80 mm unlikely to cause serious injury (AIS 3+)	No THOR-NT specific injury risk function
	Lower abdomen compression	Monitor upper abdomen compression; < 70 mm unlikely to cause serious injury (AIS 3+)	No THOR-NT specific injury risk function
	Upper and lower abdomen V*C	Monitor V*C; < 1.2 OK at ~5 to 9 $m.s^{-1}$	No THOR-NT specific injury risk function
Femur	Femur axial force	THOR-NT not directly compatible with Hybrid III	THOR-NT more biofidelic and less stiff than Hybrid III; THOR-NT specific risk function required
Lower leg	Tibia axial force	Hynd et al. (2003)	THOR-Lx specific injury risk function
	Dorsiflexion moment and angle	Rudd et al. (2004)	THOR-Lx specific injury risk function

4.3.6 Summary

The THOR biofidelity appears to offer an improvement compared with that of the Hybrid III, although there is still scope for further improvements in biofidelity and performance. Not much information has been published on repeatability and reproducibility with the THOR (often due to difficulties with durability). Where repeatability and reproducibility information has been published, the THOR is reported to be as good as, or better than, the Hybrid III.

As such, the THOR represents a promising option for the future and remains a good candidate to replace the Hybrid III dummy worldwide in future frontal impact test procedures. However, the dummy is still being assessed and updated within the SAE THOR Task Group and a final, agreed version of the dummy is likely to be a minimum of several years' away, and several years' further work to validate the dummy and develop dummy-specific injury risk functions may also be required.

4.4 Conclusions and Recommendations

The Hybrid III was developed in 1976 and has been the most advanced frontal impact dummy, ready for regulatory use, for many years. Use of two 50th percentile Hybrid III dummies, is currently specified in the UNECE frontal impact regulation (Regulation 94), U.S. FMVSSs, and in consumer testing around the world. Limitations in the biofidelity and injury prediction capability of the Hybrid III dummy have been established in the research literature and are acknowledged widely. Therefore, to address these limitations, NHTSA commissioned the THOR (Test device for Human Occupant Restraint) as the next generation of advanced frontal impact dummy.

Initial prototypes of the THOR have been evaluated since the late 1990s and early 2000s. Evidence on the performance of the THOR prototypes, often in comparison with the Hybrid III, has been published by authors throughout the world. In general it is agreed that the THOR does represent a substantial improvement in biofidelity and offers greater injury measurement capabilities than the Hybrid III, noting that there is still some room for improvement. However, some issues with the design of the THOR remain areas of concern for the implementation of the dummy in regulations.

- Some groups have reported durability problems with the THOR dummies (e.g. van Don et al., 2003a), to the extent that it was difficult to assess repeatability of the dummy. Other groups have reported good repeatability of THOR dummy measurements and kinematics.
- Different versions of THOR have arisen from the dummy manufacturers GESAC and FTSS. Whilst efforts have been made to harmonise designs, the exact status of progress is unknown to the authors at this time. For the THOR dummy to be specified in a regulation, it is of critical importance that one single design can be identified. Therefore design differences must be resolved.
- The SAE THOR Task Group is currently assessing and updating the THOR dummy design, but a final version of the dummy is not likely to be available before 2011, and agreed injury risk functions may not be available until after that date.

Based on the literature reviewed for this study, it is clear that the biofidelity and injury assessment capability of the Hybrid III dummy is insufficient to drive the development of advanced restraint systems suitable to protect all vehicle occupants in a range of crash configurations. At its current design level, the THOR dummy has resolved some of these issues. However, the THOR is not yet at a design status which could be implemented in a regulation (and it is unlikely to reach such a status for a number of years). Therefore the recommendation for the most suitable frontal impact dummy to be used in frontal impact regulatory testing will depend upon the timescale for the regulation to become effective. If a short timescale is set, then there appears to be no option but to recommend the continued use of the Hybrid III family of dummies. However, if a longer timescale is more likely, then the THOR should offer the regulator additional biofidelity and injury measurement capabilities.

As an interim measure, it may useful to consider incorporating the THOR-Lx, and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy. NHTSA are currently developing an offset deformable barrier test. One of the principal justifications for this test is the reduction of high cost, high frequency lower extremity injury. The review of accident analysis data also suggested that the additional assessment of lower extremity risk may be beneficial in full width test procedures because approximately half of lower extremity injuries were in full-width impacts, although the review does not demonstrate whether the THOR-Lx (or Hybrid III retrofit) would be effective for that purpose, in such a test procedure. Recent testing by Olson et al. (2007) suggests that only marginal differences can be observed between full-scale testing with either the THOR-Lx or original Hybrid III lower extremities. Agreed injury risk functions are also not available for all of the injury assessment measurements in the THOR-Lx and femur, and these parts are undergoing further assessment and review within the SAE THOR Task Group.

5 Proposed Test Procedures and Identification of Potential Options to Change Legislation

Passive safety equipment operates well under idealised crash test conditions. However, the behaviour of car structures and safety systems during real world conditions is not always directly comparable with crash-tested behaviour, especially in car-to-car crashes. In response to this, much research work has been performed as to how a vehicle's frontal impact protection can be improved further. This research has focused mainly on developing test procedures to improve compatibility in vehicle-to-vehicle impacts. Compatibility describes the ability of a vehicle to protect its own occupants (self protection) and its ability to minimise the occupant injury in the vehicle which it strikes (partner protection).

In Europe the focus has been on developing test procedures to improve compatibility in car-to-car impacts where a car is defined as an M1 vehicle with a mass less than 2.5 tonnes. However, in the USA and Canada, because of the difference in the vehicle fleet composition, namely the large proportion of Light Trucks and Vans (LTVs), the research has focused on LTV-to-car impacts with the objective of developing procedures to assess and control the aggressivity of the LTV in these impacts.

The main objective of this part of the study is to review potential new and modified test procedures for frontal impact testing and associated proposals and identify possible options for how future legislation may be improved. These options will be reviewed later in the report to provide recommendations for the way forward, which can be used to contribute to the review of Regulation 94 that is being conducted currently under GRSP. It should be noted that the focus of this part of the study is therefore on the identification of options for possible consideration in this review.

To achieve this objective, this chapter firstly describes strategies of how future legislation may be improved. It then summarises the recommendations from the review of the Directive made by EEVC in 2000 (EEVC 2000). After this, it describes potential test procedures which could be used to modify future legislation. This description includes detail on the test procedure as well as a discussion of how the test may be incorporated into future legislation highlighting the possible advantages and disadvantages. Following this, a list of possible options for the improvement of future legislation is given. This list also includes options for changes to the dummy test tool identified in section 4.

5.1 Strategies to modify future legislation

In the past ten years a number of strategies of how to modify future legislation for frontal impact have been proposed. The main ones have been made by international working groups, namely the International Harmonisation of Research Activities (IHRA) compatibility and frontal impact working group and the European Enhanced Vehicle-safety Committee (EEVC) Working Group 15 (compatibility and frontal impact). The purpose of these groups was to co-ordinate compatibility research world-wide and within Europe, respectively. It should be noted that IHRA stopped its activities in 2005 and EEVC WG15 activities have been on hold since May 2007, although it is expected that they will resume in the near future.

In 2001, to help harmonise regulation, the IHRA frontal impact working group recommended the adoption of offset deformable barrier and full width tests worldwide (Lomonaco and Giamotti, 2001). The reasons given for this recommendation were as follows:

- A full width test is required to provide a high deceleration pulse to control the occupant's deceleration and check that the vehicle's restraint system provides sufficient protection at high deceleration levels.

- An offset test is required to load one side of the front of a vehicle to check compartment integrity, i.e. that the vehicle can absorb the impact energy in one side of its frontal structure without significant compartment intrusion. The offset test also provides a softer deceleration pulse than the full width test which checks that the restraint system provides good protection for a range of pulses and is not over-optimised to one pulse.

In 2007, EEVC WG15 published a strategy and a route map to develop test procedures to modify future legislation (Faerber, 2007). This strategy states that to assess a car's frontal impact performance, including its compatibility, an integrated set of test procedures is required. The set of test procedures should assess both the car's partner and self protection. To minimise the burden of change to the automotive industry the set of procedures should contain as few procedures as possible which ideally are based on current regulatory tests and harmonised internationally. Above all, the procedures and associated performance limits should ensure that the current self protection levels are not decreased. Indeed, if possible, for light vehicles they should be increased. Good self protection is required for cars involved in impacts with other cars, and for all vehicles involved in impacts with road side obstacles.

EEVC WG15 incorporated the recommendation given by IHRA into their strategy and stated that the set of test procedures should contain both a full overlap test and an offset (partial overlap) test, because both of these tests are required to assess a car's frontal impact crash performance fully.

Also the strategy stated that compatibility is a complex issue which consists of three major aspects, structural interaction, frontal force matching and compartment strength. Structural interaction is relevant for all frontal impacts and describes how well vehicles interact with their impact partner, either another vehicle or a road-side obstacle. If the structural interaction is poor, the energy absorbing front structures of the vehicle may not function as efficiently as designed, leading to an increased risk of compartment intrusion at lower than designed impact severities and a less optimum (more back-loaded) compartment deceleration pulse. Also, 'triggering' of the restraint system may be less effective due to a less predictable crash pulse. Examples of poor structural interaction are override and the fork effect. A vehicle's frontal force levels are related to its mass. In general, heavier vehicles have higher force levels as a result of the current test procedures and manufacturer's desire to keep crush space to a minimum. As a consequence, in a collision between a light vehicle and a heavy vehicle, the light vehicle absorbs more than its share of the impact energy as it is unable to deform the heavier vehicle at the higher force level required. Matched frontal force levels would ensure that both vehicles absorb their share of the kinetic energy, which would reduce the risk of injury for the occupant in the lighter vehicle. Compartment strength is an important factor for self-protection, especially for light vehicles. In the event where vehicle front structures do not absorb the impact energy as designed the compartment strength needs to be sufficiently high to ensure minimal compartment intrusion. Beyond this, there is scope for better optimisation of the car's deceleration pulse to minimise restraint induced deceleration injuries.

To make vehicles more compatible, substantial design changes will be needed which will require some years to implement. This means that the set of test procedures need to be designed so that compatibility requirements can be introduced in a stepwise manner over a number of years. The EEVC WG15 route map, shown below, proposed that compatibility should be introduced in at least two steps:

- Short term
    - Improve structural interaction
    - Ensure that force mismatch (stiffness) does not increase and compartment strength does not decrease from current levels.
- Medium term

  - Improve compartment strength, especially for light vehicles
  - Take first steps to improve frontal force matching
  - Further improve structural interaction

In the EEVC WG15 report to the EEVC steering committee (EEVC WG15, 2007), the route map was re-evaluated and some changes were made. These were that increasing the compartment strength of light cars should be considered as a short term instead of a medium term priority and that possibly the issues of structural interaction and frontal force levels should not be separated but addressed in parallel.

In addition, it was recommended that the test speed of the UNECE R94 test must not be raised to 60 km/h without modification of the test procedure because of the risk that this may increase the current frontal force mismatch between vehicles of different mass. It should be noted that in Euro NCAP the most popular model is tested in contrast to regulation in which the worst case is tested (which is generally the heaviest model with the largest engine size). Because of this, increasing the R94 test speed would still have an effect on the vehicle's frontal force levels even though the Euro NCAP test speed is 64 km/h.

In summary the latest EEVC WG15 strategy aims are:

- To have an integrated set of test procedures to assess a car's frontal impact protection. This would:
  - Assess and control a car's partner and self protection without decreasing its current self protection levels
  - Involve the minimum number of procedures
  - Allow for internationally harmonised procedures
- Both full width and offset tests required
  - Full width test to provide high deceleration pulse to assess the occupant's deceleration and restraint system
  - Offset test to load one side of car for compartment integrity
- Procedures designed so that compatibility can be implemented in a stepwise manner

5.2 EEVC review of Frontal Impact Directive 96/79/EC

When the EC Frontal and Side Impact Directives were published, they included the requirement to review certain technical aspects, within two years of their implementation date (1 October 1998). The European Commission invited EEVC to help perform this review. Therefore the EEVC performed a research programme to review the following technical issues for the frontal impact Directive:

- Test speed,
- Extension of scope to N1 vehicles
- Measurement of footwell intrusion
- Consideration of a biomechanical alternative to the steering wheel movement requirement

As a result of this work EEVC made the following recommendations in 2000 (EEVC, 2000). It should be noted that none of the changes which were recommended have been adopted in the Directive.

Increase in test speed

The accident analysis indicated that the test speed which would include 25% of fatal injuries in frontal impacts was about 42 km/h in the Swedish data, 77 km/h for Germany and 64 km/h for the UK. For 50% of the MAIS • 3 injuries, the test speeds were about 46 km/h for Sweden, 66 km/h for Germany and 64 km/h for the UK. It was noted by the EEVC that, for the Swedish data, based on Volvo cars, the average age of the occupants was more than ten years older than for the German and UK data, which might help to explain the differences observed. Taking this into account led the majority of the EEVC Working Group (WG) members to conclude that the test speed should be increased to include a significant range of the serious and fatal injury cases (as was described in the original EEVC proposal).

According to the EEVC at the time, a more detailed breakdown of the injury distribution (see Wykes, 1998) into contact-associated injuries and acceleration-based injuries suggested that an increase in speed would not result in car design that would give an overall increase in injuries due to an increase in the overall stiffness of cars.

Comparative tests at 50 km/h, of two cars with differing performance at 64 km/h in the Euro NCAP test indicated that the better performing car at the higher speed also performed best at the lower speed. This confirmed that good performance at 64 km/h did not necessarily result in stiffer cars that would perform worse at lower speeds. However, the EEVC noted that this was only one comparison and it would be advantageous to undertake a larger but limited test programme to determine whether it is generally the case that a good performance at the Euro NCAP speed was not necessarily associated with increased stiffness.

While the accident analysis described by the EEVC had been used to suggest that the speed should be increased to perhaps 65 km/h, concerns by some EEVC experts regarding compatibility had led to the recommendation to increase the speed, initially, to 60 km/h until there was a better understanding of compatibility. It was recommended by the EEVC that this should be reviewed again when more was known about the likely influence of compatibility.

Extension to N1 vehicles (and passenger vehicles with up to nine seats)

Accident analysis showed that N1 vehicles were involved in similar accidents to M1 vehicles. The accident type and exposure were similar. However, the EEVC noted some concern regarding the aggressivity of the heavier N1 vehicles. Consequently the EEVC did not recommend the application of the Directive to vehicles above 2.5 tonnes total permissible mass until there was a better understanding of the influence that this would have on the compatibility of these vehicles.

Nearly all of the N1 vehicles in the mass range below 2.5 tonnes were based on car designs. An analysis of the vehicle type and structure indicated that application of the test procedures for car-derivative N1 vehicles should pose few problems. Therefore the EEVC recommended extending the scope to N1 vehicles below 2.5 tonnes at the same test speed as that used for M1 vehicles until a test requirement for compatibility was developed and implemented.

The EEVC also commented on the need for a research study on the application of the test procedure to N1 vehicles between 2.5 and 3.5 tonnes before the EEVC could comment on the extension to this category.

Similar concerns regarding the application of the test procedure to M1 vehicles greater than 2.5 tonnes maximum permissible mass were raised. Therefore, as for N1 vehicles above 2.5 tonnes, the EEVC did not recommend extending the scope to M1 vehicles above 2.5 tonnes, even at the current test speed; until a requirement for compatibility was developed and implemented.

Review of all existing performance requirements and the addition of new requirements relating to footwell intrusion

The EEVC confirmed that the criteria originally proposed and adopted for use in the Directive remained the best available at the time and addressed, as far as possible with the current dummy, the injury patterns seen in the accident analysis. The EEVC concluded that there was an urgent need for more biomechanical research and for the development of improved dummies.

The EEVC was developing a proposal for a criterion on intrusion in the footwell and a method for the reliable and consistent measurement of this intrusion. The current draft method was subject to further development and assessment.

Possible replacement of steering wheel movement criterion with a biomechanical requirement

A review of Euro NCAP test results, analysed for application of the Euro NCAP modifiers, showed that there was a need for an additional lateral displacement criterion of 100 mm. Therefore, the EEVC recommended the retention of the existing geometrical requirements and the addition of a lateral displacement limit of 100 mm.

Additional comments

In a previous report the EEVC concluded that the Regulation should include a requirement for manufacturers to demonstrate that a mechanism was provided to ensure that fuel pumps were switched off at impact or when the engine stopped. They suggested that it was appropriate to include additional requirements for fuel system integrity in the ODB test.

Following the report from the EEVC, the European Transport Safety Council (ETSC, 2001) published their priorities for EU motor vehicle safety design. This review was carried out by ETSC's Road Vehicle Safety Working Party which brought together a multi-disciplinary group of safety experts from across the European Union.

The priorities listed were said to comprise those measures which offered the greatest opportunities for large reductions in casualties in the short to medium term with due account being taken of the state of the art research and development in each case.

The relevant top priorities for legislation were:

- Improved offset frontal impact test, extended to cover additional vehicle types
- Universal ISOFix child restraint anchorages with an effective third restraint
- High deceleration frontal crash test for restraint system assessment

As one of the top priorities for consumer information was:

- Incorporation of a high deceleration frontal impact test in Euro NCAP

In the summary of conclusions and recommendations within the report, clear similarities can be seen with the recommendations from the EEVC, made in the previous year.

With regard to improving EU frontal impact protection requirements the following points were made:

- The test speed for the frontal impact test should be raised to 64 or 65 km/h (EEVC had recommended 60 km/h)

    - This was based on the experience in Euro NCAP, which had shown that testing at 64 km/h was having a beneficial effect on compatibility; increasing the stiffness of small cars much more than that of large cars and hence improving force matching.

- The frontal impact Directive should be extended to cover N1 vehicles up to 2.5 tonnes, M1 vehicles above 2.5 tonnes and M2 vehicles
    - This recommendation was made on the basis that the extension to larger M1 cars and M2 vehicles could be justified on the grounds of protecting their occupants but could be opposed on the grounds that they may become more aggressive to other car occupants. However, in practice testing these vehicles should bring about some improvement in their aggressivity because it should encourage frontal structures to become better connected.
- A requirement to limit the lateral displacement of the steering column to 80 mm should be added to the existing vertical and horizontal requirements
- All the current injury criteria need to be maintained
- When available, consideration should be given to using an improved dummy with improved criteria for the lower legs
- Research is needed to develop criteria and instrumentation to assess the risk of injury to the abdomen and knees
- The recommended limit on footwell intrusion recommended by the EEVC should be adopted with a requirement for its review in the light of further accident experience
- For the present time the current design of deformable barrier face should be retained
- An additional full frontal high deceleration crash test is required to provide a better test of restraint protection

With regard to reducing injuries through contact with the car interior another two salient points were made:

- Footwell intrusion requirements need to be added to the Frontal Impact Directive
- Improved injury protection criteria need to be developed for use with improved dummy lower limbs

Some of the points arising from the ETSC accident analysis are summarised below:

- There were differences in the nature of the collision partner between the UK CCIS data and that from the Medical University of Hannover, Germany. Of UK fatalities, 41% died in collisions with other cars compared with only 25% in Germany. In contrast 50% of German fatalities died in collisions with poles or trees compared with only 12% in the UK. These data were for all car impact configurations (front, side rear and so forth).
- Even when intrusion is prevented and the restraint system works well, there is still a high likelihood that the occupants' knees will impact the fascia. Until the introduction of Euro NCAP, little or no attention had been paid to the safety of the knee impact area, other than at the specific locations where the dummies' knees impact. Significant hazards continue to exist for the knees themselves and for the upper legs and hip joints.
- Loading of the feet and ankles by the footwell and pedal is inevitable in frontal impacts. Although injuries below the knees are rarely life-threatening, disabling

injuries often result. Improvements to dummies, biomechanical requirements and the cars themselves are all required.

- The head continues to be the highest priority for protection against life-threatening injury. Although airbags can do much to help, currently they cannot prevent contact with the car's interior in all circumstances. Angled frontal impacts present considerable head injury risk because restraint and airbag systems are optimised for forward impact and may not prevent contact with parts of the car such as the windscreen pillar. There is a need to ensure that those interior surfaces that can be impacted by the head are correctly padded.

5.3 Potential new and modified test procedures

In Europe, the research work has focused on the development of test procedures to assess and control a car's frontal impact and compatibility performance, namely the Progressive Deformable Barrier (PDB) test procedure and the Full Width Deformable Barrier (FWDB) test procedure. This development work has been undertaken mainly by national governments and the EC through framework projects. The EEVC WG15 has helped to co-ordinate these activities (EEVC, WG15 2007). Also, in Europe some initial effort has been directed at the development of a Mobile Barrier test which uses the PDB (Schram and Versmissen, 2007).

As part of its remit to develop candidate test procedures to assess a car's frontal impact and compatibility, EEVC WG15 has proposed two potential candidate sets of test procedures in line with the strategies discussed above (EEVC WG15 2007). The sets of procedures are:

<u>Set 1</u>

- Full Width Deformable Barrier (FWDB) test
    - To provide a high deceleration pulse to test the restraint system
    - To assess structural interaction potential
- Offset Deformable Barrier (ODB) test as in UNECE Regulation 94
    - To load one side of the car to check its compartment integrity
    - To asses frontal force levels
    - To provide a softer deceleration pulse than the full width test to check the restraint system performs over a range of decelerations

<u>Set 2</u>

- Full Width Rigid Barrier (FWRB) test
    - To provide a high deceleration pulse to test the restraint system
- Progressive Deformable Barrier (PDB) test
    - To load one side of the car to check its compartment integrity
    - To assess structural interaction potential
    - To asses frontal force levels
    - To provide a softer deceleration pulse than the full width test to check the restraint system performs over a range of decelerations

EEVC WG15 has also stated that a possible alternative set of procedures could be an FWDB test coupled with a PDB test. However, they have not performed any work to investigate this proposal.

At the GRSP meeting in December 2007, France proposed an amendment to UNECE Regulation 94. In summary this proposal was for the current Offset Deformable Barrier

(ODB) test be replaced with the PDB test (GRSP 2007). EEVC WG15 has not performed any specific work to investigate this proposal.

In the USA, research work performed by the National Highway Traffic Safety Administration (NHTSA) has focused on the development of procedures to assess and control the compatibility of Light Trucks and Vans (LTVs) for impacts with cars because this is the major compatibility problem in the USA. Recently, this research work has concentrated on short term solutions and hence the modification of existing test procedures to incorporate compatibility measures, namely a full width rigid wall test with Load Cell Wall (LCW) measurements and an associated override barrier test (ORB) (Patel et al., 2007). Also, NHTSA has performed some joint work with France to investigate the possibility of using the PDB for improved frontal impact test procedures in the USA (Delannoy et al., 2007).

The Enhanced Vehicle Compatibility (EVC) technical working group in the USA have also performed research work to improve the compatibility of LTVs for impacts with cars. One of the results of this work is a voluntary standard which controls the geometry and strength of an LTV's frontal structure (Barbat 2005) and (Verma 2007). The following Phase I requirements, which were announced on 3rd December 2003, were developed as a first step towards improving geometrical compatibility between LTVs and passenger cars. Participating manufacturers will design LTVs in accordance with one of the following two geometric alignment alternatives, with the LTV at unloaded vehicle weight:

> OPTION 1: The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone AND at least 50 percent of the light truck's primary frontal energy-absorbing structure shall overlap the Part 581 zone (if the primary frontal energy-absorbing structure of the light truck is greater than 8 inches tall, engagement with the entire Part 581 zone is required).
>
> Note: The Part 581 zone extends from 16 inches to 20 inches above the ground and cars have their primary energy absorbing structures based on this specification.
>
> 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. This secondary structure shall withstand a load of at least 100 kN exerted by a loading device, before this loading device travels 400 mm as measured from a vertical plane at the forward-most point of the significant structure of the vehicle. This test of the SEAS was proposed as a quasi-static push test to show that the SEAS could resist 100kN loading within 400mm of the front of the rails.

NTHSA have indicated that this standard is probably not suitable for introduction into legislation because it is design based rather than performance based, i.e. it controls the height of the LTV's main frontal structure using a geometric requirement as opposed to a performance requirement such as achieving a minimum load in specified rows on a Load Cell Wall in a crash test. Partly in response to this and to improve LTV to car compatibility further, the EVC technical working group have performed additional work to develop further test procedures, which include a FWDB test approach, CAE based evaluations of LTV to car impacts and development of a car surrogate mobile deformable barrier as a test device (Verma 2007). However, it should be noted that the geometric approach described by EVC is very similar to the methods used in European directives to control the compatibility of heavy trucks and cars through the mandatory requirements for front and rear underrun protection.

As mentioned previously in section 2 the USA Insurance Institute for Highway Safety have performed research which indicated the need for a frontal pole test (Lund, 2007). However, Padmanaban and Okabe (2008) reported that narrow impacts have a relatively low risk of fatal injury, although lower extremity injury risk was high in these crashes, hence questioning the need for this test.

In other areas of the world, work has been performed to support the development of the proposals above and their possible application to regulation in that individual country. An example of this is research performed in Japan to investigate the suitability of the FWDB test and associated metrics to assess and improve structural interaction in SUV to car frontal collisions (Arai et al. 2007).

In the sections below the following potential test procedures have been reviewed:

- Progressive Deformable Barrier (PDB) test (Section 5.3.1)
- Full Width Deformable Barrier (FWDB) test (Section 5.3.2)
- Full Width Rigid Barrier (FWRB) test (Section 5.3.3)
- Override Barrier (ORB) test (Section 5.3.4)
- Mobile Barrier test (Section 5.3.5)

This review includes a description of the test and how it differs from existing procedures, focusing on differences such as the impact barrier used. Also included is a discussion of how the test may be incorporated into future legislation and what its possible advantages and disadvantages are, such as whether it is practical and effective and whether there are possible difficulties with it such that it may not achieve its aims.

5.3.1 Progressive Deformable Barrier (PDB) test

Development of the PDB test has been ongoing for nearly ten years. The initial proposal for the PDB test was made in 2001 by Renault (Delannoy and Diboine, 2001). At this stage definite performance criteria were not proposed. However, it was suggested that for self protection they could be based on the performance of the car and dummies as in the current regulatory tests, and for partner protection they could be based on the deformation of the barrier and the force measured on a Load Cell Wall (LCW) positioned behind the barrier face. Since this initial proposal, much work has been performed to develop the test procedure and associated performance criteria further, although the test principles remain the same. This has resulted in modifications to the barrier to overcome identified problems and a number of proposals for criteria, some of which have been superseded because problems were found with them. For the sake of brevity, only the latest version of the PDB test configuration and performance criteria is reported below. This information was based on the recent EEVC WG15 report (EEVC WG15, 2007), the reports from the EC 5th framework VC-COMPAT project, (VC-COMPAT, 2007) and the proposal to amend UNECE Regulation 94 by France made at GRSP in Dec 2007 (GRSP, 2007).

5.3.1.1 Test Configuration

The PDB test (GRSP, 2007) subjects the test vehicle to an offset frontal impact with a 50 percent overlap at a speed of 60 km/h (Figure 5.1).

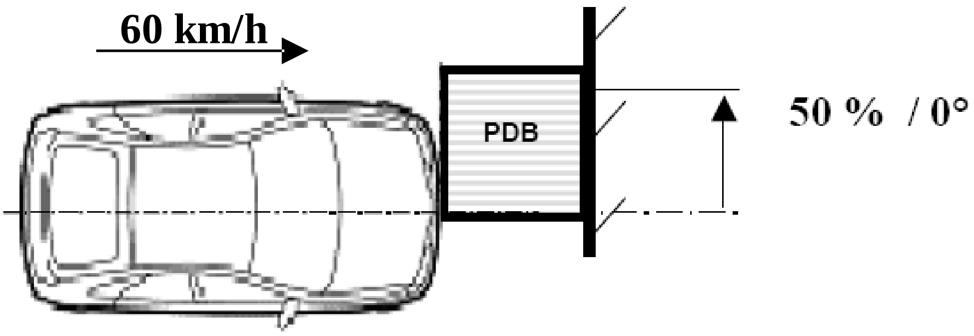


Figure 5.1: PDB test configuration

The barrier (Version XT) is an aluminium honeycomb construction, consisting of three blocks of different crush strength which are bonded together with different aluminium sheets, including a 0.8 mm thick aluminium cladding sheet which is riveted to the outside of the barrier (Figure 5.2).

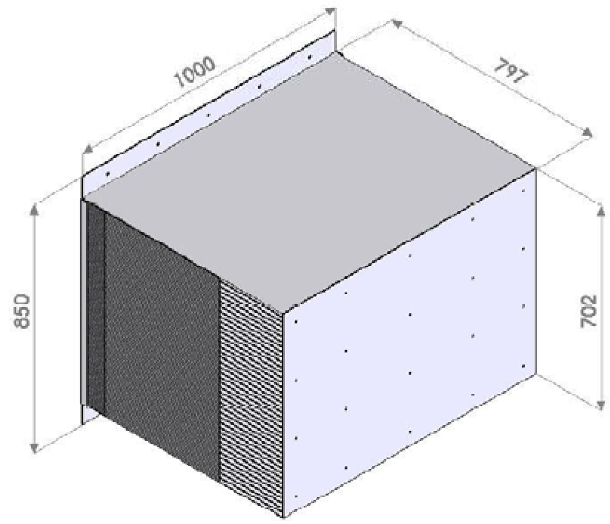
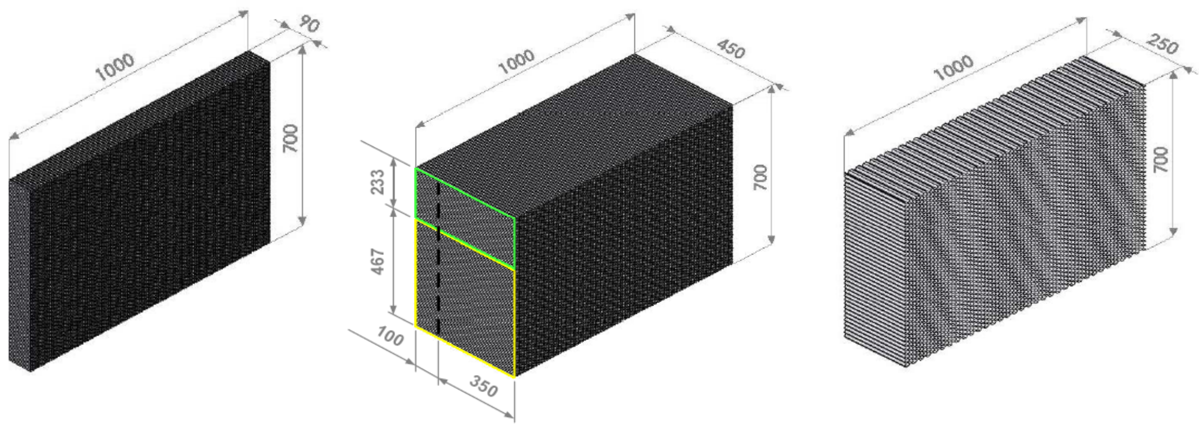


Figure 5.2: Progressive Deformable Barrier (PDB).

The dimensions of the three blocks are shown in Figure 5.3. The front honeycomb block is 250 mm deep and has a constant crush strength of 0.34 MPa, whilst the rear honeycomb block is 90 mm deep and has a constant crush strength of 1.71 MPa. The middle block is 450 mm deep, and has progressively increasing crush strength over the first 350 mm crush and constant crush strength over the last 100 mm crush. The block consists of two different levels of load path, an upper load path and a lower load path (as shown in yellow in Figure 5.3), with different crush strengths in each load path. The lower load path has a progressive crush strength ranging from 0.75 MPa to 1.09 MPa over the first 350 mm depth and a constant crush strength of 1.09 MPa thereafter, whilst the upper load path has a lower crush strength ranging from 0.41 MPa to 0.75 MPa in the progressive section and a constant crush strength of 0.75 MPa thereafter.



Rear block | Middle block | Front block

Figure 5.3: Dimensions of the PDB's three honeycomb blocks.

The main differences between this test and the current Regulation 94 test are:

- Deformable element

  The deformable element in the PDB test is substantially different to the one in the Regulation 94 test both in terms of its dimensions and stiffness.

- Test speed

  The speed of the PDB test is 60 km/h whereas the speed of the Regulation 94 test is 56 km/h.

- Test overlap

  The vehicle to barrier overlap in the PDB test is 50% whereas in the Regulation 94 test it is 40%.

5.3.1.2 Test Performance Criteria and Limits

It has been proposed that the PDB test could be used to assess and control both a vehicle's self and partner protection (compatibility).

For self protection it has been proposed to use a combination of dummy injury criteria and vehicle measures (e.g. steering wheel movement) with associated performance limits, in the same way as in the current Regulation 94 test.

For the partner protection it has been proposed that the assessment could be based on the deformation of the barrier and possibly the global force measured on a Load Cell Wall positioned behind the barrier face. A number of candidate parameters have been proposed (EEVC WG15 2007). These are based on the deformation of the barrier and possibly on measurements from a Load Cell Wall positioned behind the barrier face as shown in Figure 5.4. It is proposed that the barrier deformation would be measured using laser scanning techniques.

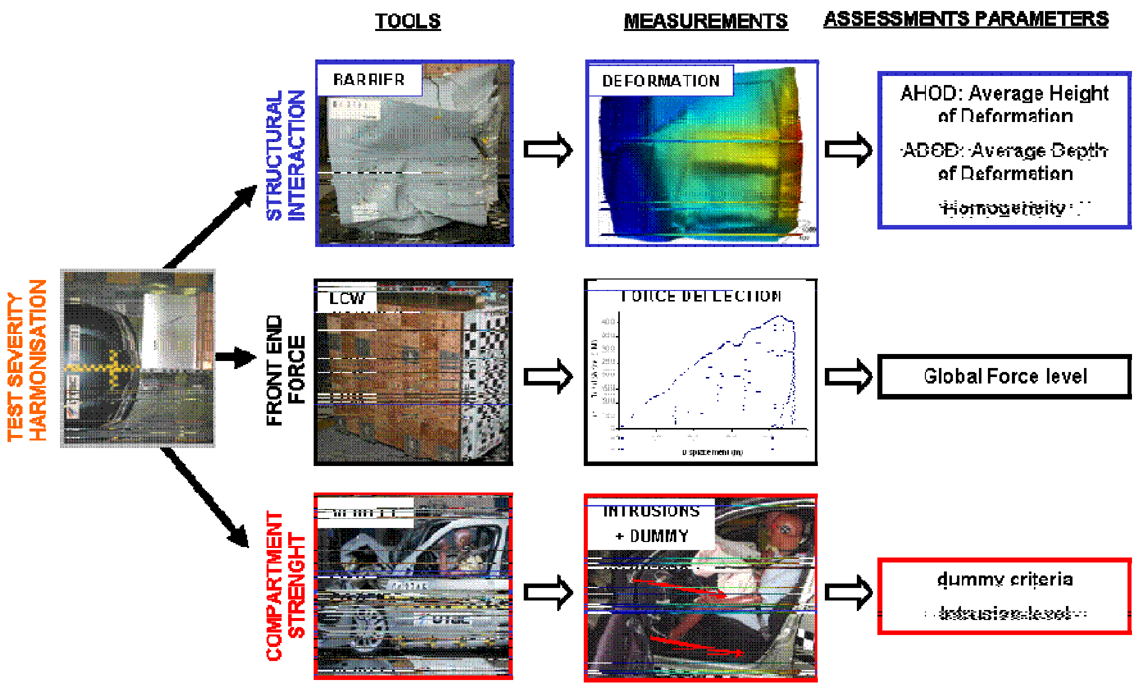


Figure 5.4: Candidate parameters for compatibility assessment using PDB test.

For assessment of structural interaction 3 parameters have been proposed as shown in Figure 5.5. It should be noted that how to calculate the homogeneity parameter has not been defined yet and so it is still only a concept at present.

- Average Height Of Deformation (AHOD): linked to the geometry and architecture.
- Average Depth Of Deformation (ADOD): linked to the front force of the car
- Homogeneity: supposed to detect local penetration in the front barrier face that indicates bad homogeneity.

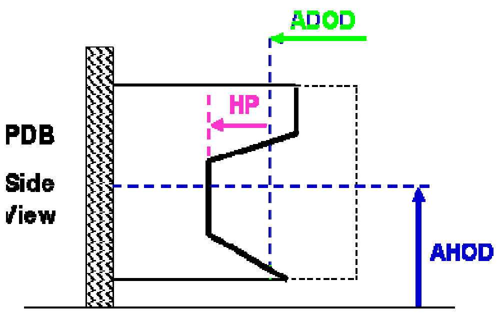


Figure 5.5: Parameters proposed to assess a vehicle's structural interaction potential in the PDB test.

For assessment of frontal force it is proposed to use an average depth of deformation type measure or the force measured on the Load Cell Wall (LCW).

At present these parameters have been shown to be able to distinguish differences between cars that perform differently in car to car tests. However, how these parameters could be used to form criteria to assess and control a vehicle's compatibility still has to be determined. Also, there are still some major potential issues to resolve such as the repeatability and reproducibility of a deformation based measure and the influence of the barrier on the measurement of a vehicle's frontal force levels.

In summary, much further work is required to develop partner protection assessment criteria and associated performance limits suitable for regulatory application.

5.3.1.3 Incorporation into future legislation, potential advantages and disadvantages

Two possible ways have been proposed for how the PDB test may be incorporated into future legislation; firstly as a replacement for the current UNECE Regulation 94 Offset Deformable Barrier (ODB) test by France at GRSP (GRSP, 2007) and secondly as part of an integrated set of test procedures with a Full Width Rigid Barrier (FWRB) test to assess a car's frontal impact and compatibility performance by EEVC WG15 (EEVC WG15, 2007)

<u>Option: Replacement of current UNECE Regulation 94 ODB test with PDB test</u>

The main potential advantages of this option are that it will resolve the current issues with test severity and barrier 'bottoming out' that are seen with the ODB test as noted in the justification produced by France to support this proposed change presented to GRSP. The main potential disadvantage of this option is the unintended consequence that it could possibly allow the design of unsafe vehicles with insufficient front-end energy absorption capability. Further details are discussed below.

The ODB test was originally designed to replicate the structural loading experienced in a car-to-car collision. One of the issues with the current ODB test is that the barrier design is more than 10 years old and is consequently based on old vehicle designs. The barrier has a low crush strength compared to that of current cars, which allows the stiff longitudinal structures of most current cars to 'bottom out' the barrier face and load the rigid block behind the barrier face directly.

One consequence of the barrier 'bottoming out' is that it will absorb a similar amount of impact energy for all cars independent of their mass because it is crushed approximately the same amount in all tests. This results in a higher test severity for heavier cars than for lighter cars because heavier cars have to absorb a greater proportion of their initial kinetic energy than lighter cars [Figure 5.6]. This in turn leads to heavier cars having higher strength frontal structures than they would have if the test severity were equal for cars of all masses [Figure 5.7]. In turn this exacerbates the frontal force mismatch between light and heavy cars in car to car crashes, thus increasing the compatibility problem. The PDB test aims to equalise the test severity in terms of EES (Equivalent Energy Speed) independent of vehicle mass and thus resolve this issue. It is intended that this will be achieved as a result of the progressive increase in the force level of the PDB. The PDB should absorb more impact energy for heavier vehicles than lighter vehicles because heavier vehicles have higher force levels than lighter vehicles and hence will crush the PDB more than lighter vehicles.

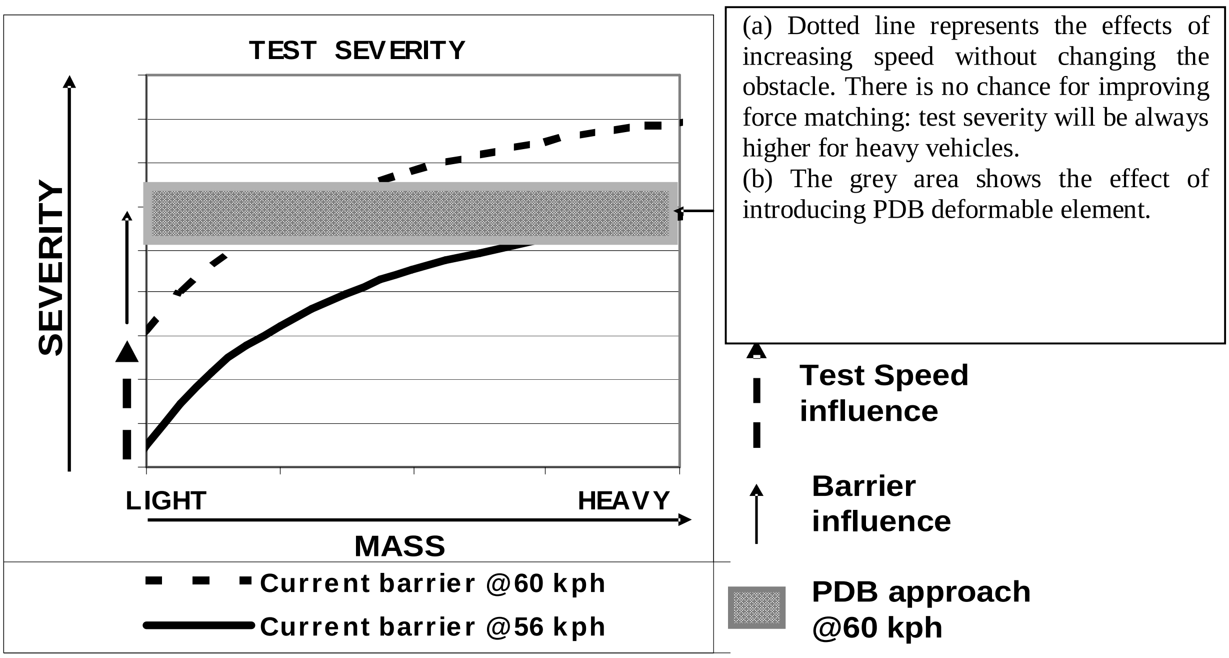


Figure 5.6: Influence of the test speed and barrier design on the test severity for a vehicle mass.

Due to test severity harmonization, the front force will be better harmonised among vehicles:

(a) light vehicles will become stiffer,

(b) heavy vehicles will stay more or less equivalent.

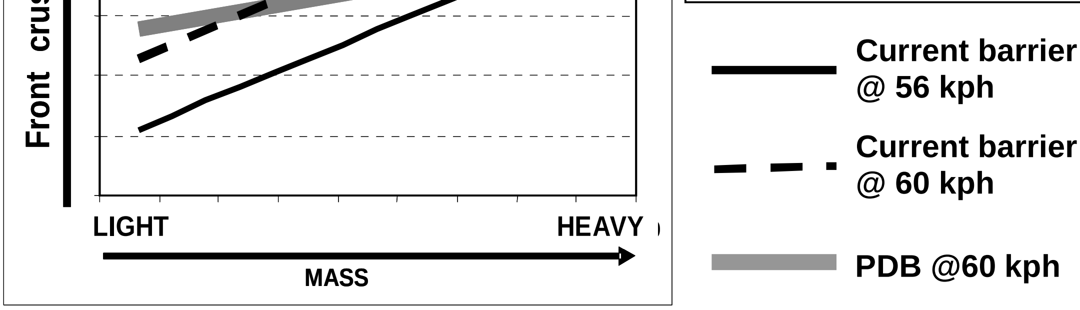


Figure 5.7: Force level tendency to meet self-protection requirements vs. vehicle mass.

Another consequence of the ODB barrier ‘bottoming out’ is that the loading in the test does not replicate that experienced in a car-to-car collision. The PDB aims to prevent vehicles ‘bottoming out’ in the test and thus replicate better the loading experienced in a car-to-car collision. The similarity of the deformation of several cars in car to car crash tests with their deformation in a PDB test was shown in the VC-Compat project (VC-Compat 2007, Deliverable 27) [Figure 5.8]. Unfortunately, a comparison of these deformations with the deformations in ODB tests was not shown in the project report. However, from their involvement in the project TRL know that the deformations of the cars in the PDB tests were much closer to the deformations of the cars in the car to car tests compared to the ODB tests, in particular for the main longitudinal rail.

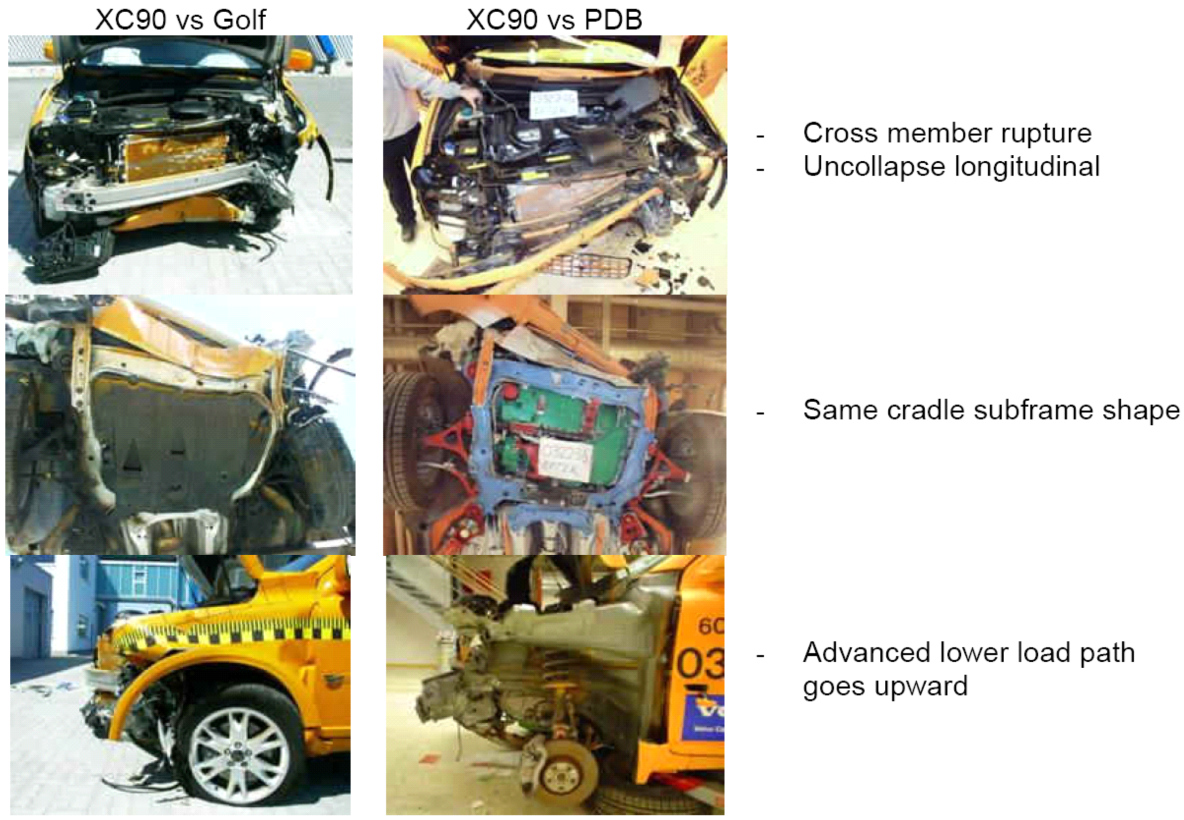


Figure 5.8: Comparison of deformation of a Volvo XC90 in crash test with VW Golf compared to its deformation in a PDB test showing similar deformation of front end structures, in particular the main longitudinal rail.

The main disadvantage with this option is the potential unintended consequence related to the higher energy absorption potential of the PDB because of its increased stiffness compared to the ODB. This could possibly allow the design of vehicles with a reduced front-end ‘crumple zone’ and, in theory, rigid vehicles. Such a vehicle design could perform well in the PDB test by using the energy absorption capability in the barrier face but perform catastrophically in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential, which would lead to deformation of the occupant compartment and its failure.

This concern is illustrated by comparing the deceleration pulse from a PDB test with a rigid trolley at 60 km/h with one from a full width car crash test [Figure 5.9]. It is seen that there is little difference between them which indicates that a restraint system could be designed to meet the dummy injury criteria performance limits for the rigid trolley deceleration pulse. It should be noted that the rigid trolley deceleration was calculated from the force corridors specified for PDB barrier certification test (GRSP, 2007) using the assumption that the barrier force levels were in the middle of the defined corridors.

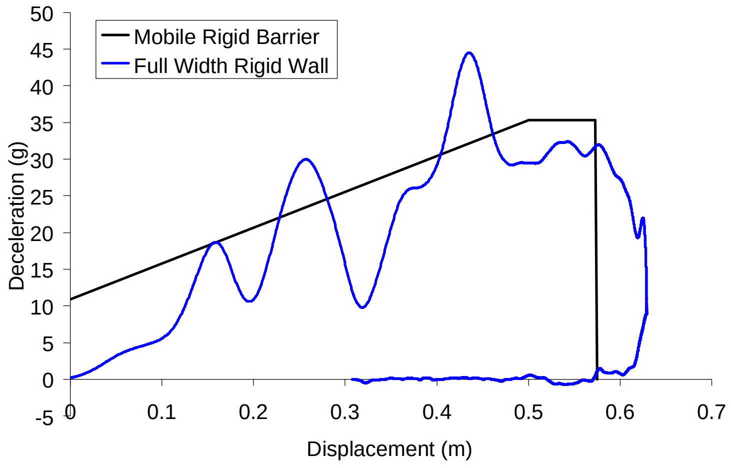


Figure 5.9: Comparison of deceleration of rigid trolley in PDB test to car compartment in Full Width Rigid Barrier (FWRB) test.

This concern was highlighted further by BASt who performed a series of PDB and ODB tests with mobile barriers which they reported recently to the GRSP frontal impact informal working group (Lorenz 2008). The following four tests were performed:

- A full-width mobile PDB vs PDB representing a car to PDB test.
- A full-width rigid mobile barrier vs PDB representing a rigid car to PDB test.
- A full-width mobile PDB vs ODB representing a car to ODB test.
- A full-width rigid mobile barrier vs ODB representing a rigid car to ODB test.

Comparison of the deceleration pulses from the tests showed that for the PDB tests there was little difference between the peak deceleration for the mobile PDB and rigid barriers (32g mobile PDB trolley cf 36g mobile rigid trolley) whereas in contrast for the ODB tests the difference in the peak deceleration was large (29g mobile PDB trolley cf 54g mobile rigid trolley) [Figure 5.10]. This shows that the ODB test can detect the difference between the PDB and rigid barriers but the PDB cannot, which implies that whereas cars with a reduced front end ‘crumple zone’ could not be designed to fulfil the current ODB Regulation 94 test requirement, they could possibly be designed to fulfil future PDB test requirements.

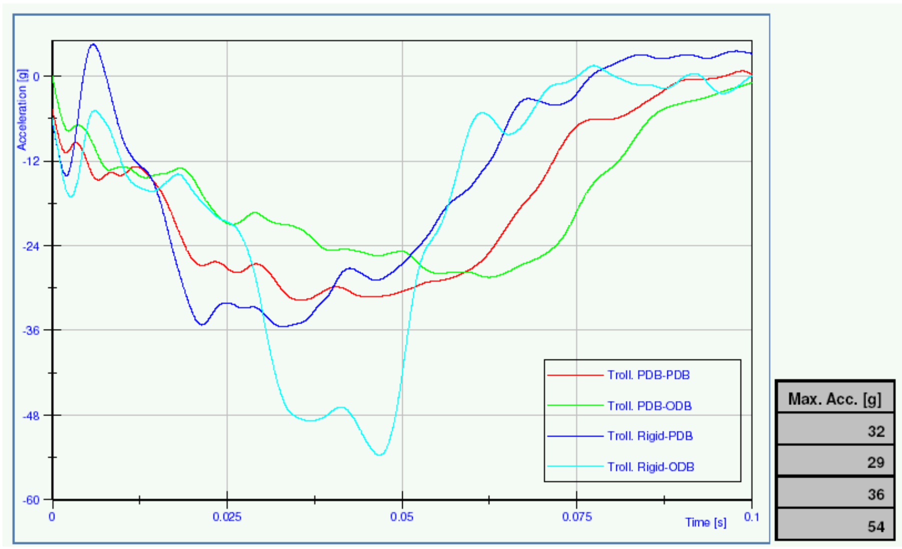


Figure 5.10: Comparison of mobile barrier deceleration pulses for PDB and ODB tests.

To highlight this concern even further the German Automotive Manufacturers Association (VDA) performed simulation work to show specific examples of how vehicles with reduced front end crumple zones and insufficient energy absorption capacity could be designed which could meet the requirements of a PDB test but not an ODB test. This work was also reported to the GRSP frontal impact informal working group (VDA 2008). One realistic example given was the reduction of the crumple zone by an increase in the engine size. It should be noted that for all of the examples given the mass of the vehicle was increased significantly which would be in conflict with requirements to reduce weight to reduce CO_2 emissions.

Other potential issues that have been raised with the PDB test include:

- Confirmation that replacement of the ODB with the PDB test will guarantee that the self-protection level of future vehicles will not decrease, that it will equalise the test severity for light and heavy vehicles and that the PDB barrier face stiffness is appropriate for testing of future vehicles. Further explanation of these issues is given below:
    - Figure 5.11 shows a comparison of Equivalent Energy Speed (EES) vs vehicle mass for a 56 km/h ODB test, a 60 km/h ODB test and a 60 km/h PDB test. It is clearly seen that for heavier vehicles (circled in red) the PDB test severity is lower than the current ODB (56 km/h) test severity.

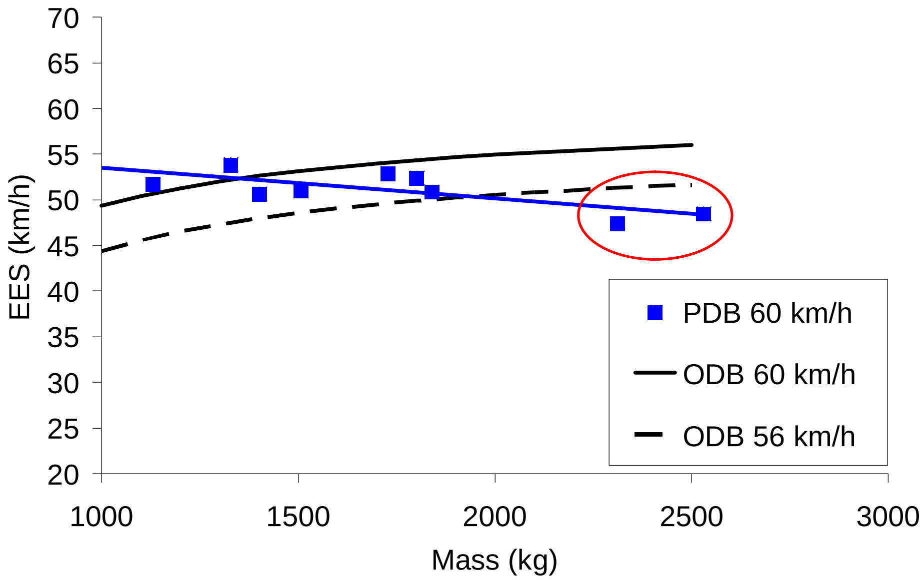


Figure 5.11: Comparison of Equivalent Energy Speed (EES) vs Vehicle Mass for PDB and ODB Tests

Please note that the ODB curves were calculated using the approximate assumption that the barrier absorbed 40 kJ of energy independent of the mass of the vehicle tested and the remainder of the impact energy was absorbed by the vehicle. The PDB values were calculated from an estimation of the energy absorbed by the barrier in physical tests performed as part of the VC-COMPAT project.

    - Currently, heavier vehicles have higher frontal force levels than lighter ones as illustrated by the forces measured by a Load Cell Wall positioned behind the deformable element shown in Figure 5.12. The PDB force deflection characteristic was developed with the aim that it absorbs more energy for vehicles with higher force levels to equalise test severity by ensuring that that the barrier absorbs a fixed proportion of the vehicle's initial kinetic energy independent of its mass (Figure 5.13). Hence the severity of the PDB test is a function of the vehicle's force levels.

PDB Test Severity = f(Vehicle frontal force level)

Currently, data from the VC-COMPAT project shows that the PDB test severity is higher for lighter vehicles than heavy vehicles, the opposite of the current ODB test (Figure 5.11). PDB test proponents expect this to encourage lighter vehicles to raise their force levels as illustrated in Figure 5.12 to ensure that compartment integrity is maintained. Confirmation that this will occur is required.

- o If the PDB test raises the force levels of lighter vehicles as intended, the result of this would be to lower the test severity for lighter vehicles, but by how much has not been estimated. Hence, it may be that the barrier force deflection profile may be inappropriate for the new generation of vehicles. To address this possible problem it is recommended that if the PDB is adopted, its force deflection profile should be reviewed after a fixed period to ensure that it is still appropriate.

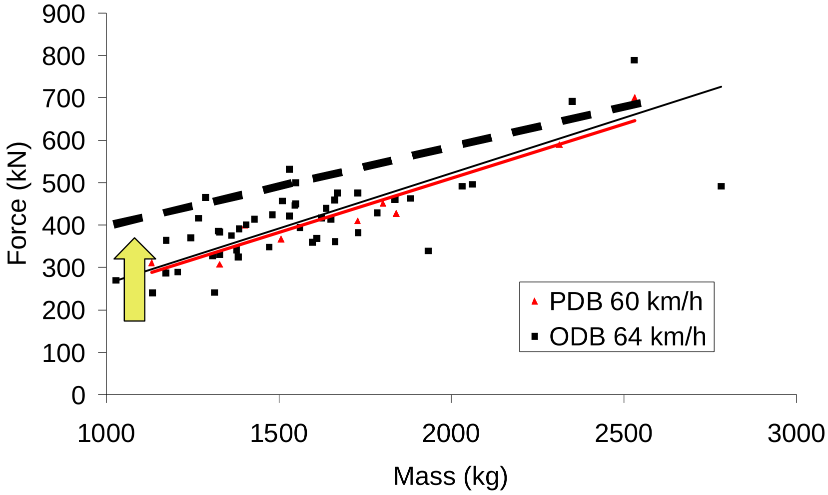


Figure 5.12: Vehicle Frontal Force Levels vs Mass

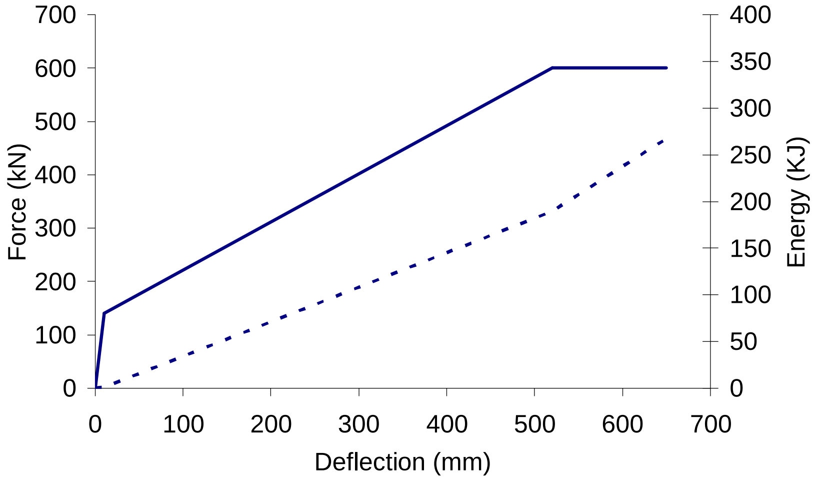


Figure 5.13: PDB Force / Energy vs Deflection

- Confirmation that adoption of the PDB will not encourage the height of vehicle main structures to be lowered as this could lead to structural interaction type compatibility problems.
  - The bottom edge of the PDB is lower than ODB (150 mm cf 200 mm). The main reason for this is to interact with car subframes to be able to detect them for the assessment of a car's compatibility in the future. This could permit development of vehicle designs with much lower main structures which could be over-ridden in crashes with cars with higher structures, thus causing a compatibility problem. For example, electric cars may be designed with this type of lower structure because they will not require conventional structure of today's cars to support the engine.
- Confirmation of the repeatability and reproducibility of the PDB test.
  - As far as TRL is aware, to date the repeatability and reproducibility of the PDB test has only been investigated for one car, using a series of two tests with an Opel Astra (VC-Compat 2007 Deliverable 27). Further tests are required with a variety of vehicles with focus on the barrier's stability.

In summary, the main potential advantage of this proposal is that it could help resolve the current issues with test severity (i.e. heavier vehicles are subjected to a more severe test than lighter vehicles in terms of EES) and barrier 'bottoming out' (i.e. structural loading of car is not representative of car-to-car collision) that are seen with the ODB test. The main potential disadvantage is that the increased energy absorption capability of the PDB could permit the design of vehicles with a reduced front-end 'crumple zone' and, in theory, rigid vehicles. Such a vehicle design may perform well in the PDB test by using the energy absorption capability in the barrier face but have catastrophic results in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential. This would consequently lead to deformation of the occupant compartment and its failure.

One solution to help overcome this potential problem would be to introduce a full width test in parallel with the change to the PDB test. One characteristic of the full width test is that it produces a high compartment deceleration pulse because both sides of the vehicle's structure are engaged in the impact and hence the impact forces are higher than an offset test in which only one side of the vehicle's structure is engaged. Hence a full width test could be used to limit a vehicle's stiffness because excessively stiff vehicles would produce a deceleration pulse that would not allow the dummy injury criteria performance limits to be met.

In relation to the EEVC strategy, this option does not contain a full width high deceleration test and hence does not fulfil the strategy aims. It is interesting to note that if a full width high deceleration test were included, as well as meeting the strategy aims, the potential problem that theoretically a rigid car could be designed and pass the test could also be solved.

<u>Option: Replacement of UNECE Regulation 94 with integrated set of test procedures consisting of PDB and Full Width tests</u>

EEVC WG15 has proposed that a PDB test and a Full Width Rigid Barrier (FWRB) test could form the basis of an integrated set of procedures to assess a car's frontal impact and compatibility performance. However, they note that a number of issues need to be resolved before this proposal would be suitable for introduction into regulation. Also, it should be noted that at this stage EEVC have stated that a PDB test with a Full Width Deformable Barrier (FWDB) test could also be a potential option, but they have not performed specific research work to investigate it. Proposed test configurations and performance criteria for a full width test with a deformable element (FWDB) and without a deformable element (FWRB) are described in the sections below.

In relation to the EEVC strategy described above this proposal contains both an offset and a full width test and therefore has the potential to fulfil the strategy aims provided measures to assess and control compatibility could be developed in the future.

5.3.2 Full Width Deformable Barrier (FWDB) test

Development of the FWDB test has also been ongoing for nearly ten years. The initial proposal for the FWDB test was made in 2001 by the UK (Edwards et al., 2001). Since this initial proposal much work has been performed to develop the test procedure and associated performance criteria further, although the test principles remain the same. This has resulted in modifications to the deformable face to overcome identified problems and a number of proposals for criteria, some of which have been superseded because problems were found with them. For the sake of brevity, only the latest development status for the FWDB test configuration and performance criteria are reported below. This was found in the recent EEVC WG15 report (EEVC WG15 2007) and the reports from the EC 5th framework VC-COMPAT project, (VC-COMPAT 2007).

5.3.2.1 Test Configuration

The FWDB test is a full width (100 percent overlap) frontal impact test into a deformable barrier at 56 km/h, as shown in Figure 5.14.

Figure 5.14: FWDB test configuration.

A LCW, consisting of cells of nominal size of 125 mm by 125 mm, is positioned at the rear face of the deformable barrier. The load cells are mounted 80 mm above ground level so that the division line between rows 3 and 4 is at a height of 455 mm which is approximately mid-point of the US part 581 bumper beam test zone (Figure 5.15).

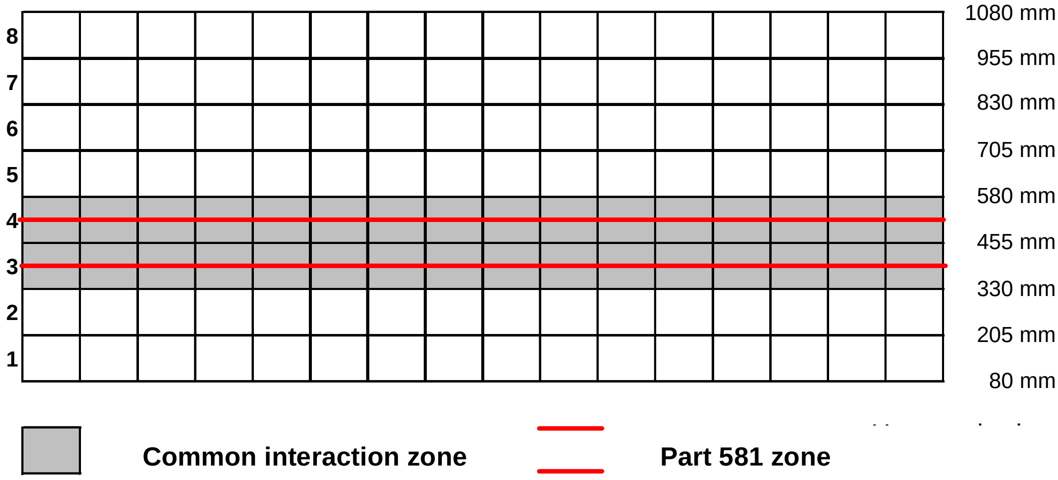


Figure 5.15: LCW configuration.

The FWDB is an aluminium honeycomb construction which consists of two layers each 150 mm deep (Figure 5.16). The front layer is made from honeycomb of crush strength of 0.34 MPa which is the same as the main body honeycomb of the current EEVC barrier. The rear layer is made from honeycomb of crush strength of 1.71 MPa. The rear layer is segmented into 125 mm by 125 mm blocks which align with each of the load cells. The reason for the segmentation is to effectively reduce the shear strength of the layer to prevent it spreading load applied in alignment with one load cell to adjacent load cells.

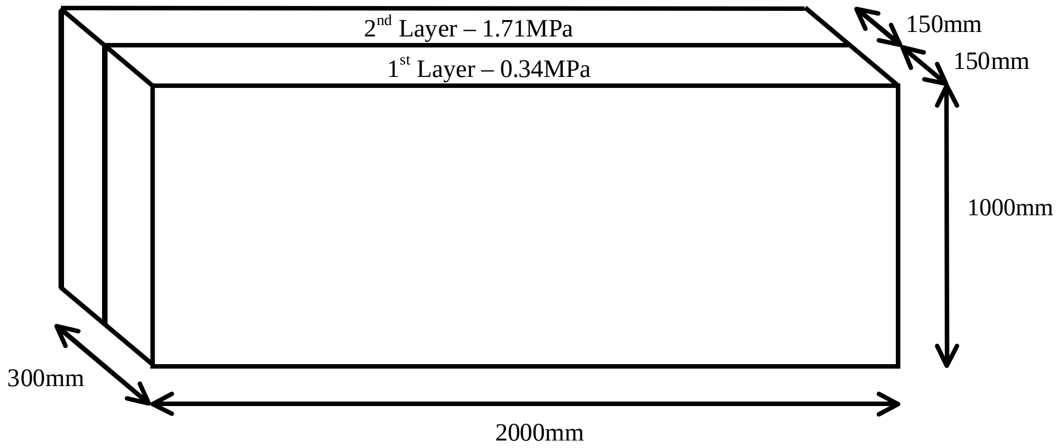


Figure 5.16: Dimensions of FWDB.

The purpose of the barrier is:

- To generate relative shear in the front structure to exercise any shear connections between load paths and allow the assessment of horizontal structures, such as bumper crossbeams.
- To attenuate the engine dump loading. When the engine impacts a rigid wall, it is brought to rest very rapidly generating high inertial forces. In a car to car impact, the engine can rotate or move slightly out of the way of the other car's engine, so reducing its deceleration.
- To prevent unrealistic decelerations at the front of the car. The parts of the car that first impact the wall are decelerated instantaneously giving rise to large inertial forces. Such forces are not present in impacts with deforming structures, such as other cars.

- To prevent localised stiff structures forming preferential load paths to the wall and reduce the loading from adjacent structures which are slightly set back. This does not occur in impacts with other cars.

An additional consideration in the design of the deformable face was to ensure that it had a minimal effect on the occupant compartment deceleration pulse compared to a rigid wall test because it is also intended to function as a high deceleration test.

The main differences between this test and the US FMVSS208 test are the addition of the deformable element and the high resolution Load Cell Wall (LCW).

5.3.2.2 Test Performance Criteria and Limits

The FWDB test is designed to assess a car's structural interaction potential and also to provide a high deceleration pulse to test the occupant restraint systems. The intention of the FWDB test is to control both self and partner protection.

For self protection it is proposed to assess the occupant's deceleration and restraint system performance using dummy measures in a similar way to the current US FMVSS208 or UNECE Regulation 94 tests.

For partner protection, it is proposed to assess the car's structural interaction potential using measures from the LCW. The premise is that cars that exhibit a more homogeneous force distribution on the LCW should have a better structural interaction. The Structural Interaction (SI) criterion has been developed for this purpose (Edwards et al. 2007). The Structural Interaction (SI) criterion is calculated from the peak cell loads recorded in the first 40 ms of the impact. Compared to using peak cell loads recorded through the duration of the impact, this has the advantage of assessing structural interaction at the beginning of the impact when it is more important and minimising the loading applied by structures further back into the vehicle such as the engine.

To allow manufacturers to gradually adapt vehicle designs to become more compatible, the criterion consists of two parts which could be adopted in a stepwise manner. The first part assesses only the common interaction area (Area 1) which is from 330 mm to 580 mm above ground level and consists of LCW rows 3 and 4 [Figure 5.15]. The intention of this part of the assessment is to ensure that all vehicles have adequate structure in alignment with this area to ensure interaction. The second part assesses a larger area (Area 2) which is from 205 mm to 705 mm above ground level and consists of LCW rows 2, 3, 4 and 5. The intention of this part of the assessment is to encourage cars to better distribute their load over a larger area to reduce the likelihood of over/under-ride and the fork effect. The results of tests performed as part of the VC-COMPAT project have demonstrated that cars that distribute their load vertically have better structural interaction potential (VC-COMPAT, 2007). Each part of the SI criterion consists of two components, a vertical component (VSI) and a horizontal component (HSI). The VSI component is designed to encourage alignment and distribution of vehicle structures vertically. The HSI component is designed to encourage the use of strong crossbeam structures which can distribute the load from the vehicle's main longitudinal structures horizontally.

Initial validation of these criteria has been performed using test data available to EEVC WG15 (EEVC WG15, 2007). Recent work reported in the APROSYS programme indicated that there were significant potential issues with the repeatability/reproducibility of the SI criterion even when there was reasonable repeatability of the LCW results (APROSYS, 2008). The work found that the vertical component of the compatibility Structural Interaction (SI) metric was repeatable / reproducible when using assessment area 1 (rows 3 and 4) but not repeatable when using assessment area 2 (rows 2, 3, 4, 5). The horizontal component of the compatibility metric was not repeatable when using either area. It was thought that this was due to the high sensitivity of the criterion to small variations in individual load cell measurements. These variations were most likely due to contributory factors such as load spreading in the deformable barrier and possible bridging of load cells by vehicle components or the barrier.

In the USA, the Enhanced Vehicle Compatibility technical working group are investigating criteria to control an LTV's compatibility in an LTV to car impact. These criteria are aimed at ensuring that an LTV has sufficient structure in alignment with the Part 581 zone. Current proposals consist of a requirement for a minimum row load for rows in alignment with the Part 581 zone (rows 3 and 4) (Verma 2007).

In summary, although initial proposals for performance criteria and limits have been made, much further work is required to develop them to a level suitable for regulatory application.

5.3.2.3 Incorporation into future legislation, potential advantages and disadvantages

As mentioned above it has been proposed by EEVC WG15 that the FWDB test could possibly be incorporated into legislation as part of an integrated set of test procedures to assess frontal impact and compatibility coupled with the current UNECE Regulation 94 test. For this proposal it should be noted that modification of Regulation 94 would be needed, namely the addition of a Load Cell Wall to enable the assessment of vehicle frontal force levels in this test.

In relation to the EEVC strategy described above, this proposal contains both an offset and full width tests and therefore has the potential to fulfil the strategy aims provided measures to assess and control compatibility could be developed in the future.

From a harmonisation point of view, one of the main issues with this proposal is that a Full Width Rigid Barrier (FWRB) test could be seen as a better option than a Full Width Deformable Barrier (FWDB) provided that appropriate measures to assess compatibility could be developed for the FWRB test. This is because the FWRB test is already included in legislation in many regions of the world, e.g. USA, Canada, Japan and Australia. However, if the FWDB test has significant advantages over a FWRB test in terms of its capability to assess a car's frontal impact protection including its compatibility, this may provide sufficient reason to choose the FWDB test.

The purpose of the deformable face has been explained above. The main advantages of it in terms of assessing a vehicle's frontal impact performance are:

<u>For self protection</u>

- With the deformable face the impact is more similar to a car to car impact, in particular at the beginning of the impact. This enables a more realistic loading of the tested vehicle and consequently a better assessment, in particular of the restraint triggering system which operates at the beginning of the impact.

  Note: In tests performed in the EC 6th framework APROSYS project to investigate the effect of the deformable face the restraint system of one car tested fired about 20 ms later in the test with the deformable face compared to the test with the rigid wall which resulted in a substantial increase in the dummy head injury criteria values (APROSYS 2008 Deliverable 1.2.2).

<u>For partner protection</u>

- With the deformable face the 'engine dump' load on the Load Cell Wall is attenuated, which makes it easier to identify the loads from the car structure, which in turn helps enable a better assessment of a vehicle's compatibility.
- The deformable face generates relative shear in the vehicle's front structure which exercises any shear connections between load paths and allows the assessment of horizontal structures, such as bumper crossbeams, which is not possible with a rigid wall. However, work performed in the APROSYS project to investigate the repeatability / reproducibility of the FWDB test found that

the Structural Interaction (SI) criterion horizontal component was not repeatable / reproducible (APROSYS 2008 Deliverable 1.2.).

EEVC WG15 has also stated that a possible alternative set of procedures could be an FWDB test coupled with a PDB test. If it were found that it was not possible to develop a criterion for the FWDB test to assess a vehicle's horizontal structures, then possibly this set of test procedures could offer a solution by using the PDB test to perform the assessment of the horizontal structures.

5.3.3 Full Width Rigid Barrier (FWRB) test

A Full Width Rigid Barrier (FWRB) test is currently used in the USA, Canada, Australia and Japan as part of the regulatory frontal impact requirements (see section 2 'Existing frontal impact legislation'). There is no current European full width frontal impact test.

5.3.3.1 Test Configuration

The proposed test configuration is a 56 km/h test speed with 100% overlap of the vehicle. Also in some proposals a high resolution Load Cell Wall (LCW) is included to enable compatibility measures to be taken. Currently, there is no definite specification for this LCW but many investigative tests have been performed with the LCW specification defined above for the FWDB test.

5.3.3.2 Test Performance Criteria and Limits

Performance criteria and limits are already available for the FWRB test to assess a vehicle's self protection capabilities because it is a legislative test in many parts of the world (see section 2 'Existing frontal impact legislation').

For assessment of a vehicle's partner protection capability, work has been performed mainly in the USA to develop criteria to assess an LTV's compatibility in an LTV to car impact. NHTSA have performed work on the development of two LCW based criteria to control the geometry and stiffness of cars and LTVs that have their primary energy absorbing structures (PEAS) in alignment with the Part 581 zone, also known as 'option 1' LTVs from the definition in the Alliance voluntary agreement (Patel et al. 2007). The objective behind the criteria is to encourage design of a common crush box at the front of cars and LTV's that would have similar structural characteristics and thus create a compatible fleet. The common structural characteristics that were selected were average height of force and frontal stiffness. To control these characteristics two criteria were selected for investigation. These were an Average Height of Force (AHOF) and a stiffness related crush energy absorbed by the vehicle (Kw400) both measured over the first 400 mm of crush of the vehicle.

AHOF400 = average height of force delivered by a vehicle in the first 400 mm of crush.

Kw400 = stiffness related crush energy absorbed by a vehicle in the first 400 mm of crush.

Some initial work to validate these criteria has been performed, but much further work is necessary before they could be used for regulatory application.

5.3.3.3 Incorporation into future legislation, potential advantages and disadvantages

As mentioned above it has been proposed by EEVC WG15 that the FWRB test could possibly be incorporated into legislation as part of an integrated set of test procedures to assess frontal impact and compatibility coupled with the PDB test.

For assessment of an LTV's compatibility, the FWRB test requires a supplementary Override Barrier (ORB) test for 'Option 2' LTVs whereas the FWDB test may not. Option 2

LTVs are higher LTVs that do not have their Primary Energy Absorbing Structure (PEAS) in alignment with the Part 581 zone but have Secondary Energy Absorbing structure (SEAS) in alignment with it.

5.3.4 Override Barrier (ORB) test

The override Barrier (ORB) test was proposed by NHTSA as a supplementary test to the FWDB test for assessing 'option 2' LTVs (Patel et al. 2007).

The Secondary Energy Absorbing Structure (SEAS) on an 'option 2' LTV cannot be assessed consistently in a FWRB test because usually it is positioned rearwards of the Primary Energy Absorbing Structure (PEAS). Hence, in a crash test the PEAS interacts with the wall before the SEAS and can prevent or influence the interaction of the SEAS with the wall and consequently an assessment of it.

To overcome this problem NHTSA proposed an Override Barrier (ORB) test which has a limited height so that the LTV's PEAS override it which allows the LTV's SEAS to interact with it [Figure 5.17] (Patel et al. 2007). A definite test configuration is not available yet because the test is still under development. However, initial tests have been performed with a test speed of 25 mile/h (40km/h).

Figure 5.17: Override Barrier with a supporting LCW behind it.

NHTSA has proposed that a Kw400 type criterion as described in the FWRB section above could be used to assess the stiffness characteristics of the LTV's SEAS.

One potential issue with this test is that it does not ensure that the SEAS has an adequate cross member structure which is needed for good interaction with the impacting partner. This is because horizontal structures, in particular flat ones, cannot be assessed using a rigid barrier technique because they may not be strained in the impact as explained in the FWDB test section 5.3.2.3 above. A deformable element fitted to the barrier could help overcome this problem.

It should be noted that the relevance of this test for Europe may not be that high because there are relatively few 'option 2' type LTVs in the European vehicle fleet compared to the US fleet.

5.3.5 Mobile Deformable Barrier test

Some initial research work has been performed to develop a Mobile Deformable Barrier test using the PDB deformable face to assess a vehicle's compatibility (Schram and

Versmissen, 2007). The work showed that repeatable tests could be performed. This test is envisaged as a long term option to aid harmonisation, although exactly how it would fit into a set of test procedures to assess a vehicle's compatibility is not described in the paper. The focus of this work is on the short term, i.e. identification of options for possible consideration for the review of Regulation 94 currently being conducted under GRSP, so this test procedure is not described further in this report.

NHTSA have performed some research work to develop an offset oblique MDB test (Ragland 2003). However, this work was discontinued in 2004 for reasons such as test repeatability problems.

As mentioned above, the US EVC technical working group have performed work to develop a car surrogate mobile deformable barrier as a test device to assess an LTV's compatibility.

In summary, some research work has been performed to develop MDB type tests, but the development of the procedures is not sufficiently advanced for consideration of their inclusion into legislative testing in the short term. However, they may offer the best solutions for the longer term.

5.4 Potential options for the improvement of future legislation

In this section options for consideration for the improvement of future frontal impact legislation are identified and listed.

The approach used consisted of two parts. The first part identified options related to changes to the test configuration and / or the addition of new tests, referred to as 'main' options. These were identified from:

- Official proposals to amend regulation, namely the proposal to amend UNECE Regulation 94 made by France at the GRSP meeting in December 2007.
- Proposals made by working groups such as EEVC WG15 and combinations of new and modified test procedures identified in the literature that have the potential to fulfil the aims of the strategies developed by IHRA and EEVC to improve future legislation for frontal impact and compatibility.

The second part consisted of identification of options which could be incorporated into the 'main' options, such as changes to the dummy test tool and / or assessment criteria, referred to as 'supplementary' options. These options were identified from the dummy review work (Section 4) and proposals made in the past by groups such as the EEVC and ETSC.

The 'main' options are:

1. No change.
2. Replace the current R94 ODB test with a PDB test.

    This option was proposed as an amendment to UNECE Regulation 94 by France at the GRSP meeting in December 2007. The justification given by France to support this proposed change is that it will resolve the current issues with test severity and the barrier 'bottoming out' that are seen with the ODB test. However, it does not have the potential to fill all of the aims of the IHRA and EEVC strategies as it does not include a full width test.

3. Add a full width high deceleration test to the current R94 ODB test procedure.

    A number of potential ways exist to fulfil this option. These are:

    - Add a Full Width Deformable Barrier (FWDB) test.

      Note: this option is one of the set of procedures proposed and investigated by EEVC WG15.

- Add a Full Width Rigid Barrier (FWRB) test.

  Note: For the USA, this option would require a supplementary Override Barrier (ORB) test for the assessment of the compatibility of LTVs, in particular ‘option 2’ LTVs.

Because they add a full width test both of these options have the potential to fulfil all the aims of the IHRA and EEVC strategies. The main differences between them are their relationship with present international legislative requirements (a FWRB test is required in legislative requirements in many parts of the world whereas a FWDB test is not) and their potential for further development to include measures to control compatibility.

4. Combination of options 2 and 3.

A number of potential ways exist to fulfil this option. These are:

- Replace ODB test with PDB test and add FWDB test.
- Replace ODB test with PDB test and add FWRB test.

  Note: this option is one of the set of procedures proposed and investigated by EEVC WG15.

Again because they add a full width test both of these options have the potential to fulfil all the aims of the EEVC and IHRA strategies.

The supplementary options identified from the review of the dummy test tool were:

a. Incorporating the THOR-Lx (Test device for Human Occupant Restraint – Lower extremity), and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy.

   o As reported in Section 2, NHTSA are developing an offset deformable barrier test using a Hybrid III with the THOR-Lx lower extremity, and the test procedure is primarily targeted at reducing high cost, high frequency lower extremity injury. The review of accident analysis data also suggested that this may be beneficial in full width test procedures because approximately half of lower extremity injuries were in full-width impacts, although the review does not demonstrate that the THOR-Lx would be effective in such a test procedure. Agreed injury risk functions are also not available for all of the injury assessment measurements in the THOR-Lx and femur, and these parts are undergoing further assessment and review within the SAE THOR Task Group.

Other supplementary options identified and the reasons for their identification were:

b. Extension of scope

   o Extend the scope of the Directive to include N1 vehicles, in particular those less than 2.5 tonnes, and all M1 vehicles.

     In 2000 EEVC recommended that the scope of the Directive was extended to include N1 vehicles < 2.5 tonnes. In 2001 ETSC recommended that the scope was extended to include larger M1 vehicles and M2 vehicles. This recommendation was made on the basis that the extension to larger M1 cars and M2 vehicles could be justified on the grounds of protecting their occupants but could be opposed on the grounds that they may become more aggressive to other car occupants. However, in practice testing these vehicles should bring about some improvement in their aggressivity as it should encourage frontal structures to become better connected.

c. Steering wheel movement criterion

- o Add a lateral displacement limit of 100 mm to the current vertical and horizontal displacement limits.

  This was recommended both by EEVC in 2000 and ETSC in 2001 to ensure a stable base for airbag deployment.

d. Footwell intrusion

- o Add an appropriate footwell intrusion criterion and associated limit

  In 2001 ETSC recommended that the footwell intrusion is measured and the limit proposed by EEVC is adopted. Since this time Euro NCAP has used various criteria to assess intrusion in the footwell area. It is proposed now that the option of adding an appropriate footwell intrusion criterion based on the EEVC proposal and the experience of Euro NCAP is included.

e. Assessment of rear seated positions

- o Consider the assessment of the rear seated positions

From analysis of US NASS CDS accident data Kent (2007) found that the fatality and serious injury risk in frontal crashes is higher for older occupants in rear seats than for those in front seats. In addition, the relative effectiveness (to mitigate serious injury and death) of rear seats with respect to front seats for restrained adult occupants in newer vehicle models was found to be less than it is in older models, presumably due to the advances in restraint technology that have been incorporated into the front seat position but not into the rear seat position. On the basis that good protection should be offered to all occupants in all seating positions it is proposed that an option to consider the assessment of the rear seated positions is included.

In 2000 EEVC also recommended that the ODB test speed should be increased. However, since 2000, EEVC WG15 have recommended that the test speed should not be raised without modification of the test procedure and / or adoption of compatibility measures because of the risk that this may increase the current frontal force mismatch between vehicles of different mass. On the basis of this, it is recommended that a change of the test speed is only considered for the PDB test procedure. It should be noted that the PDB test option already includes a change to the test speed.

A number of other minor options for the improvement of Regulation 94 have been identified based on the review of other similar test procedures. They include:

- Front seat position - longitudinal adjustment

  Currently, Regulation 94 specifies that the front seat should be positioned in the middle position of travel in the fore/aft direction or in the nearest locking position thereto. The intention is that this seating position should be representative of the seating position for a 50th percentile male. Since the Regulation was introduced some manufacturers have increased the rearwards adjustment of the seats in their vehicles to help accommodate persons larger than the 95th percentile male. To ensure that the specified seating position is still representative of the seating position of a 50th percentile male some test procedures, such as EuroNCAP, use a different seat adjustment specification. This is that the front seat should be positioned in the middle position of travel or nearest locking position between its foremost position of travel and the foreaft position of travel which corresponds to the 95th percentile male seating position.

- Hybrid III Dummy - neck shield

To help ensure a more realistic interaction between the HybridIII dummy and airbags some test procedures, such as Euro NCAP, use a neck shield on the Hybrid III dummy.

6 Cost Benefit Analyses

One of the main issues associated with this work is how to perform the cost and benefit part of the review. To perform a rigorous benefit analysis final definition of the test procedure and data for a selection of vehicles representative of the vehicle fleet tested to the defined test procedure are required. Because this information is not fully available for the potential options and the cost of this type of analysis was beyond the budget of the project, a rigorous analysis of this type could not be performed. However, it should be noted that this type of analysis is normally performed as a final step before a measure is introduced into legislation. The aim of the work was to review the potential of a number of possible options to improve legislation, so a preliminary type of analysis was more appropriate. This type of analysis is usually based on simple assumptions of how a future vehicle that meets the test requirements will perform in accidents and how that enhanced performance will reduce injuries for casualties within the target population. However, to perform this type of analysis for all the potential options was again beyond the budget of the project.

Therefore, the approach followed was to review the literature to find cost benefit analyses performed previously which could be used to help estimate the costs and benefits for the potential options. Two appropriate cost benefit analyses were found.

The first was a preliminary analysis performed as part of the EC 5th framework VC-Compat project to estimate the benefits and costs to introduce regulatory measures in Europe to improve a car's compatibility (VC-Compat 2007 Deliverable 24). It was assumed that this analysis could be used to give an upper bound for the benefits and costs for the replacement of the current ODB test with the PDB test. This assumption was based the premise that the PDB test will help to equalise the test severity in terms of Equivalent Energy Speed (EES) for all vehicles and hence improve vehicle frontal force matching for light and heavy cars and in turn help to improve compatibility in car-to-car crashes. Frontal force matching is one aspect of a car's compatibility, the other two being its structural interaction potential and compartment strength, so hence the costs and benefits for the PDB test can be assumed to be at most a fraction of those for compatibility.

The second was a preliminary analysis performed as part of the EC 6th framework APROSYS project to estimate the benefits and costs for the introduction of a full width test in Europe (Edwards and Tanucci 2008). It was assumed that this analysis could be used to give an estimate of the benefits and costs for the option to add a full width test to the current Regulation 94 ODB test.

A description of each of the analyses is given below.

6.1 Compatibility Analysis

The benefit was estimated for the UK and Germany using the UK Co-operative Crash Injury Study (CCIS) and the German In Depth Accident Study (GIDAS) accident databases, respectively. The analyses were undertaken based on the assumption that cars with improved compatibility would be able to absorb more energy in their frontal structures and prevent compartment intrusion in accidents less than the test severity, hence resulting in improved occupant protection. The UK and German benefit estimates were scaled to give the benefit for the EU15 countries. The benefit was estimated to be between about 700 and 1300 fatalities saved and between about 5,000 and 15,000 seriously injured casualties prevented per year in the EU15. In 2004 there were 32,951 road accident fatalities and 251,203 seriously injured casualties in the EU15. The monetary value of this benefit was calculated to be between €2 billion and €6.5 billion per year.

The cost of improved compatibility was estimated based on the costs required to modify a current car to meet assumed compatibility requirements. Costs of between €102 and €282 per car were estimated depending on the cars current safety performance and the size of the production run. Based on the assumption that 14,211,367 cars are registered each year in the EU15, this equates to a total cost of between about €1.5 billion and €4 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 was 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.

6.2 Full Width Test Analysis

The benefit for Europe was estimated by scaling the results from a study which estimated the benefit for GB (Thompson et al. 2007). Another study, based on German accident data, was also considered for use in this work. However, it was not used because a review of the analysis found that it did not take into account a key confounding factor which, most likely, significantly influenced the results. It is known that a full width test produces a higher compartment deceleration in a car than the offset deformable barrier test, and so it is a more severe test for the restraint systems in the car. Following this argument, the GB benefit analysis was based on the assumption that the introduction of a full width test in Europe would encourage improved restraint systems, which would in turn reduce restraint-induced injury. It was assumed that the main body regions that would benefit from a reduction in restraint-induced injury would be those normally loaded by the webbing of a three-point seat belt, namely the thorax and abdomen. Restraint induced injuries were identified as those which occurred in impacts where the occupant was loaded by the restraint system only, i.e. those where there was little or no steering wheel or compartment intrusion.

The benefit for GB was estimated to be a reduction in annual car occupant fatalities of approximately 3 percent (47 occupants) and serious casualties of approximately 6 percent (812 occupants) [Table 6.1].

Table 6.1. Annual reduction in car occupant casualties for GB.

	GB National Benefit		
	Original number	Reduction No	Reduction %
Fatalities	1695	47	3
Serious Casualties	14,512	812	6

An additional interesting finding was that if the calculation was repeated using a target population that included elderly casualties, i.e. those over 65 years old, the benefit predicted increased substantially to a 5 percent reduction in fatalities and a 7 percent reduction in seriously injured casualties. This indicates a large potential benefit for restraint systems that could provide better protection to elderly occupants.

The benefit for Europe was estimated by simple scaling of the GB benefit. It should be noted that scaling of benefit in this manner will only give an order of magnitude estimate of the benefit for Europe. This is because the accident pattern varies considerably from country to country and hence this type of direct scaling can introduce large errors. The Monetary Value of this benefit was calculated using GB quoted values for each life saved (£1,489,450) and serious injury avoided (£167,360) (RCGB 2006). An exchange rate of 1.2 € per £ was assumed. It should be noted that, in general, the GB values are higher than those used for other European countries as they include a ‘Willingness to Pay’ element. For the EU15 countries the monetary value of the benefit was about €2,000 million per year [Table 6.2].

Table 6.2. Estimated benefit for Europe for introduction of full width test.

	Casualties Prevented		Financial Benefit (€Million)
	Fatal	Serious	
EU15	430	6,017	€1,976
EU25	574	8,038	€2,640
EU27	625	8,756	€2,876

The cost analysis performed was based on the cost to modify a typical European car to meet either UNECE Regulation 94 or US FMVSS208 equivalent performance limits in a full width test. Full width tests were performed with a 'Small family' car as part of the APROSYS project. The results from these tests were assumed to be representative of a typical European car and used for the cost analysis. The crash test results for the 'Small family' car were examined and necessary modifications to the car to consistently meet Regulation 94 or FMVSS208 performance limits in the test were identified using expert judgement. The costs of these modifications were estimated and scaled to give an estimate of the total cost per year for the EU15 countries. This was achieved by multiplying the cost per car by the average number of new cars registered per year in the EU15 countries. ACEA data showed this to be 14,221,978 for the years 1999 to 2004 inclusive.

Table 6.3. Cost of restraint system modifications to meet US FMVSS208 or UNECE Regulation 94 performance limits per car and for the EU15 countries.

Performance limit	Cost per car (€)	Total Cost for EU15 per year (€)
FMVSS208	17	242 Million
UNECE R94	32	455 Million

Many cars sold in Europe are also sold in countries, such as the US, where a full width test is already part of the regulatory requirements. These cars are likely to perform better in a full width test than the typical European 'Small family 1' car on which the analysis was based and therefore require fewer modifications to meet the performance requirements. Hence the costs estimated are likely to be high.

In summary, for the EU15, a potential benefit of up to approximately €2,000 million per year was estimated for the introduction of a full width test. A cost of €242 million was estimated to meet FMVSS208 limits in the test and €455 million to meet Regulation 94 limits. Assuming that performance limits similar to the Regulation 94 ones are required to deliver the potential benefit, this results in a cost to benefit ratio of about 1:4. However, more stringent performance limits and other measures are likely to be needed to deliver all of the estimated benefit, which would require additional modifications to the car and inevitably increase the cost. These modifications may include adaptive restraint systems. Further work is required to determine appropriate performance limits and update the cost benefit analysis.

7 Review of Potential Options to Change Legislation

7.1 Introduction

In this section the potential options identified in Section 5 to improve frontal impact legislation in the short term are reviewed and recommendations for the way forward provided.

The potential options identified were:

'Main' options

1. No change.
    - The option to keep the frontal impact legislation as it is now. This option provides the baseline against which the other options should be considered.
2. Replace the current R94 ODB test with a Progressive Deformable Barrier (PDB) test.
    - As proposed by France at the December 2007 GRSP meeting this option was suggested as a means of resolving current issues with the ODB test severity and barrier stability. The existing ODB design would be replaced by a PDB.
3. Add a full width high deceleration test to the current UNECE Regulation 94 ODB test procedure.
    - Two approaches have been identified to fulfil this option; the introduction of a Full Width Deformable Barrier (FWDB) or a Full Width Rigid Barrier (FWRB) test. The FWDB test is more advanced with respect to measures that can be used to control compatibility whilst a FWRB is more closely aligned with legislative requirements in other parts of the world.
4. Combination of options 2 and 3.

'Supplementary' options

Dummy related:

a. Incorporation of the THOR-Lx, and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy.

Other:

b. Extension of scope to include all vehicles of M1 category and N1 vehicles.

c. Steering wheel movement controlled through the addition of a 100 mm horizontal displacement limit.

d. Footwell intrusion controlled through the assessment against a specifically developed criterion and associated pass or fail limit.

e. Assessment of protection afforded in rear seated positions.

It should be noted that these potential options were presented to the GRSP informal working group on frontal impact for their consideration at a meeting in March 2009.

In alignment with the 'better regulation' principles introduced by the Commission and the CARS 21[2] initiative, ideally a full proposal to change regulation should contain the following:

- An evidence base showing the reason why the regulation needs to be changed.
- A detailed proposal showing how the regulation should be changed, i.e. additional test procedures and/or amendments required to current test procedures
- An impact assessment for the proposed change, i.e. an assessment of the benefits and the costs and other possible consequences.

In the longer term it is expected that Regulation 94 will be updated to incorporate measures to assess and control a vehicle's compatibility. Hence, any changes that are made to the Regulation now need to be suitable for upgrade to include compatibility measures in the future to ensure that these changes will not have to be undone when compatibility measures are added and put an unnecessary burden on manufacturers.

Bearing the above in mind, the review of the main options included consideration of:

- Whether the option will address the needs identified in the accident studies
- Potential for unintended consequences
- Potential for further development to include measures to assess and control compatibility
- Relationship with present international requirements
- Cost-benefit

From the results of the review a list of issues, if any, that require further investigation to ensure each option's suitability for regulatory application was made.

For the supplementary options the review considered the pros and cons of each option and listed issues that require further investigation to ensure their suitability for regulatory application. As the exact means of implementation and interactions with the main options were not known, cost-benefit evaluations were not considered in detail for the supplementary options.

As part of the review, industry was consulted to obtain comment on the costs and other issues that the proposed options may impose on vehicle manufacturers over and above that which is already incurred with the existing Regulation 94 standard. The consultation was performed by sending motor manufacturer associations, such as ACEA, and individual vehicle manufacturers a letter requesting this information. The letter is contained in Appendix A. Responses were received from eleven manufacturers, namely Audi, BMW, Daimler, Ford, Honda, Jaguar Landrover, PSA, Renault, Toyota, Volvo and VW AG.

The comments from the manufacturers on the individual proposed options are described in the relevant sections below. However, general comments were also made. These comments emphasized that any potential upgrade to Regulation 94 must be justified by a need, a benefit and an assessment of costs which considers the accident situation in Europe. This is in alignment with the CARS 21 initiative and the 'better regulation' principles introduced by the Commission, in particular the requirement for an impact assessment for a change to regulation.

[2] CARS 21 was initiated in 2005 and championed by the European Commission to strengthen the 'engine of Europe', the automotive industry. CARS 21 (Competitive Automotive Regulatory System for the 21st Century) involved representatives of national governments, European Commissioners, the European Parliament, the automotive industry, environmentalists, trade unions, suppliers, consumers and the oil industry. Together, they made recommendations on the regulatory framework of the European automotive industry, with the goal of "enhancing global competitiveness and employment while sustaining further progress in safety and environmental performance at a price affordable to the consumer".

7.2 Review of the Main Options

7.2.1 Option 1: No Change

7.2.1.1 Needs identified from accident studies

Accident studies have identified three principle types of loading to the vehicle front structure, namely loading to one longitudinal beam and the engine (given by the current Regulation 94 test), loading to both longitudinal beams and the engine (given by a full width test) and loading to either one longitudinal and side structures or side structures only (given by a small overlap test). By making no change to the existing frontal impact legislation, regulatory testing will still only address one of these three principal types of frontal impact collisions and will still not accurately address the loading conditions experienced in accidents that occur with full-width or low overlap engagement of the vehicle frontal structure. Accidents in which the full width of the vehicle front is involved have been identified as a priority for safety improvements. These impacts are typically associated with a more severe deceleration pulse than impacts involving less of the vehicle front. As such they provide a stern test of the occupant restraint system.

Accident studies have identified that the majority (~50%) of front impact casualties are in car-to-car crashes when considering the object hit in the collision. A smaller proportion of fatal frontal impacts are car-to-car than the proportion of all severity frontal impacts. However, car-to-car impacts still appear to be of the greatest importance before pole/tree or heavy vehicle collisions. The Offset Deformable Barrier (ODB) was designed to replicate the structural loading experienced in a car-to-car collision. However, concerns are being raised now as to how well the stiffness of the ODB represents that of modern vehicles. Also, the stiff longitudinal structures of many vehicles are able to 'bottom out' the ODB and load the rigid block behind the ODB directly. This creates a loading regime which is obviously unlike that of a real world car-to-car collision. By making no change to the regulation, this issue will not be addressed.

Accident analyses have also identified thoracic injuries as a priority for mitigation and/or prevention. Thorax injuries are primarily related to interaction between the occupant and the restraint system and hence mainly related to the occupant compartment deceleration. The offset test is primarily a test to control intrusion related injuries whilst the full width test is primarily to control deceleration related injuries. Hence, by making no change regulatory testing will not address thoracic injuries fully.

7.2.1.2 Potential for unintended consequences

By definition, the 'no change' option will not have any potential for unintended consequences, over and above any existing potential. This assumes that changes to vehicle frontal structures brought about by existing regulation and consumer information testing programmes, such as Euro NCAP, will not create potential issues. One potential issue is that the ODB test is more severe for heavier cars than light cars. This encourages an increase in the frontal force mismatch between light and heavy cars, which in turn exacerbates compatibility problems in car to car crashes. This issue has been discussed previously in section 5.3.1 and is part of the main justification given for the proposal to change the current Offset Deformable Barrier (ODB) to a Progressive Deformable Barrier (PDB). Another potential issue is that the increased vehicle frontal force levels encouraged for good frontal impact self protection may be dis-beneficial in side impacts. At present there is no definite evidence in the literature that this is 'real' issue; however it is an area that some researchers are concerned about.

7.2.1.3 Potential for further development to assess and control compatibility

There are three aspects to compatibility; structural interaction, frontal force matching and compartment strength. The EC 5th framework VC-Compat project (VC-Compat 2007) identified that the ODB test had some potential to assess and control a vehicle's frontal force levels using measurements from a Load Cell Wall (LCW) mounted behind the deformable barrier face. This measure could also be used to give some indication of the compartment strength. However, it should be noted that there are problems with this measure related to 'engine dump' loading which the PDB barrier resolves. The ODB test has no potential for making assessments about the structural interaction between vehicle frontal structures.

7.2.1.4 Relationship with present international requirements

Making no change to Regulation 94 would obviously maintain the current relationship with present international requirements. In particular this would maintain the use of the ODB test, which is currently virtually a defacto worldwide harmonised test procedure.

7.2.1.5 Cost-benefit-related information

Whilst the 'no change' option has no additional cost associated with it, there is on-going benefit accruing as the vehicle fleet is updated to meet the requirements of Regulation 94. In Europe the Frontal Impact Directive 96/79/EC, which is equivalent to Regulation 94, came into force on 1st October 1998. It was introduced in two phases. Phase 1 mandated that all new vehicle types approved after 1st October 1998 had to comply with the Directive requirements. Phase 2 mandated that all vehicles registered after 1st Oct 2003 had to comply. The outcome of this phased introduction is that some vehicles registered between 1st October 1998 and 2003 may not meet the Directive requirements, but all vehicles registered after 2003 will. Figure 7.1 shows that the proportion of the vehicle fleet greater 10 years old which did not have to meet the Directive requirements is about 30%. This gives an indication of the number of vehicles in the current fleet whose safety level could potentially be improved to meet the Directive requirements as the vehicle fleet is updated. It should be noted that some of these older vehicles may already meet the Directive requirements even though they were not tested.

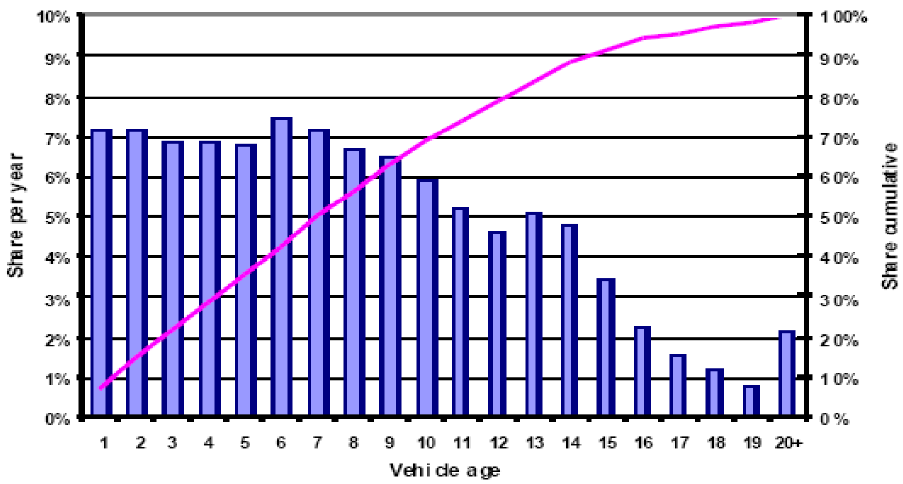


Figure 7.1: Vehicle fleet age distribution in Germany. (Data provided by BASt)

The European New Car Assessment Programme (Euro NCAP) which was established in 1997 provides consumers with a safety performance assessment for the majority of the most popular cars in Europe. In conjunction with the Regulation 94 test, Euro NCAP continues to motivate advances in vehicle frontal impact performance in excess of those required for regulation. It should be noted that Euro NCAP generally tests the most popular model size whereas for regulatory purposes the worst case is tested. A study performed by SARAC[3] has shown that the Euro NCAP star rating correlates to the crash outcome in accidents (SARAC 2006). The advances in vehicle frontal impact performance encouraged by Euro NCAP and their associated benefits are expected to continue into the future as more cars achieve high Euro NCAP star ratings and the vehicle fleet is updated. It is also expected that Euro NCAP will drive further advances in vehicle safety, although no specific measures have been announced to upgrade the frontal impact assessment to date.

7.2.1.6 Manufacturer comments in response to consultation

A number of manufacturers pointed out that over the past ten years the number of road accident fatalities has decreased year on year and there is evidence to suggest that improved car safety design driven by Regulation 94, Euro NCAP and additional manufacturer specific in-house safety requirements has helped contribute to this reduction. They also emphasized that it is expected that the increasing share of vehicles in the European fleet with modern safety designs (year 2000 and newer) in the future will help to continue this decrease. An additional supportive effect is expected by the increasing fleet penetration of active safety technologies such as Electronic Stability Control (ESC) and Brake Assist Systems (BAS). On this basis the majority of manufacturers (nine out of eleven) supported the ‘no change’ option.

7.2.1.7 Issues that require further investigation

Issues that require further investigation if this option is taken forward are noted below together with proposals for specific work items:

- Because the Regulation 94 test is more severe for heavy cars than light cars this could encourage an increase in the frontal force mismatch between light and heavy cars which could exacerbate compatibility problems in car to car frontal impacts.
    - To help address this issue the frontal force levels of vehicles could be monitored to check if the magnitude of the problem is increasing or not. If it was found that the problem was increasing then remedial action would need to be taken. Monitoring the force levels could be achieved by placing a load cell wall behind the Offset Deformable Barrier in Regulation 94 type approval tests to collect force data to give an indication of how the frontal force levels of vehicles is evolving. This data could also be collected in Euro NCAP tests.
- Some researchers are concerned that increased vehicle frontal force levels encouraged by regulation and Euro NCAP for improved frontal impact self protection may be dis-beneficial in side impacts, although there is no definite evidence to support this.
    - To help address this issue accident analysis work could be performed to investigate and if necessary quantify the magnitude of this possible problem.

7.2.1.8 Summary

If this option were chosen casualties in frontal impacts would be expected to continue to decrease in the short term as a result of increasing market penetration of Regulation 94

[3] SARAC: Safety Rating Advisory Committee (SARAC) is an international forum initiated by the German insurance organisation GDV and the European Comité Europeén des Assurances (CEA).

compliant cars and Euro NCAP ‘5 star’ rated cars. However, in the longer term this effect would cease, although casualty numbers may continue to decrease as a result of other interventions such as ESC and BAS. However, there is the possibility that the frontal force mis-match between light and heavy cars could increase and exacerbate the compatibility problem which would negate some of the casualty savings. Also, there is a small possibility that increased frontal force levels of cars encouraged by Regulation 94 and Euro NCAP may cause increased casualties in side impacts. If this option is chosen it is recommended that these issues are investigated further.

7.2.2 Option 2: Replace the current Regulation 94 ODB test with PDB test

7.2.2.1 Needs identified from accident studies

This option offers no improvement over the ‘no change’ option, in terms of accurately representing the three main collision types identified in the accident data. It also offers no significant improvement for the assessment of thoracic injury because the deceleration pulse is not substantially higher than for the ODB test. However, this option should help improve the replication of the structural loading experienced in car-to-car collisions compared to the ODB test. As described in Section 5.3.1.3, this is because the PDB barrier face is designed so that a car’s structure does not ‘bottom out’ the barrier face and load the rigid wall behind it as with the ODB test. It should be noted that better replication of car-to-car collisions was one of the original aims of the ODB test.

7.2.2.2 Potential for unintended consequences

One of the main objectives of the current Regulation 94 test is to ensure vehicles have sufficient energy absorption capability in their front ends to absorb the impact energy in an offset collision in accidents up to an Equivalent Energy Speed (EES) of about 50 km/h, i.e. a collision with an identical car with a closing speed of 100 km/h. (Note: the barrier absorbs some energy so that is why the test speed is 56 km/h). As described in Section 5.3.1.3, because the PDB deformable element has a significantly higher energy absorption capability than the current ODB due to its increased stiffness, this option has a potential unintended consequence that it could potentially permit the design of vehicles with a reduced front-end ‘crumple zone’ and, in theory, rigid vehicles. Such a vehicle design may perform well in the PDB test by using the energy absorption capability in the barrier face but have catastrophic results in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential. This would consequently lead to deformation of the occupant compartment and its failure.

7.2.2.3 Potential for further development to assess and control compatibility

A number of candidate parameters have been proposed for the PDB test which could potentially be used as criteria to assess and control a vehicle’s compatibility, i.e. partner protection (EEVC WG15 2007). These are based on the deformation of the barrier and possibly on measurements from a Load Cell Wall positioned behind the barrier face as detailed in Section 5.3.1.2. Although these parameters show good potential to be used to assess a vehicle’s compatibility in the future, some fundamental issues still need to be resolved to confirm their feasibility and much further work is required to develop compatibility assessment criteria and associated performance limits suitable for regulatory application.

7.2.2.4 Relationship with present international requirements

The ODB test used in Regulation 94 is currently virtually a defacto worldwide harmonised test procedure. Hence, if the ODB test was replaced by PDB test in Regulation 94, then to maintain this relationship it would be necessary for consumer test programmes and other approval bodies throughout the world that use the ODB test to switch to a PDB test as well, otherwise manufacturers would have to design for both ODB and PDB tests. However, to do this would require prior arrangement and alignment of implementation with other approval and consumer testing bodies. Such organisation would involve a large amount of negotiation.

7.2.2.5 Cost-benefit-related information

Currently, France is performing a benefit analysis based on French national data (Chauvel C 2009). This analysis is scheduled to be completed and reported to the GRSP frontal impact informal working group in December 2009.

An analysis was performed as part of the EC 5th framework VC-Compat project to estimate the benefits and costs to introduce regulatory measures in Europe to improve a car's compatibility (Section 6.1). It was assumed that this analysis could be used to give an upper bound for the benefits and costs for the replacement of the current ODB test with the PDB test. This assumption was based the premise that the PDB test will help to equalise the test severity in terms of Equivalent Energy Speed (EES) for all vehicles and hence improve vehicle frontal force matching for light and heavy cars and in turn help to improve compatibility in car-to-car crashes. Frontal force matching is one aspect of a car's compatibility, the other two being its structural interaction potential and compartment strength, so hence the benefits and costs for the PDB test can be assumed to be at most a fraction of those for compatibility. How a large a fraction is unknown.

The benefit estimated for improved compatibility was between about 700 and 1300 fatalities saved and between about 5,000 and 15,000 seriously injured casualties prevented per year in the EU15. This is a substantial benefit but the question is what fraction of this benefit would the PDB test deliver?

In considering this question it should also be noted that a French test programme which compared the performance of cars in an ODB test that in a PDB test showed that although the dummy injury criteria values were higher in the PDB test for a vehicle designed in 1998, they were similar for vehicles designed in 2000 and 2004, i.e. modern vehicles (Figure 7.2) (VDA 2008). In addition, all the injury criteria values were below the Regulation 94 performance limits.

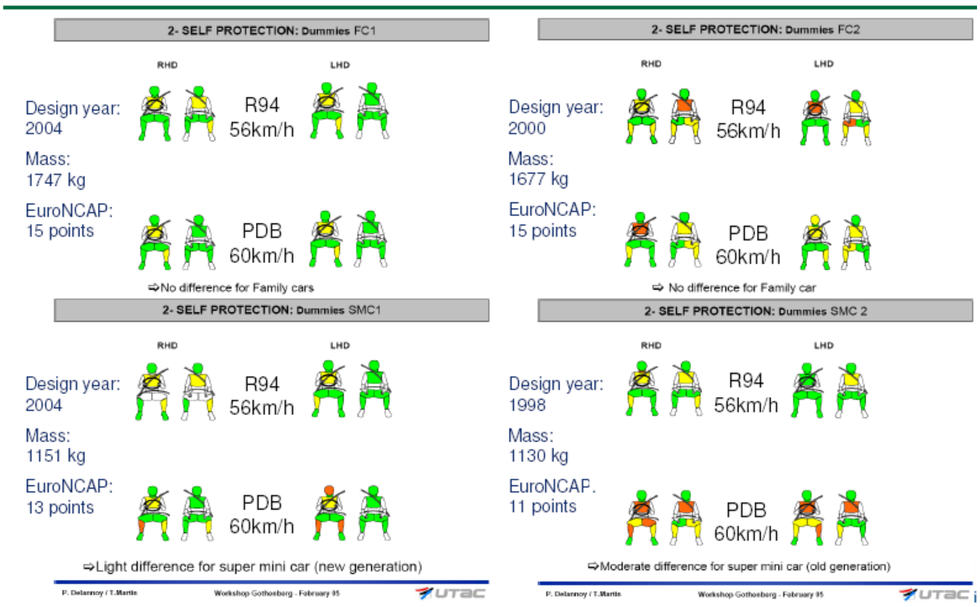


Figure 7.2: Comparison of dummy injury criteria values for ODB and PDB tests.

For there to be a benefit in replacing the current ODB test with the PDB test then this change must enforce changes to the vehicle design which improve its safety performance. The results above indicate that a change to the PDB test may not enforce any changes to the design of modern vehicles and thus may not offer any benefit.

Recent tests performed in Japan by JMLIT and reported to the GRSP frontal impact informal working group also show no significant difference in the dummy injury criteria values for 56 km/h ODB and 60 km/h PDB tests performed with a mini-car (JMLIT 2009).

It is difficult to envisage how replacement of the ODB test with the PDB test could guarantee any benefit if it does not enforce vehicle design to change. However, even though it may not enforce vehicle designs to change, it could encourage them to change. For example, to help meet CO_2 emission requirements manufacturers will wish to reduce the weight of their vehicle designs. The PDB test may offer manufacturers the opportunity to reduce the weight of their heavy vehicles by reducing their frontal force levels, which in turn would offer benefit in terms of an improvement in vehicle crash compatibility through better matching of vehicle force levels. It will be interesting to observe how this issue is dealt with in the benefit analysis currently being performed by France.

In conclusion the benefit of the PDB test could be substantial but it is most likely to be close to zero because comparison of ODB and PDB test data indicates that it does not appear to enforce substantial design changes to the vehicle.

Because it is uncertain what changes to vehicle design would be needed if the ODB test was replaced with a PDB test - it may be the case that no changes are needed – it is not possible to estimate the costs for this change. However, even if no changes to the vehicle design were needed there would be a minimum cost for the changes that a manufacturer would need to make to incorporate the PDB test into the design process. These costs would include items such as an FE model of the PDB barrier face and building the design engineer’s experience for the PDB test. One manufacturer estimated that costs could be anywhere between 0 and €50 per car.

7.2.2.6 Manufacturer comments in response to consultation

The majority (nine out of eleven) of the manufacturers that responded did not support the replacement of the current ODB test with a PDB test. The reasons given were:

- There is currently no evidence that this change would result in any benefit.
- There is a possibility that the high energy absorption capability of the PDB face could be mis-used and allow vehicles to be designed with insufficient energy absorption capability for self protection in collisions with more rigid objects such as poles.

Two manufacturers supported the replacement of ODB test with a PDB test. The main reason given was:

- It resolves problems with the current R94 barrier face, in particular the increased severity of the test for heavier vehicles caused by the barrier ‘bottoming out’ in the test.

It is interesting to note that both these manufacturers also supported the introduction of a Full Width Rigid Barrier (FWRB) test. The introduction of this test in parallel with the PDB test could help resolve the PDB mis-use problem highlighted by the other manufacturers above.

7.2.2.7 Issues that require further investigation

The following two major issues need to be resolved before this option could be considered suitable for regulatory application:

- An accurate assessment of the benefits and costs
  - Note: As mentioned above France is currently performing a benefit analysis which is scheduled to be reported in Dec 2009.
- Evidence to show that the potential unintended consequence that this option may allow the design of unsafe vehicles with a reduced front-end 'crumple zone' is not feasible and so will not happen.
  - Note: This issue is currently being debated within the GRSP frontal impact informal working group.

Other issues which require further investigation include:

- Confirmation that replacement of the ODB with the PDB test will guarantee that the self-protection level of future vehicles will not decrease, that it will equalise the test severity for light and heavy vehicles and that the PDB barrier face stiffness is appropriate for testing of future vehicles.
- Confirmation that adoption of the PDB will not encourage the height of vehicle main structures to be lowered as this could lead to structural interaction type compatibility problems.
- Confirmation of the repeatability and reproducibility of the PDB test.

Note: Further details can be found in Section 5.3.1.3.

7.2.2.8 Summary

This option has the potential to resolve a number of issues with the current ODB test procedure, namely to represent better the loading experienced in a car-to-car impact which should help encourage car designs which perform better in car-to-car impacts and to equalise the test severity which should help improve the frontal force matching aspect of compatibility. However, its increased energy absorption capability compared to the ODB test could permit the design of vehicles with a reduced front-end 'crumple zone' and, in theory, rigid vehicles. Such a vehicle design would be unsafe in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential. There is insufficient information available for a detailed cost benefit analysis but a preliminary study suggests that the benefit is likely to be low because comparison of ODB and PDB test data indicates that it does not appear to enforce substantial design changes to the vehicle. As the current Regulation 94 ODB test is virtually a worldwide harmonised test procedure a change to the PDB test would be detrimental for harmonisation unless other approval and consumer testing bodies also changed to the PDB test.

To consider this option further for regulatory application further work is required to assess the benefits and costs more accurately and to assess the risk of that it could permit the design of unsafe vehicles.

7.2.3 Option 3: Add Full Width test to current R94 ODB test

7.2.3.1 Needs identified from accident studies

The accident studies identified three principle types of frontal impact collisions which regulatory tests should ideally replicate, offset, full-width and low overlap. Adding a full-width test to the current ODB test would mean that two principle types of collisions were replicated by regulation, offset and full width. This would also meet the IHRA and EEVC recommendation that a set of test procedures to assess a car's frontal impact crashworthiness should contain both offset and full-width tests.

The accident studies also identified thoracic injuries as a priority for mitigation and/or prevention. The thorax was the highest priority for AIS 3+ injury (UK and German data) and that the thorax was also very important when considering fatal accidents. A study of the factors related to serious thorax injury showed more than half of the injuries occurred in full overlap configurations (UK data). Thorax injuries are primarily related to interaction between the occupant and the restraint system and hence mainly related to the occupant compartment deceleration. The full width test is primarily a test to control deceleration related injuries and hence would be useful to drive improvements in restraint technology and therefore reductions in thorax injury risk. However, it should be noted that although some benefit may accrue from the use of the current Hybrid III frontal impact dummy in a full width test, ideally a new dummy with better biofidelity and injury assessment capability would be required to properly assess the protection offered by improved restraint systems and thus ensure that potential benefits were maximised.

Based on GIDAS data, it was estimated that advanced adaptive restraint systems of the future could provide better protection for 31 percent of all car drivers with MAIS 3+ injuries (Gonter et al., 2004). A full width test could be used to help encourage this type of restraint system.

7.2.3.2 Potential for unintended consequences

No unintended consequences are expected with the introduction of a full-width test because full-width tests are used already throughout the world in the countries such as the USA, Canada, Australia and Japan.

7.2.3.3 Potential for further development to assess and control compatibility

As mentioned previously, to improve compatibility in car frontal collisions it is generally agreed that better structural interaction, matching frontal forces (stiffnesses) and a strong occupant compartment, in particular for small cars, are required.

Two types of full-width test are proposed one with a rigid barrier and one with a deformable face. As noted in section 5.3.3.2, work has been performed in the USA to develop Load Cell Wall (LCW) based criteria to control a vehicle’s structural interaction and its stiffness in a Full Width Rigid Barrier (FWRB) test. Although some initial work to investigate the feasibility of these criteria has been performed they are still at the ‘research stage’.

The deformable face in the Full Width Deformable Barrier (FWDB) test has a number of advantages over the rigid face for the assessment of compatibility. These include the attenuation of the ‘engine dump’ load seen with the rigid face which makes it easier to identify loads from the vehicle’s structure and the generation of relative shear in the vehicle’s front structure which makes it possible to detect horizontal structures such as bumper crossbeams. As noted in section 5.3.2.2 much work has been performed to develop criteria for the FWDB test to assess a vehicle’s structural interaction potential using LCW measurements. Proposals include the Structural Interaction (SI) criterion to assess a car’s structural interaction potential and a minimum row load criterion to control the compatibility of Light Trucks and Vans (LTVs). Initial validation of these criteria has been performed and shows that they have potential. However, recent work (APROSYS 2008) has found repeatability problems with the horizontal component of the Structural Interaction criterion.

In summary, for both the full width rigid and deformable barrier tests although initial proposals for performance criteria and limits have been made which show promise, much further work is required to resolve identified problems and develop them to a level suitable for regulatory application.

7.2.3.4 Relationship with present international requirements

As detailed in section 2 a full width test with a rigid barrier face is already part of the regulatory requirements in many parts of the world, namely the USA, Canada, Japan, Australia, China and the Gulf States, and hence is virtually a defacto worldwide harmonised test procedure. It should be noted that there are some differences between the test in the various countries. The most significant of these is the test speed; for all countries except the USA it is 50 km/h, in the USA it has recently changed to 56 km/h.

Therefore, the adoption of a full-width test with a rigid barrier into European frontal impact legislative requirements would help harmonisation. However, the majority of recent research within Europe has been based on a full-width deformable barrier test. This is because of the advantages the deformable element offers for the assessment of compatibility. To introduce a full-width test with a deformable face into Regulation 94 would, therefore, entail changing the current full-width rigid test to a deformable one in countries which have adopted Regulation 94, such as Japan and Australia. This would also cause harmonisation problems with countries such as the USA and Canada which have not adopted Regulation 94.

In summary, the adoption of a full-width test into Regulation 94 would help harmonisation. At present all regulatory full-width tests have a rigid face, so the inclusion of a deformable face would be detrimental for harmonisation. A test speed of 56 km/h would harmonise with the USA, whom have recently changed from 50 km/h to 56 km/h. However, a test at 56 km/h would not harmonise with other countries such as Canada, Japan and Australia but these countries may increase the test speed in the near future to harmonise with the USA.

7.2.3.5 Cost-benefit-related information

An initial cost benefit analysis was performed by the EC 6th framework APROSYS project to estimate the benefits and costs to introduce a full-width test into the European regulatory regime (Section 6.2). A test speed of 56 km/h was assumed for this analysis.

A potential benefit of up to 3 % of car occupant fatalities saved and 6% of seriously injured car occupants prevented per year was estimated based on the assumption that the introduction of a full-width test would improve restraint systems which in turn would reduce restraint-induced injury. For the EU15 countries this equates to 430 fatalities saved and 6,017 serious injuries prevented, which in monetary terms is approximately €2,000 million. A cost of €242 million was estimated to meet FMVSS208 equivalent limits in the test and €455 million to meet Regulation 94 limits. Assuming that performance limits similar to the Regulation 94 ones are required to deliver the potential benefit, this results in a cost to benefit ratio of about 1:4. However, it is likely that more stringent performance limits and other measures would be needed to deliver all of the potential benefit, which would require additional modifications to the car and inevitably increase the cost. These modifications may include adaptive restraint systems. To assess these systems an improved dummy would be needed because the biofidelity and injury assessment capability of the Hybrid III dummy is insufficient to drive the development of adaptive restraint systems (Section 4). Much further work is required to develop appropriate performance limits and other measures needed to deliver all of the potential benefit and update the cost benefit analysis. At stage it is not possible to estimate accurately the benefits and costs for the introduction of a full-width test. However, in the authors' opinions the introduction of a full-width test with the Regulation 94 equivalent performance limits and the current Hybrid III dummy would have a cost benefit ratio much less than 1:4 and maybe as low as 1:1. This is because adaptive restraint systems would not have to be fitted to meet these performance limits. However, a full width test which enforced the fitting of adaptive restraint systems could have a cost benefit ratio close to 1:4.

7.2.3.6 Manufacturer comments in response to consultation

The manufacturers that responded were, in general, supportive of adding a full-width test to the current Regulation 94 ODB test provided that the benefit of this action could be clearly shown in a regulatory impact assessment. Nearly all manufacturers stated a preference for a test with a rigid barrier and a test speed of 50 km/h because they believed that this configuration offered the best solution for harmonisation even though this would not harmonise with the test in FMVSS208 which has a test speed of 56 km/h.

7.2.3.7 Rigid or deformable barrier face

As noted above (Section 7.2.3.3) the deformable face in the Full Width Deformable Barrier (FWDB) test has a number of advantages over the rigid face for the assessment of compatibility. Also, research has shown that a deformable face could be useful to help ensure a more realistic assessment of a vehicle's crash sensing capability although it should be noted that this has not been shown to be a problem in accidents. However, the rigid face is far better from the harmonisation point of view because all current regulatory full-width tests have a rigid face. If it was decided to introduce a full-width test in the short term the authors suggest that a test with a rigid face would be the best option. This is because:

- Currently it is not known whether or not a deformable face will be needed for the assessment of compatibility and one could be added at a later date if necessary if and when the regulation is updated to include the assessment of compatibility.
- A test with a rigid face is clearly better from a harmonisation point of view

7.2.3.8 Issues that require further investigation

The following major issue needs to be resolved before this option could be considered suitable for regulatory application:

- Determination of appropriate performance criteria and limits and update of cost benefit analysis

7.2.3.9 Summary

The addition of a full width test would mean that two of the principle types of collision, namely offset and full-width, were replicated by regulation. It would also fulfil the IHRA and EEVC recommendation that both offset and full-width tests should be used to assess a car's frontal impact crashworthiness and aid the harmonisation of test procedures worldwide because Europe is one of the few areas in the world that does not have a full-width regulatory test procedure. A full-width test is primarily a test to control deceleration related injuries and hence has the potential to drive improvements in restraint technology and consequently reductions in thorax injury risk which has been identified as a priority for mitigation. At stage it is not possible to estimate accurately the benefits and costs for the addition of a full-width test. Examination of the literature suggests that for a test with a test speed of 56 km/h and Regulation 94 equivalent performance limits, although the cost benefit ratio could be as high as 1:4, it is likely to be much less, maybe as low as 1:1. This is because more stringent performance limits and other measures are likely to be needed to deliver all of the potential benefit, which would require additional modifications to the car and inevitably increase the cost. These modifications may include adaptive restraint systems. To assess these systems an improved dummy would be needed because the biofidelity and injury assessment capability of the Hybrid III dummy is insufficient to drive the development of adaptive restraint systems. Unfortunately, an improved dummy is not likely to be available in the short term. Hence the cost benefit ratio for this option is likely to be low unless a way can be found to deliver the potential benefit estimated using the current Hybrid III with appropriate performance criteria and limits. This conclusion is in line with the comments made by manufacturers.

For the introduction of a full-width test in the short term a rigid face would be a better option than a deformable face.

To consider this option further for regulatory application work is required to determine appropriate performance criteria and limits and other measures needed to deliver the potential benefit and also to update the cost benefit analysis.

7.2.4 Option 4: Combination of Options 2 and 3

7.2.4.1 Needs identified from accident studies

This option addresses the needs identified for its individual components that have been detailed in the previous sections; namely that the addition of a full-width test means that this option replicates two of the principle loading types (offset and full-width) identified in the accident analysis and the change to a PDB test means that this option also gives a better replication of the loading seen in car to car impacts.

7.2.4.2 Potential for unintended consequences

As mentioned in section 7.2.2.2, option 2 to replace the current ODB test with the PDB test could have the unintended consequence of allowing the design of vehicles with a reduced front-end ‘crumple zone’ and, in theory, rigid vehicles. Such a vehicle design would be unsafe in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential.

By including a full-width test, this option at least limits this potential unintended consequence and possibly resolves it. One characteristic of the full-width test is that it produces a high compartment deceleration pulse because both sides of the vehicle’s structure are engaged in the impact and hence the impact forces are higher than for an offset test in which only one side of the vehicle’s structure is engaged. Hence the full-width test would limit a vehicle’s stiffness and in turn the minimum length of the ‘crumple zone’ because excessively stiff vehicles would produce such a high deceleration pulse that dummy injury criteria performance limits would not be able to be met.

7.2.4.1 Potential for further development to assess and control compatibility

This combined option would give the largest choice for the introduction of compatibility assessment measures because deformation based measures are potentially available for the PDB test and Load Cell Wall force based measures potentially available for the full-width test. It should be noted that more measures are potentially available for the full width test with a deformable face compared to a rigid face. The potential measures available and their development status has been detailed in previous sections.

7.2.4.2 Relationship with present international requirements

The relationship of this combined option with present international requirements is simply a summation of the relationship of its component parts, which have been described in previous sections. In summary, replacement of the current ODB test with the PDB test would be detrimental for harmonisation unless other regulatory and consumer test procedures which use the ODB test also switch to the PDB test and addition of a full-width test would help harmonisation as long as a rigid wall test was adopted.

7.2.4.1 Cost-benefit-related information

As a first approximation it should be possible to estimate the costs and benefits of this combined option by simple addition of the costs and benefits for the individual test changes. This is because replacing the ODB test with the PDB test is related to the vehicle's structure whereas the addition of a full-width test is related to the restraint system. Unfortunately as there is insufficient information available for a detailed cost benefit analysis for either component of this option, there is obviously insufficient information for this option. However, the benefit for the change to the PDB test is likely to be low and so benefit for this option would have to come from the full-width test. Although the cost benefit ratio for the full-width test could be as high as 1:4 it is likely to be much less, maybe as low as 1:1. Hence, as for the option 3 – addition of full-width test – the cost benefit ratio for this option is also likely to be low unless a way can be found to deliver the potential benefit estimated using the current Hybrid III with appropriate performance criteria and limits.

7.2.4.1 Manufacturer comments in response to consultation

There were few comments from the manufacturers on this option possibly because they believed that they had covered it with the comments that they made on the component options that make up this option. Generally, the comments made were not supportive of this option because it contained the PDB test. However, two manufacturers (the ones that were also supportive of the PDB test option) commented that the full-width test included in this combined option could help resolve the potential unintended consequence that the option to change to the PDB alone may cause, i.e. allow the design of unsafe vehicles with a reduced front-end 'crumple zone'. This was one of the main objections to the PDB test.

7.2.4.2 Issues that require further investigation

The issues that require further investigation for this combined option are the sum of the issues for the component options with the exception of the issue of the potential unintended consequence for the PDB test.

7.2.4.3 Summary

This option is effectively the summation of its component options with the advantage that the addition of the full-width test helps to at least limit and possibly resolve the potential unintended consequence with the PDB test; namely that the high energy absorption capability of the PDB could permit the design of unsafe vehicles with insufficient front-end energy absorption capability.

7.3 Review of the Supplementary Options

7.3.1 Dummy related

7.3.1.1 Lower extremity

The accident analysis review concluded that protection of the upper and lower legs remains a priority both in terms of frequency and impairment. Improved dummy lower extremities, injury criteria and injury risk functions would be beneficial in both the ODB test procedure and a future full-width overlap test. The current version of the THOR-Lx/HIIIr (Note: THOR-Lx/HIIIr is a Hybrid III with THOR lower legs) represents an improvement over the existing Hybrid III lower extremity design and has associated injury risk functions available for use in determining injury criteria.

It should be noted that there is a fundamental issue when considering the use of a dummy to assess and control lower leg injury. This issue stems from the fact that in the real-world the position of an occupant's feet is variable and in a regulation the dummy's feet can only be placed in one position for each test. The issue is how to devise a procedure that can make a representative assessment of the protection offered for the full range of occupant foot positions in a repeatable and reproducible manner given the variable nature of footwell intrusion with ideally one test. Possible solutions are to measure the most representative position possible, to specify a number of positions that could be measured in the one regulatory test or to complement this dummy type measure with a footwell intrusion type measure.

In the USA an NPRM (Notice of Proposed Rule-Making) is being drafted by NHTSA to bring the THOR-Lx/HIIIr into Part 572 of the Code of Federal Regulations (NHTSA, 2004). NHTSA consider the THOR-Lx/HIIIr to be the likely lower extremity device used in future frontal full-width and possible frontal-offset high-speed testing. Recently research has been directed towards the development of a test procedure with repeatable positioning of the THOR-Lx/HIIIr feet with respect to the pedals (Saunders et al., 2007). However, as announced last year, NHTSA has decided not to incorporate the use of the lower legs from the THOR dummy to evaluate lower leg injuries into their NCAP at this time (NHTSA 2008). Instead they are awaiting the completion of research programmes and progress within an SAE task group. The notice released by NHTSA also states that the tool has not yet undergone the necessary robustness, reproducibility, and repeatability testing that the agency believes is necessary for incorporation into an NCAP ratings program. Further assessment and review of the design of the THOR-Lx/HIIIr is expected in the future.

It is should be noted that that this option is likely to be cost-beneficial because of the large frequency and impairment costs of lower extremity injuries.

In general, the feedback from the manufacturers supported the concept of the introduction of the THOR-Lx/HIIIr. However, they also pointed out that it was not yet ready for inclusion in a regulatory test procedure.

This information shows that further work is needed before the THOR-Lx/HIIIr would be ready for inclusion in a regulatory test procedure. This work should include a cost benefit analysis.

7.3.1.2 Upper leg

Along with the adoption of the THOR-Lx as a retrofit tool for use with the Hybrid III dummy, it has been suggested that use of the THOR upper leg (thigh) and knee should be considered. The accident analyses indicated that thigh and knee injuries remain a priority for prevention based on the frequency of their occurrence and the impairment that can result.

Despite there being room for improvement, Rupp et al. (2003) found that the THOR knee and femur offered an improvement in the biofidelity (force-deflection stiffness) over the Hybrid III, when compared with a response corridor based on PMHS tests. Also, because of differences in the anthropometry of the two legs (Hybrid III and THOR) retro-fitting of the THOR legs will change the sensitivity of the dummy to seating position (Masuda et al., 2008). With the THOR legs being longer from knee to hip, one might expect higher femur compression forces and different responses at the pelvis and thorax than with the complete Hybrid III dummy (Forman et al., 2006). However, it is not expected that this effect would be large because if it was it would indicate a more fundamental problem that vehicle designs were over-optimised for performance with the Hybrid III dummy.

At this time no dummy-specific injury risk functions are available for the THOR-NT thigh, so these would need to be developed before the THOR upper leg could be adopted as a retro-fit part for use with the Hybrid III and THOR-Lx.

7.3.1.3 Summary

The accident analysis review clearly indicates that improved protection for lower extremity injuries is a priority. Retrofit of the THOR Lx (lower leg) and/or upper leg to the Hybrid III offers opportunity to improve the assessment of lower extremity injury. At present neither of these dummy improvements is ready for regulatory application in the short term although the THOR Lx is closer. These improvements are likely to be cost beneficial because of the large frequency and impairment costs of lower extremity injuries.

7.3.2 Other

7.3.2.1 Extension of scope

Consideration of the extension of the scope of the Regulation to include all M1 passenger cars and N1 light goods vehicles up to 3.5 tonnes is dependent on what test procedures are included in Regulation 94 and hence on which of the main options above is chosen. Therefore, consideration of the extension of the scope is presented for each of the test procedures which could possibly be included in Regulation 94.

For the current Regulation 94 ODB test procedure the EEVC commented that extending the scope of frontal impact legislation to include all vehicles of M1 and N1 categories up to 3.5 tonnes could encourage the heavier vehicles to become even stiffer. This would result in exacerbation of compatibility problems between those heavier vehicles and the smaller M1 vehicles tested currently. Based on this potential unintended consequence, WG15 recommended that the scope of R94 should not be extended until measures to control compatibility were in place and/or the current ODB test had been changed to allay such concerns.

The PDB test is designed to equalise test severity between light and heavier vehicles. Hence for this test the risk of exacerbating compatibility problems by including heavier vehicles in the scope would be less than for the ODB test. However, ideally to ensure that compatibility problems were not exacerbated it would be best if measures to control compatibility were in place before the scope was extended to include heavier vehicles. Also, it should be confirmed that the PDB barrier and test procedure still operate as expected with heavier vehicles.

For the full-width rigid barrier test the test severity is equal for light and heavy vehicles. Hence the situation is similar as for the PDB test, i.e. there is some risk that increasing the scope to include heavier vehicles could encourage them to become stiffer and ideally compatibility measures should be in place before the scope is extended. However, it should be noted that the full-width rigid barrier (FWRB) test is already used in the US NCAP to test some heavier vehicles and no adverse affects have been reported. The situation for the full-width deformable barrier test is expected to be similar to that for the rigid barrier test because the deformable face only absorbs a small proportion of the vehicle's impact energy.

The accident studies revealed little recent data in the literature for M1 and N1 vehicles not covered by the current legislation. EEVC reported in 2000 that N1 vehicles were involved in similar accidents to M1 vehicles. Smith and Knight (2005) reported more recently that for the UK between 1993 and 2003 that, although the accident rate had reduced more for Light Commercial Vehicles (LCV – N1 vehicles not including car-derived N1 vehicles) than for all vehicles (43% cf 21%), since 1999 the fatality rate for accidents involving LCVs has risen or stayed constant. They also estimated the likely benefits from possible countermeasures. For enforcement of wearing a seatbelt and improved frontal crashworthiness they estimated that 1.9% of fatalities (327 per year for the UK) could be saved.

In general, feedback from the manufacturers did not support this change for the following reasons:

- The potential unintended consequence of worsening compatibility.
- Justification of the need for the change in terms of the benefit.

In summary, there are significant benefits to extending the scope of the Regulation to include at least LCVs in terms of improved protection for the LCV occupants (self protection). However, there may also be an unintended consequence in terms of worsening compatibility (partner protection) as LCVs may become stiffer and hence more aggressive. Hence, ideally it would be best to introduce measures to control compatibility before consideration of an increase in the scope. However, if it could be shown that the unintended consequence of increasing the aggressiveness of the heavier vehicle would not be likely to occur or its effects would be minimal, then the scope could be increased sooner provided that a regulatory impact assessment showed that it was worthwhile.

7.3.2.2 Steering wheel movement

In 2000 EEVC recommended that a lateral steering wheel movement requirement should be adopted into Regulation because it is important that the airbag has a stable deployment platform. This criterion is already used within Euro NCAP. Because of this, it has been suggested that no/little additional cost would be required by vehicle manufacturers to design for inclusion of a steering wheel movement requirement in Regulation 94. On the assumption that most vehicles are already being designed with consideration given to this criterion it is not expected that there would be much benefit associated with its adoption.

In general feedback from the manufacturers supported the principle of including this criterion, but questioned its benefit.

In summary, both the benefits and costs of this requirement are likely to be low. However, not all cars are tested by Euro NCAP. Therefore if other changes were being made to the Regulation, it would probably be worthwhile to include this change as well to ensure all cars have a stable platform for airbag deployment.

7.3.2.3 Footwell intrusion

The option to add a footwell intrusion criterion may be superfluous if it is decided that lower extremity injury risk could be assessed using just dummy type measures such as the THOR-Lx/HIIIr. As no criterion is under development now, it seems appropriate to wait until developments with the lower extremity test tool become clearer. Then the addition of such a footwell assessment may be reconsidered as being either important or unnecessary.

It should also be noted that lower extremity injuries occur even without significant footwell intrusion, so an intrusion measurement alone cannot provide the greatest benefit in lower extremity protection. For this reason a dummy-based assessment method should be able to demonstrate substantial additional benefit over a vehicle-based assessment; assuming that the dummy tool and assessment principle are appropriate.

7.3.2.4 Assessment of rear seated positions

Accident analysis work performed by the EC APROSYS project using the German GIDAS and UK CCIS databases found that the proportion of rear seated occupants wearing a seatbelt was much lower than for front seated occupants (Cuerden et al. 2007b). This clearly indicates that there is a problem with the seat belt wearing rate in the rear. The accident analysis also found that the rear seat occupancy rate in collisions was low, about 10% of all occupants. Analysis of the GIDAS data showed that the risk of injury for the rear seated occupant was lower than for the front seated one. However, in contrast an analysis of the NHTSA CDS data showed that the risk of injury for the elderly was higher in the rear seats than the front seats.

Test work performed by the APROSYS project showed that the inclusion of rear seated dummies did not influence the assessment of the front seated positions thus indicating no major technical obstacles to include rear seated dummies in a full-width test (Edwards 2009). It also showed strong evidence of dummy submarining in some of the tests illustrating a problem with the restraint system for that particular car. This does tie in with the accident data which indicated a high incidence of abdominal injury, although it should be noted that the accident sample size was very low so this result may not be statistically meaningful.

On this basis of the low occupancy rate for the rear seated position, a requirement for equivalent protection in the rear seating positions to the front seating positions is not expected to have a cost benefit ratio greater than one. However, it may be that the option to assess rear seated positions could be justified through the necessity to offer equivalent protection in all seating positions, rather than just on a cost benefit basis.

At present, no regulatory tests, throughout the world, are known in which the rear seating positions are assessed with respect to adult occupants (in frontal impacts). In their notice regarding the development of an offset US NCAP test, NHTSA reported that more analysis would be needed before a rating program that included rear seat occupants could be established (NHTSA, 2008). Therefore implementation of a rear seat position assessment for adult occupants would not aid worldwide harmonisation of procedures.

To provide equivalent protection for rear seat occupants, compared with the front seats, it is expected that improved restraint systems with pretensioners and load limiters would have to be used in the rear seats routinely. The effect of these systems on child restraint systems should be considered as part of the assessment to change the regulation. Also, because the main purpose of a full-width test is to provide a high deceleration pulse to assess the vehicle’s restraint system and the purpose of assessing the rear seated position is mainly to assess the restraint system, then it is suggested that if there were a choice, assessment of the rear seated position should be made using a full-width test.

In summary, the accident analysis indicated that there is a problem with the seat belt wearing rate in the rear. The assessment of the rear seated occupant position is unlikely to have a cost benefit ratio greater than one because low occupancy rate for the rear seated position. However, the risk of injury for the rear seat occupants has been shown to be higher than for front seat occupants for the elderly, so assessment of the rear seat position may be deemed necessary to ensure equivalent levels of protection in these different seating positions. At present, no regulatory tests throughout the world are known in which the rear seating positions are assessed with respect to adult occupants in frontal impacts. However, it has been shown to be technically feasible to assess the rear seat position without affecting the assessment of the front seat position.

8 Conclusions and Recommendations

From a total of about 41,000 road accident fatalities annually in the EU25 countries about 10,000 fatalities still occur in car frontal impacts, the type of accident that UNECE Regulation 94 addresses. This shows that there remains much potential to improve car occupant safety in frontal impacts and thus Regulation 94 further. However, it should be noted that over the past ten years the number of road accident fatalities has decreased year on year and there is strong evidence to suggest that the Regulation 94 has helped contribute to this reduction.

From a review of the existing legislation, available accident data and proposed new and modified test procedures potential options to improve Regulation 94 were identified. Two types of option were identified. The first type consisted of changes to the test configuration and / or the addition of new tests, referred to as 'main' options. The second type consisted of options which could be incorporated into the 'main' options, such as changes to the dummy test tool and / or assessment criteria, referred to as 'supplementary' options. A review of these options was made taking into consideration the needs identified in accident studies, potential for unintended consequences, compatibility, harmonisation, cost benefit issues and comments received from consulting manufacturers. The following conclusions and recommendations were made:

'Main' options

1. No change.

This is the default option. If chosen, casualties in frontal impacts would be expected to continue to decrease in the short term as a result of increasing market penetration of Regulation 94 compliant cars and Euro NCAP '5 star' rated cars. However, in the longer term this effect would cease, although casualty numbers may continue to decrease as a result of other interventions such as ESC and BAS. However, there is the possibility that the frontal force mis-match between light and heavy cars could increase and exacerbate the compatibility problem which would negate some of the casualty savings. Also, there is a small possibility that increased frontal force levels of cars encouraged by Regulation 94 and Euro NCAP may cause increased casualties in side impacts. If this option is chosen it is recommended that these issues are investigated further.

2. Replace the current R94 ODB test with a Progressive Deformable Barrier (PDB) test.

This option has the potential to resolve a number of issues with the current ODB test procedure, namely to represent better the loading experienced in a car-to-car impact which should help encourage car designs which perform better in car-to-car impacts and to equalise the test severity which should help improve the frontal force matching aspect of compatibility. However, its increased energy absorption capability compared to the ODB test could permit the design of vehicles with a reduced front-end 'crumple zone' and, in theory, rigid vehicles. Such a vehicle design would be unsafe in real world collisions with trees or other rigid objects, because the vehicle front end would have insufficient energy absorption potential. There is insufficient information available for a detailed cost benefit analysis but a preliminary study suggests that the benefit is likely to be low because comparison of ODB and PDB test data indicates that it does not appear to enforce substantial design changes to the vehicle. As the current Regulation 94 ODB test is virtually a worldwide harmonised test procedure a change to the PDB test would be detrimental for harmonisation unless other approval and consumer testing bodies also changed to the PDB test.

To consider this option further for regulatory application, further work is required to assess the benefits and costs more accurately and to assess the risk that it could permit the design of unsafe vehicles.

3. Add a full width high deceleration test to the current UNECE Regulation 94 ODB test procedure.

The addition of a full width test would mean that two of the principle types of collision, namely offset and full-width, were replicated by regulation. It would also fulfil the IHRA and EEVC recommendation that both offset and full-width tests should be used to assess a car's frontal impact crashworthiness and aid the harmonisation of test procedures worldwide because Europe is one of the few areas in the world that does not have a full-width regulatory test procedure. A full-width test is primarily a test to control deceleration related injuries and hence has the potential to drive improvements in restraint technology and consequently reductions in thorax injury risk which has been identified as a priority for mitigation. At this stage it is not possible to estimate accurately the benefits and costs for the addition of a full-width test. Examination of the literature suggests that for a test with an impact speed of 56 km/h and Regulation 94 equivalent performance limits, although the cost benefit ratio could be as high as 1:4, it is likely to be much less, maybe as low as 1:1. This is because more stringent performance limits and other measures are likely to be needed to deliver all of the potential benefit, which would require additional modifications to the car and inevitably increase the cost. These modifications may include adaptive restraint systems. To assess these systems an improved dummy would be needed because the biofidelity and injury assessment capability of the Hybrid III dummy is insufficient to drive the development of adaptive restraint systems. Unfortunately, an improved dummy is not likely to be available in the short term. Hence the cost benefit ratio for this option is likely to be low unless a way can be found to deliver the potential benefit estimated using the current Hybrid III with appropriate performance criteria and limits.

For the introduction of a full-width test in the short term a rigid face would be a better option than a deformable face.

To consider this option further for regulatory application work is required to determine appropriate performance criteria and limits and other measures needed to deliver the potential benefit and also to update the cost benefit analysis.

4. Combination of options 2 and 3.

This option is effectively the summation of its component options with the advantage that the addition of the full-width test helps to at least limit and possibly resolve the potential unintended consequence with the PDB test; namely that the high energy absorption capability of the PDB could permit the design of unsafe vehicles with insufficient front-end energy absorption capability.

'Supplementary' options

Dummy related:

a. Incorporation of the THOR-Lx, and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy.

The accident analysis review clearly indicates that improved protection for lower extremity injuries is a priority. Retrofit of the THOR Lx (lower leg) and/or upper leg to the Hybrid III offers opportunity to improve the assessment of lower extremity injury. At present neither of these dummy improvements is ready for regulatory application in the short term although the THOR Lx is closer. These improvements are likely to be cost beneficial because of the large frequency and impairment costs of lower extremity injuries.

Other:

b. Extension of scope to include all vehicles of M1 category and N1 vehicles.

There are significant benefits to extending the scope of the Regulation to include at least LCVs in terms of improved protection for the LCV occupants (self protection). However, there may also be an unintended consequence in terms of worsening compatibility (partner protection) as LCVs may become stiffer and hence more aggressive. Hence, ideally it would be best to introduce measures to control compatibility before consideration of an increase in the scope. However, if it could be shown that the unintended consequence of increasing the aggressiveness of the heavier vehicle would not be likely to occur or its effects would be minimal, then the scope could be increased sooner provided that a regulatory impact assessment showed that it was worthwhile.

c. Steering wheel movement controlled through the addition of a 100 mm horizontal displacement limit.

Both the benefits and costs of this requirement are likely to be low. However, if other changes were being made to the Regulation, it would probably be worthwhile to include this change as in parallel to ensure all cars have a stable platform for airbag deployment.

d. Footwell intrusion controlled through the assessment against a specifically developed criterion and associated pass or fail limit.

The option to add a footwell intrusion criterion may be superfluous if it is decided that lower extremity injury risk could be assessed using just dummy type measures. As no criterion is under development now, it seems appropriate to wait until developments with the lower extremity dummy test tool become clearer. Then the addition of such a footwell assessment may be reconsidered as being either important or unnecessary.

e. Assessment of protection afforded in rear seated positions.

The assessment of the rear seated occupant position is unlikely to have a cost benefit ratio greater than one because of the low occupancy rate for the rear seated position. However, the risk of injury for the rear seat occupants has been shown to be higher than for front seat occupants for the elderly, so assessment of the rear seat position may be deemed necessary to ensure equivalent levels of protection in these different seating positions. At present, no regulatory tests throughout the world are known in which the rear seating positions are assessed with respect to adult occupants in frontal impacts. However, it has been shown to be technically feasible to assess the rear seat position without affecting the assessment of the front seat position.

It should be noted that accident analysis has indicated that there is a problem with a low seat belt wearing rate in the rear. Resolution of this problem is fundamental and should be given high priority.

The main observations from the industry consultation were:

- A major difference in the response between manufacturers from different countries regarding option 2, ‘To replace the current ODB test with a PDB test’. Manufacturers from France supported this option whereas manufacturers from other countries opposed this option.

   - Note: Option 2 is the proposal made by France at the December 2007 GRSP meeting to amend Regulation 94. Hence, French industry support for this is not unexpected.
- An emphasis that any potential upgrade to Regulation 94 must be justified by a need, a benefit and an assessment of costs which considers the accident situation in Europe.
   - Note: this is in alignment with the CARS 21 initiative and the 'better regulation' principles introduced by the Commission, in particular the requirement for an impact assessment for a change to regulation.

Overall it is clear that much further work is required, in particular to assess cost benefit implications, before any of the main options would be suitable for regulatory application.

A number of other minor options for the improvement of Regulation 94 have also been identified based on the review of other similar test procedures. They include:

- Front seat position - longitudinal adjustment

  Currently, Regulation 94 specifies that the front seat should be positioned in the middle position of travel in the fore/aft direction or in the nearest locking position thereto. The intention is that this seating position should be representative of the seating position for a 50th percentile male. Since the Regulation was introduced some manufacturers have increased the rearwards adjustment of the seats in their vehicles to help accommodate persons larger than the 95th percentile male. To ensure that the specified seating position is still representative of the seating position of a 50th percentile male some test procedures, such as EuroNCAP, use a different seat adjustment specification. This is that the front seat should be positioned in the middle position of travel or nearest locking position between its foremost position of travel and the foreaft position of travel which corresponds to the 95th percentile male seating position.

- Hybrid III Dummy - neck shield

  To help ensure a more realistic interaction between the HybridIII dummy and airbags some test procedures, such as Euro NCAP, use a neck shield on the Hybrid III dummy.

One of the problems found in the work performed was that that the accident data available to review the current frontal impact situation in Europe was limited. The last comprehensive and co-ordinated European accident analysis study was performed 10 years ago. As a result of the limited data available it was not possible to definitely prioritise frontal impact scenarios for injury reduction as originally intended. Instead, from the information available it was only possible to say in general terms how much the data supported preconceived ideas and /or previously made recommendations to change the legislation, for example, the introduction of a full width test in Europe. To address this issue it is recommended that the EC consider funding a co-ordinated and comprehensive European accident study for frontal impact similar to the one performed previously in 1998, which EEVC used to help review the Directives. As part of this analysis it is suggested that a comparison of the real world safety performance of cars with that observed in current regulatory test is made. The results of this work could be used to identify the real world crash configurations which are not addressed by this test and quantify the number of casualties in these crashes. This would give an initial approximation of the size of the target population for potential changes to the regulation, which in turn could form the first step of a benefit analysis. Also, a detailed comparison of the performance of vehicles in crashes similar to the Regulatory test procedure could be used to help identify how well the test replicates the structural behaviour of the car and the types of injury the casualty sustains, which in turn could be used to identify any weaknesses in the current test.

Acknowledgements

The work described in this report was carried out in the Vehicle Engineering division of the Transport Research Laboratory. The authors are grateful to Iain Knight who carried out the technical review and auditing of this report.

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Glossary of terms and abbreviations

Acetabular – relating to the acetabulum – the cup-shaped depression on the outer aspect of the hipbone for the reception of the head of the femur.

AIS – The Abbreviated Injury Scale was first developed by the Association for the Advancement of Automotive Medicine (AAAM) in 1971. At this time a need was identified for a standardised injury collection system which would assist in the study of vehicle design in relation to injury incidence and mechanisms. AIS became the standard used by accident investigation specialists leading to the publication of the first AIS dictionary in 1976. The AIS is a threat-to-life scale and every injury is assigned a score, ranging from 1 (minor, e.g. bruise) to 6 (currently untreatable). The Maximum AIS injury a casualty sustains is termed MAIS. The scale is not linear; for example, an AIS 4 is much more severe than two AIS scores of 2. Since the first dictionary was published in 1976, the AIS has gradually evolved to allow coding of penetrating injuries, the additions of vascular and skin injuries and the expansion in the range of injuries and their severity. The concepts and purposes have not changed over time neither has the severity, however the outcome of certain injuries may change depending on treatment, time to treat and medical developments and advances in trauma care. Each new edition of AIS has been refined to reflect these changes leading to the latest AIS 2005 version (Gennarelli and Wodzin, 2005).

CCIS – Co-operative Crash Injury Study - CCIS is a UK study of car occupant injury causation, which investigates more than 1,200 crashes involving cars each year. The CCIS investigates and interprets real-world, police-reported, car occupant injury crashes retrospectively. The basic selection criteria are: the accident must have occurred within the investigating teams geographical area, the vehicle must be a car or car derivative, the vehicle must have been less than seven years old at the time of the accident, the vehicle must have at least one occupant who is injured (according to the police) and the vehicle must have been towed from the scene of the accident. CCIS is sponsored by the DfT, along with Autoliv, Ford, Nissan and Toyota.

Change in velocity (•v) – This is one measure of the severity of an accident. It reports the change in velocity experienced by the investigated vehicle as a result of a collision. In principal the •v for a vehicle can be estimated based on knowledge of the mass, velocity and angle of impact of the vehicle being investigated and its collision partner. However, in retrospective studies such information is not always known. In these cases, the velocity change value reported is derived based on experience from car impacts performed under specific conditions where the •v can be controlled. ‘Crash 3’ is an example of analysis software which helps crash investigators go through the steps involved in relating post impact vehicle profiles to pre-impact conditions and hence derive •v values.

CIREN - Crash Injury Research and Engineering Network - A multi-centre research programme on crashes and injuries, involving clinicians and engineers at eight Trauma centres in the US. CIREN's mission is to improve the prevention, treatment, and rehabilitation of motor vehicle crash injuries to reduce deaths, disabilities, and human and economic costs. Six centres are funded by NHTSA, one by Honda R&D and one by Toyota Motor North America.

FARS - Fatality Analysis Reporting System - A NHTSA-managed census of fatal traffic crashes within the 50 States, the District of Columbia, and Puerto Rico. FARS has been operational since 1975 and has collected information on nearly one million motor vehicle fatalities.

FWRB - Full-Width Rigid Barrier

FWDB - Full Width Deformable Barrier

Injury Severity Score (ISS) – This is the sum of the squares of the highest AIS score in three different body regions (Baker et al., 1974).

LCV - Light Commercial Vehicle - In the UK this means N1 vehicles not including car-derived N1 vehicles.

LTV - Light Truck based Vehicle.

MDB - Mobile Deformable Barrier

NASS CDS - National Automotive Sampling System - A US nationally representative sample of police-reported tow-away crashes occurring on public roadways) Crashworthiness Data System (a subset of the NASS sample focussed on the epidemiology of injury and maintained by NHTSA).

NASS GES - National Automotive Sampling System - A US nationally representative sample of police-reported tow-away crashes occurring on public roadways) Feneral Estimates System (a subset of the NASS sample used to estimate how many motor vehicle crashes of different kinds take place, and what happens when they occur).

Occipital Condyle (OC) – The rounded eminence / joint which connects the top of the neck with the base of the head, at the occiput (occipital bone).

ODB - Offset Deformable Barrier

SCI - Special Crash Investigations - Special in-depth accident investigations from NHTSA.

Appendix A Industry consultation letter

Creating the future of transport

5th January 2008

By e-mail

Direct Tel: +44 (0)1344 770723
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Dear Sir/Madam,

Re: Study on development of legislation for frontal impact protection.

The requirements of UNECE Regulation 94 relating to frontal impact protection have now been in existence for more than ten years. A GRSP working group in Geneva has recently started a review of the requirements of Regulation 94, which could potentially lead to proposals to amend this regulation.

On behalf of the European Commission, TRL are conducting a study to gather and evaluate available information related to a potential update of Regulation 94, in particular that relevant to the current GRSP working group review. The main objective of the study is to identify and evaluate potential options to update Regulation 94. Your contribution to this work, as requested below, would be greatly appreciated to ensure that the best information available is used for this study.

The study has progressed to the stage where two types of potential options to improve frontal impact legislation have been identified. The first type consists of changes to the test configuration and / or the addition of new tests, referred to as 'main' options. The second type consists of options which could be incorporated into the 'main' options, such as changes to the dummy test tool and / or assessment criteria, referred to as 'supplementary' options. It should be noted that none of the options include metrics to assess a vehicle's compatibility potential because current proposals are not sufficiently well developed for incorporation into Regulation 94 in the timescales of the current GRSP review. The options identified are:

<u>'Main' options</u>

1. No change.
2. Replace the current R94 ODB test with a Progressive Deformable Barrier (PDB) test.

   Note: This option was proposed as an amendment to UNECE Regulation 94 by France at the GRSP meeting in December 2007.

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3. Add a full width high deceleration test to the current UNECE Regulation 94 ODB test procedure.

   A number of potential ways exist to fulfil this option. These are:

   - Add a Full Width Deformable Barrier (FWDB) test.
   - Add a Full Width Rigid Barrier (FWRB) test.

4. Combination of options 2 and 3.

   A number of potential ways exist to fulfil this option. These are:

   - Replace ODB test with PDB test and add FWDB test.
   - Replace ODB test with PDB test and add FWRB test.

'Supplementary' options

Dummy related:

- Incorporation of the THOR-Lx, and possibly the THOR upper leg, as a retro-fit to the Hybrid III dummy.

Other:

- Extension of scope

  Extend the scope of the Directive to include N1 vehicles, in particular those less than 2.5 tonnes, and all M1 vehicles.

- Steering wheel movement criterion
  - Add a lateral displacement limit of 100 mm to the current vertical and horizontal displacement limits.
- Footwell intrusion
  - Add an appropriate footwell intrusion criterion and associated limit
- Assessment of rear seated positions
  - Consider the assessment of the rear seated positions

The next stage of this study is to evaluate the potential options listed above. The issues that will be considered as part of this evaluation include:

- Whether the option will address the needs identified in the accident studies
- Potential for unintended consequences
- Potential to include all vehicles of M_1 and N_1 categories within the scope
- Potential for further development to include measures to assess and control compatibility
- Relationship with present international requirements
- Cost-benefit

There is little information freely available related to the cost benefit implications of the potential options, in particular cost information. To help ensure that the best information available is used to evaluate these implications could you please supply the following:

- Comment or specific information on the costs and other issues that the proposed options may impose on vehicle manufacturers over and above that which is already incurred with the existing Regulation 94 standard. If possible, costs should be supplied on a per vehicle basis to enable comparison of data received.

- In relation to Option 3, 'Addition of a full width high deceleration test', comment or specific information on the difference in the design of vehicles for sale within Europe where there is no full width regulatory or consumer test compared to those for sale in other countries, in particular the US, where a full width test is already included in regulatory and consumer tests.

- Comment on any additional tests for frontal impact protection that are carried out to meet in-house design targets but which are not required by regulatory testing or assessed by consumer testing. For example, full width tests with in-house design targets may be performed for vehicles designed for sale in Europe only. Also, other tests, such as low overlap tests may also be performed as part of in-house design requirements.

Also, if you wish to comment on the other issues being considered for the evaluation, it would be greatly appreciated.

Any information you provide will be treated in the strictest confidence. Furthermore, any information used will not be associated with the specific source, unless it is indicated by you that the information is already in the public domain. Please send responses by mail or e-mail by the 28th February 2009 to:

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Yours sincerely,

Mervyn Edwards