A study of possible future developments of methods to protect pedestrians and other vulnerable road users

by B J Hardy, G J L Lawrence, I M Knight, I C P Simmons, J A Carroll, G Coley and R S Bartlett

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PROJECT REPORT

TRL Limited

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Executive Summary

In most countries, including those of the European Union (EU), pedestrians and other vulnerable road users form a significant proportion of all road user casualties. Research has shown that measures to improve car design, to mitigate pedestrian injuries in collisions, can be very effective in reducing the number of fatalities and serious injuries. Therefore the European Commission (EC) and a number of national governments supported the development of test methods and test tools suitable for requiring certain standards of pedestrian protection. More recently, in 2003, the European Union agreed a European Directive 2003/102/EC that requires car manufacturers to provide pedestrian protection in vehicles of the type covered by the scope of the Directive (principally passenger cars). In order to meet the requirements of the Directive, manufacturers will need to provide an appropriate crushable surface to cushion pedestrians, and to some extent pedal cyclists, in the event of an impact. The Directive is based on test methods that were first developed by the European Enhanced Vehicle-safety Committee (EEVC) Working Group 10 (EEVC WG10) and then further refined by Working Group 17 (EEVC WG17).

The EC Directive consists of three principal test procedures each using different sub-system impactors to represent the main phases of a car-to-pedestrian impact. The three impactor types are:

- A legform impactor representing the adult lower limb to indicate lateral knee-joint shear displacement and bending angle, and tibia acceleration, caused by the contact with the bumper.
- An upper legform impactor representing the adult upper leg and pelvis to record bending moments and forces caused by the contact with the bonnet leading edge.
- Child and adult headform impactors to record head accelerations caused by contact with the bonnet top.

Each impactor is propelled into the car and the output from the impactor instrumentation is used to establish whether the energy-absorbing characteristics of the car are acceptable. The whole area of the bumper, bonnet leading edge and bonnet top likely to strike pedestrians can be assessed by carrying out several tests with each impactor. The bumper and bonnet leading edge tests represent impacts into pedestrians with the statures that were considered by the EEVC to be more vulnerable to injury (i.e. adults).

Most, if not all, of the research groups who have worked in the field of pedestrian protection test methods, including EEVC (WG 10 and 17), ISO (WG2) and IHRA (PSWG), have chosen to use sub-systems type tests. Sub-system test methods consist of a set of individual tests, each representing one of the contacts that occur within a pedestrian to vehicle accident. Collectively, the family of sub-system tests represent all of the significant contacts within an accident that are likely to result in serious or fatal injuries to the pedestrian.

Test methods making use of physical pedestrian dummies might initially appear to be the most obvious test tool for assessing a car's pedestrian protection. However, in reality, pedestrian dummy based test methods are not well suited for test methods intended for regulatory use because amongst other things they would require an unrealistically large number of tests.

Many safety regulations are upgraded over the years, for example to take account of new or improved test tools. An instance of this can be seen with the side impact regulation (UN ECE Regulation 95) which has been amended four times since it was first introduced in 1995. The most significant of these changes have been the introduction of an improved side impact dummy and deformable barrier face (used on the front of a trolley to represent a standardised car front). Therefore, although the pedestrian Directive has only recently come into force and the changes for the second phase are still not finalised, it is likely that at some time in the future it will also be upgraded, to provide a higher level of protection than that of the revised phase two.

The purpose of this study is to review research pertinent to protection of pedestrian and other vulnerable road users. From this review recommendations will be made as to how the current Regulations might be updated and what additional work is needed to achieve this.

The key conclusions from this study were:

To be of benefit, improved test methods must 'save' more pedestrians than the pedestrian protection required by current legislation and they must also be suitable for use in regulations.

Options to save more pedestrians than current legislation are to extend the scope, protect at a higher accident speed, improve the test methods, improve the test tools and improve protection criteria.

Based on a very approximate estimate, expanding the scope of the current EC Directive to cover all or most of the M and N vehicles over 2.5 tonnes would result in savings of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive's savings. The interactions of pedestrians with these larger vehicles are likely to lead to problems in using the Directive's test tools and methods. Suggestions have been made as to how the current test methods could be adapted for testing larger M1 and all N1 vehicles. As well as expanding the scope of current legislation to cover more vehicles, significant additional savings could be made by including the windscreen and windscreen frame within the scope of improved test methods.

Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. Increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be saved. Because it will make providing the protection far more difficult, it is important for regulatory use to take into account the feasibility of providing the protection when selecting the speed.

In serious road accidents pedestrians are often likely to suffer injuries that result in death, disablement or mental impairment. Therefore the protection criteria should be set at an injury risk level which could be seen to provide benefit. However, the difficulty in providing vehicle based protection and the additional margin of safety over and above regulatory minimums that vehicle manufacturers provide, should be considered when setting these levels.

The scope has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.

The literature review has identified a lot of information pertinent to developing improved test methods and tools; however, important information is missing or of insufficient quality in some key areas. This is particularly apparent in the areas of lateral knee joint stiffness for live humans and the impact conditions for the bonnet leading edge and the head.

When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures. This often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

The legs of pedestrians are the most frequently injured body region in accidents with cars. Although the EEVC WG17 lower legform impactor has been established as a regulatory sub-system test tool for many years it has some limitations and therefore there is scope for improvement. The Flex-PLI is being developed as the next generation of test tool and is undergoing development and evaluation currently.

A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Once the final version of the Flex-PLI is available, it should be assessed to determine if it satisfactory for regulatory use against the agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability. The potential of the Flex-PLI for regulatory use can only be found once a finalised specification and impactor are available.

Several recommendations have been made for new studies to support the development of improved test methods. Any new work to support new test methods, should ideally be accepted by international experts, before it is used in legislation. Given the difficulties and high cost of developing alternative impactors or of revising the test parameters and acceptance criteria, the issue of acceptability should be borne in mind when deciding which option to develop. The relevant working groups should preferably be involving in selecting the option(s) that are further developed, and obviously funding for the work will have to be provided.

Brake assist systems have been shown to have good potential to complement proposals for secondary safety pedestrian protection measures. Sensing systems capable of identifying imminent collision with pedestrians and activating safety measures are being developed by tier one suppliers and offer future potential to provide notable additional benefits. Various forms of collision avoidance systems are either available or under development. All of these systems offer a future potential to have substantial benefits for pedestrian protection but considerable technical development of the products and the test methods and performance requirements for them will be required before they can be considered as candidates for mandatory fitment. This technical development should be encouraged.

1 Introduction

In most countries, including those of the European Union (EU), pedestrians and other vulnerable road users form a significant proportion of all road user casualties. Research has shown that measures to improve car design, to mitigate pedestrian injuries in collisions, can be very effective in reducing the number of fatalities and serious injuries. Therefore the European Commission (EC) and a number of national governments supported the development of test methods and test tools suitable for requiring certain standards of pedestrian protection. More recently, in 2003, the European Union agreed a European Directive 2003/102/EC (European Parliament and Council, 2003) that requires car manufacturers to provide pedestrian protection in vehicles of the type covered by the scope of the Directive (principally passenger cars). In order to meet the requirements of the Directive, manufacturers will need to provide an appropriate crushable surface to cushion pedestrians, and to some extent pedal cyclists, in the event of an impact. The Directive is based on test methods that were first developed by the European Enhanced Vehicle-safety Committee (EEVC) Working Group 10 (EEVC WG10) and then further refined by Working Group 17 (EEVC WG17).

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Each impactor is propelled into the car and the output from the impactor instrumentation is used to establish whether the energy-absorbing characteristics of the car are acceptable. The whole area of the bumper, bonnet leading edge and bonnet top likely to strike pedestrians can be assessed by carrying out several tests with each impactor, see Figure 1.1. The bumper and bonnet leading edge tests represent impacts into pedestrians with the statures that were considered by the EEVC to be more vulnerable to injury (i.e. adults).

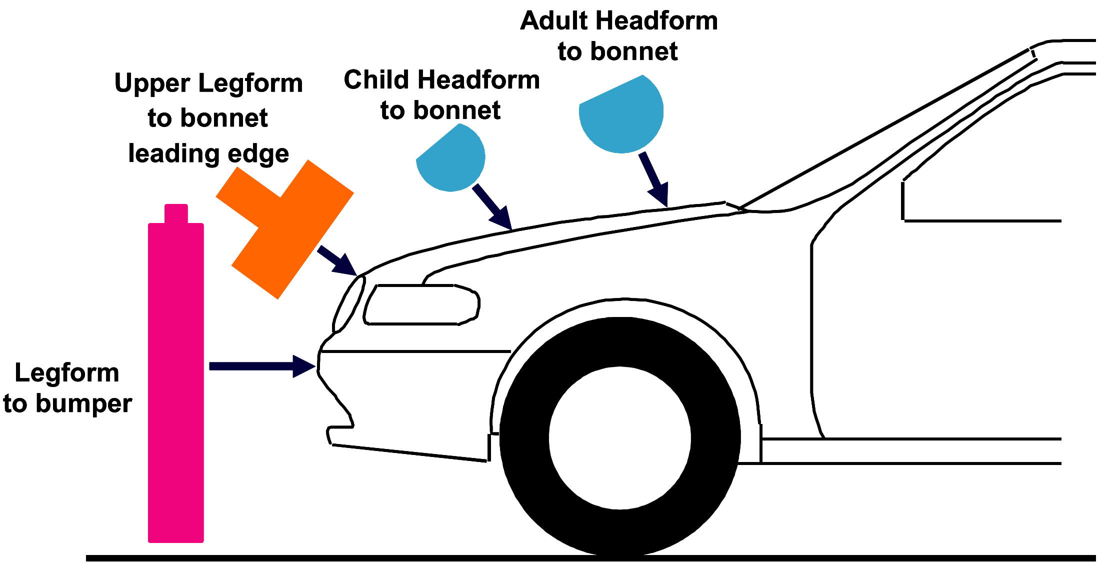


Figure 1.1. The sub-systems tests used in the second phase of the EC Directive

Directive 2003/102/EC requires pedestrian protection in two stages. An initial level of protection is required by the first phase from 2005, and a higher level will be required in a second phase from 2010. The requirements of the second phase were subject to a feasibility review, which was carried out by TRL Limited (Lawrence *et al*., 2004).

More recently a proposal for a global technical regulation (GTR) for pedestrians and other vulnerable road users has been drafted under the United Nations Economic Commission for Europe (UNECE) in Geneva (Informal Working Group on Pedestrian Safety, 2006). This proposal is based on the latest available research and test tools and makes use of data provided by international participants including the EC. The requirements of this GTR have to a large extent been developed in parallel with the EC's proposals for the revised second phase of pedestrian requirements in the EU. The EC's eventual proposal to the European Parliament for this second phase is expected to include an additional requirement for active safety measures.

Many safety regulations are upgraded over the years, for example to take account of new or improved test tools. An instance of this can be seen with the side impact regulation (Economic Commission for Europe, 1995) which has been amended four times since it was first introduced in 1995. The most significant of these changes have been the introduction of an improved side impact dummy and deformable barrier face (used on the front of a trolley to represent a standardised car front). Therefore, although the pedestrian Directive has only recently come into force and the changes for the second phase are still not finalised, it is likely that at some time in the future it will also be upgraded, to provide a higher level of protection than that of the revised phase two.

The purpose of this study is to review research pertinent to protection of pedestrian and other vulnerable road users. From this review recommendations will be made as to how the current Regulations might be updated and what additional work is needed to achieve this.

2 Method

In response to the EC request, the material reviewed within this study has been collated under the following six topics:

- Task 1 – Prospects for the Flex-PLI to bumper test: Recently there has been a considerable amount of work to obtain an improved understanding of how a pedestrian reacts when struck by a car bumper. Based on this work JARI have criticised the EEVC decision to use rigid bones in their legform impactor because it was evident that in the real pedestrian the bending action is shared to some extent between the knee joint and the long bones. Therefore, JARI and JAMA have developed a legform impactor, the Flex-PLI, using the leg of the Polar dummy as the basis. The first version was produced in 2000 and since then there have been a number of new versions, as the legform was developed further. The intention of the Japanese is to develop it into a device suitable for legislative testing. The current and future potential for the Flex-PLI to be used as a test tool will be considered in this task.
- Task 2 – High bumper: Due to their styling, Sport Utility Vehicles (SUV's) have higher bumpers than conventional car designs. Therefore the styling of the vehicle fleet had, to some extent, moved outside the range originally considered by EEVC WG10 when they developed the lower legform to bumper test method. With the recent increase in the popularity of SUV's there has also been an increase in the priority for the pedestrian subsystem bumper test method to be appropriate for SUV's. EEVC WG17, when reviewing and updating the test methods developed by WG10, noted the increasing popularity of SUV's with high bumpers and in response added a new upper legform to high bumper test method which made use of the impactor developed for testing the bonnet leading edge. The appropriateness of this alternative procedure will be considered in this task.
- Task 3 – Bonnet Leading Edge: The pedestrian's contact with the bonnet leading edge of a car is one of the principal contact phases and potentially one of the injury causing contacts. The bumper will normally make the first contact and will push the pedestrian's legs forward. This contact low on the pedestrian will both rotate the legs about the hip and start to rotate the whole body. As the pedestrian's leg rotates, the upper leg (thigh) will typically contact the bonnet leading edge of the typical car. When sub-system pedestrian test procedures were proposed in the mid 1980's, the bonnet leading edge test was one of the three areas addressed on the car. Recently, there has been much criticism of the upper legform test method because it fails to reproduce the rolling effect of a pedestrian in contact with the bonnet leading edge, and because there appears to be some conflict between accident data and the results of tests on modern cars. The requirement for a bonnet leading edge test will be considered in this task.
- Task 4 – Headform: To address pedestrian head injuries WG10, and later WG17, were given the mandate to determine test methods and acceptance levels to measure the risk of injury to the head of an adult and child pedestrian from an impact with a vehicle. However, based on a number of considerations including feasibility, the mandate for EEVC WG10 followed by WG17 was to develop test methods suitable for use on the bonnet top, up to the base of the windscreen and not the windscreen or windscreen frame. Whereas in real life the windscreen and frame may be involved in many serious and fatal head injury accidents. Also, following the feasibility review of phase two of the EC Directive (Lawrence *et al*., 2006), a number of changes to the required head impact protection have been proposed to:
  - improve the test methods (taking advantage of new research).
  - adjust the technical difficulty of achieving the protection (to take account of feasibility issues).
  - take advantage of new technologies (which would help to avoid or reduce the impact speed in pedestrian accidents).

In this task the proposed changes to the headform test methods and head impact protection requirements will be reviewed.

- Task 5 – Scope: When the pedestrian test procedures were developed, decisions were taken about the specific accident situations that were to be simulated. It was also decided to use sub-system tests rather than a dummy-based test method. However, sub-system tests require a number of simplifications and assumptions to be made. These tend to result in test methods that are only appropriate for certain styles and sizes of vehicles. When the current legislative test procedures were planned a decision was taken about the vehicle type for which they were intended, i.e. cars. The style of a typical car has changed since the test procedures were first designed, as has the mix of different car types. The test procedures are less appropriate for some car types than others. When other types of vehicle are considered the test procedures tend to become even less appropriate. Any changes to the scope, construction methods, styling fashions and changes to the fleet-make-up can all influence the suitability of the test methods. The potential benefits and limitations that may result from such changes to the scope will be considered in this task.
- Task 6 – Newer technologies: Technologies such as Brake Assist Systems (BAS) and, potentially, collision mitigation and collision avoidance systems offer significant reductions in road accidents and hence injuries. Currently new technologies are being fitted to a rapidly increasing proportion of new cars as a result of increasing customer demand and falling costs. This has not been an issue requiring legislation or the setting of minimum standards, other than the general principle that such systems should fail safe, so that the driver shouldn't ever be worse off with a failed system than without a system fitted. Within this task the potential benefits of newer technologies will be reviewed.

In addition to the gathering of existing pertinent research, the views of relevant experts and stake holders were also thought to be of value in deciding which would be the best options to recommend when different methods could be used to achieve the same ends. Therefore a series of questions were formulated asking for views and supporting research relating to the individual tasks. Letters were sent to the following organisations in early June 2006:

- Adelaide University – Centre for Automotive Safety Research (CASR)
- Association des Constructeurs Europeens d'Automobiles (ACEA – European Automobile Manufacturers Association)
- Bundesanstalt für Straßenwesen (BASt – the German Federal Highway Research Institute)
- European Enhanced Vehicle-safety Committee (EEVC)
- Institut National de Recherche sur les transports et leur Securite (INRETS – the French National Institute for Transport and Safety Research)
- National Highway Traffic Safety Administration (NHTSA – part of the U.S. Department of Transportation)
- Japan Automobile Research Institute (JARI)
- US Society of Automotive Engineers (SAE) pedestrian dummy task group

Responses were received from ACEA, BASt, CASR and JARI. NHTSA were unable to respond in the required timescale; however, a working group paper that was provisionally reviewed was published in time to be included here.

In addition, several papers known to be of interest have been obtained and over 100 documents have been obtained from the Informal Working Group on Pedestrian Safety's area of the UNECE website. Where publicly available, information gained from the authors' participation in pedestrian protection working groups will also be used.

A library search for relevant research papers for the years 1995 to 2006 was also carried out. To ensure that recent work was included, this search was initiated in late November.

3 Prospects for the Flex-PLI to Bumper Test

3.1 Introduction

Overall, the legs of pedestrians are the most frequently injured body region in accidents with cars as can be seen in the analysis of the IHRA in-depth pedestrian accident database in Table 3.1.

Table 3.1: Distributions of pedestrian injuries (AIS 2-6) by body region and country (IHRA dataset)

Body region	Australia (%)	Germany (%)	Japan (%)	USA (%)	Total (%)
Head	39.3	29.9	28.9	32.7	31.4
Face	3.7	5.2	2.2	3.7	4.2
Neck	3.1	1.7	4.7	0.0	1.4
Chest	10.4	11.7	8.6	9.4	10.3
Abdomen	4.9	3.4	4.7	7.7	5.4
Pelvis	4.9	7.9	4.4	5.3	6.3
Arms	8.0	8.2	9.2	7.9	8.2
Legs	25.8	31.6	37.2	33.3	32.6
Unknown	0.0	0.4	0.0	0.0	0.2
Total	100	100	100	100	100

The bumper is predominantly the cause of these leg injuries as can be seen in Table 3.2. The table also shows that of those injuries to the leg, injuries to the lower leg predominate followed by the knee joint, femur and foot. Therefore an improved bumper test tool could potentially save a significant number of additional leg injuries.

Table 3.2: IHRA pedestrian injuries by body region and vehicle contact source – all age groups, AIS 2-6

Contact \ Body Region		Head	Face	Neck	Chest	Abdomen	Pelvis	Arms	Legs					Unknown	Total
									Overall	Femur	Knee	Lower Leg	Foot		
Part of the Vehicle	Front Bumper	24	2		3	5	3	6	19	59	76	476	31	1	705
	Top surface of bonnet/wing	223	15	2	139	44	43	86	23	3	1	1	2	1	583
	Leading edge of bonnet/wing	15	2	4	43	78	85	35	50	40	6	30	1		389
	Windscreen glass	344	56	12	30	5	12	23	2			1	1	1	487
	Windscreen frame/A pillars	168	28	5	35	7	14	31	5	1				2	296
	Front Panel	5	1		9	13	7	6	9	14	11	35	3		113
	Others	45	7	1	38	12	13	15	15	9	5	39	18		217
	Sub-Total	824	111	24	297	164	177	202	123	126	99	582	56	5	2790
Indirect Contact Injury		13		17	1	1	7	1		3		1	2		46
Road Surface Contact		171	22	2	22	2	9	42	6	4	3	5	15	1	304
Unknown		27	6	3	19	10	16	25	1	7	9	32	3	7	165
Total		1035	139	46	339	177	209	270	130	140	111	620	76	13	3305

The EU Pedestrian Protection Directive (2003/102/EC) and associated technical prescriptions (EC Decision 2004/90/EC (Commission of the European Communities, 2004a)) use a legform impactor developed by TRL working within the European Enhanced Vehicle-safety Committee (EEVC) Working Group 17 (EEVC WG17).

The bumpers of most vehicles are at such a height that they contact the average adult leg at or around the level of the knee. Cars with a height of bumper that loads the leg below the level of the knee are likely to fracture the lower leg bones (the tibia and fibula) in moderate to severe accidents. The tibia acceleration limit in the legform EEVC bumper test is aimed at preventing these fractures by requiring that the bumper deforms; however, without additional measures this would often result in a switch to injuring the knee joint instead. Therefore, although knee joint injuries are currently relatively infrequent, the EEVC legform impactor also has a representation of the knee joint to replicate the knee in a side impact and outputs that measure the risk of knee joint injury. The combination of the tibia acceleration, knee joint bending and knee shear displacement measurements, with their performance requirements, in the second phase of the EC Directive is the means of requiring protection and preventing a switch in injury patterns from lower leg fractures to knee joint injuries.

As part of the simplification thought necessary by EEVC WG10 and WG17 to produce a ‘lower’ legform impactor suitable for use in a regulation they decided to make the upper and lower leg ‘bones’ rigid. Essentially the EEVC impactor consists of two rigid metal tubes representing the femur and tibia that are joined by deformable metal elements at the knee. The only compliance of the hard leg bones is a 25 mm thick covering of foam representing flesh and a 6 mm layer of Neoprene representing the skin. The knee joint has a lateral bending and shear displacement capability. This legform has been used for many years for testing vehicles. It was developed and offered for sale in two stages, the prototype in 1995 and the current version with a shear displacement damper in 2000.

Honda in Japan and GESAC in USA developed a new pedestrian dummy, the Polar dummy. This was completed in about 2000. This had a knee structure that is similar to that of the human, with cruciate and collateral ligaments represented by wire ropes and springs. This is far more similar to a human, in geometry and the mechanism with which it bends, than the knee of the EEVC legform.

More recently there has been a considerable amount of work, particularly by JARI in Japan, to obtain an improved understanding of how a pedestrian reacts when struck by a car bumper and to derive appropriate force deformation corridors for the flesh, bones and knee using the most recent American biomechanical data. Based on this work JARI criticised the EEVC decision to use rigid bones in their impactor because it was evident that in the real pedestrian the bending action is shared to some extent between the knee joint and the long bones. However, it should be noted that in accidents causing knee joint injuries bending at the knee joint would predominate (Konosu *et al.,* 2001).

In parallel with the refinement of the Polar dummy JARI and JAMA have developed a legform impactor using the leg of the Polar dummy as the basis. The first version was produced in 2000 and since then there have been a number of new versions, as the legform was further developed. The intention of these organisations is to develop it into a device suitable for legislative testing.

The flexible pedestrian legform impactor, Flex-PLI, has been designed and developed over a number of years. More recently it has been the subject of an assessment and development programme as part of the work of the Global Technical Regulation (GTR) informal working group under the auspices of the UN ECE (United Nations Economic Commission for Europe) Working Party on Passive Safety (GRSP). The GTR pedestrian working group set up a Technical Evaluation subgroup and the latest documents from their third meeting (Konosu, 2006a) show that the latest version of the impactor is called the Flex-GTα. The GTα is the current prototype of the ‘to be finalised’ GT model which, as far as the authors are aware, is nearing finalisation. Prior to the GTα version, the Flex-PLI has been previously known as the Flex-PLI 2003, Flex-PLI 2004 and Flex-G legform impactor.

Mechanically the knee joint of the Flex-PLI is similar to a human knee joint whereas the knee joint of the WG17 legform impactor (developed by TRL) has been designed to deform in a similar way to a human knee, but uses different mechanisms to those in the human knee. It was decided to use two separate mechanical systems that work in a different way to the human knee, but achieve the human-like deformations required (one system for lateral knee shear displacement and one for lateral knee bending). An advantage of using the two independent mechanical deformation systems is that the transducer systems can report directly and accurately the knee shear and the knee bending angle without confusion. It was thought that this was necessary in order to make the impactor suitable for use as a regulatory test device. Apart from the different knee joint design philosophies the specification for the biomechanical performance of the knee of the EEVC WG17 legform is very different to that of the Flex-PLI with the EEVC legform lateral knee bending stiffness being far stiffer.

3.2 Principles of operation of the Flex-PLI GTα legform

The Flex-PLI (Flexible Pedestrian Legform Impactor) is a sub-system test device that has been designed with flexible leg 'bones' and deformable knee and flesh.

The Flex-PLI basically consists of a flexible thigh and lower leg that are joined together by a knee joint (as shown in Figure 3.1). The long bone structure of the Flex-PLI GTα is complex compared to the TRL legform, consisting of a series of rectangular segments around a flexible core. The individual bone segments are made from aluminium or nylon and are separated by rubber spacer washers which allow them to articulate (see Figure 3.2). The aluminium and/or nylon segments are effectively square in section; however, their outer nylon layer has been extended on one side to provide a semi-circular impact face. Wire ropes are passed through holes in the four corners of each segment, one rope to each corner of the bone assembly, and are terminated at each end. The wires are not tensioned initially. However, when a large amount of long bone bending occurs, the wires start to generate high tension to prevent too much bending, thereby protecting the inner flexible core.

Figure 3.1. Photograph of Flex-PLI GTα legform (Konosu, 2006a)

Figure 3.2. Photograph of one long bone of Flex-PLI GTα showing segmental design and nylon impact face (Konosu, 2006a)

The knee joint includes simulated femoral condyles and a tibial plateau, with coil-spring tensioned wire cables representing the four knee ligaments found in the human knee joint (see Figure 3.3). The latest version of the impactor, the Flex-PLI GTα, has ligament tensioning springs twice the length of the previous version and now uses a total of eight sets of cables and springs to represent the collateral ligaments, four of the rope and spring assemblies representing the medial collateral ligament and four representing the lateral collateral ligament of the human knee. The whole legform is then covered with various layers of rubber and neoprene to represent flesh with an asymmetric layering used to produce a simplified representation of a human leg.

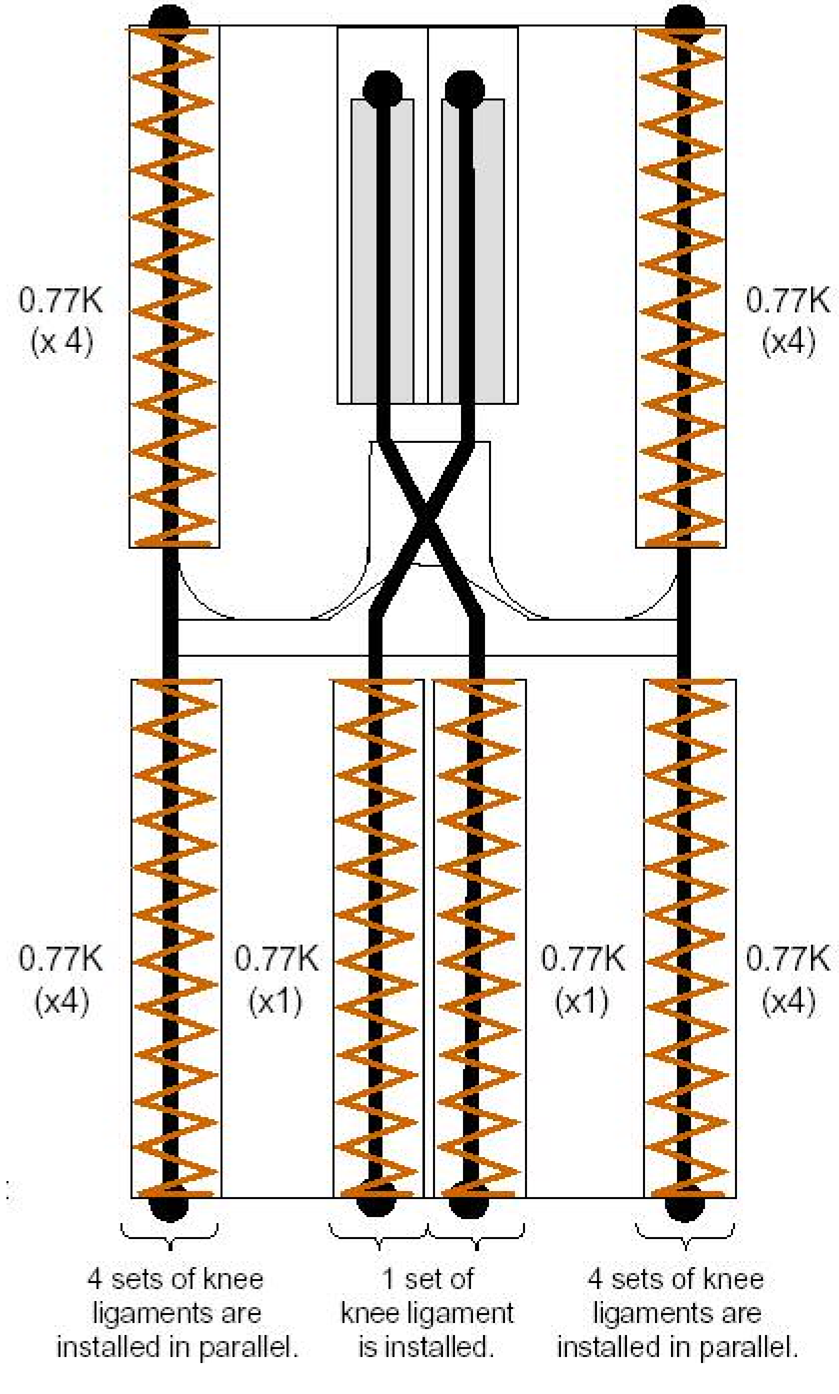


Figure 3.3. Diagram showing principle of Flex-PLI GTα knee joint (Konosu, 2006a)

The main driving force for most of the changes and improvements for previous versions of the Flex-PLI have been to improve the robustness and reliability. For the Flex-PLI GTα version the main change was to increase the ligament extension so that the impactor can provide useful data, without hitting stops (without the springs reaching their most compressed limit – going 'coil-bound'), when testing vehicles that do not meet the proposed Flex-PLI protection criteria. These design changes were in response to tests conducted by BASt, who discovered that the Flex-PLI GT version of the impactor had insufficient knee joint displacement to assess vehicles tested at an impact speed of 40 km/h. As a result of the improvements to the model, the Flex-GTα's knee bending limit was increased by 30 percent (Konosu, 2006a).

3.3 Instrumentation

The Flex-PLI GTα is instrumented to measure both long bone bending and 'knee ligament' extension. Bending moment is measured at four locations on the lower leg and at three locations on the thigh section by means of strain gauges attached to the fibreglass core. Calibration tests show that these produce a good linear relationship between strain and applied bending moment in a three-point bending calibration test (Konosu, 2006a).

In the Flex-PLI GTα the wire ropes representing knee ligaments are free to extend or to contract, by compressing or relaxing the pretension coil springs in the mechanical knee joint, as the joint bends and/or shears. This extension or contraction is measured by a number of 'string operated potentiometers' (string pots). Depending on the inertia of the moving (rotating) parts of a string pot, when rapid extension suddenly ceases (as may occur when the thigh section contacts the bonnet edge), the potentiometer may continue to rotate thereby causing errors in the measurement. Similarly, depending on inertia and the strength of the return spring, when ligaments suddenly contract the potentiometer motion may lag behind the real motion. As yet no data are available to show if the frequency response of the system used is adequate.

Measurement of tibia and femur bending moments have the advantage that they are a direct measure of the loading mechanism likely to cause bone fractures due to bending. For a car manufacturer trying to comply with a bending-moment based protection criterion, as well as providing a pass/fail output, the measured bending moments will help the manufacturer understand how their design is working and what needs to be changed if it should fail. Measurement of knee ligament extension or contraction also has the advantage that it is a direct measure of the loading mechanism likely to cause ligament injuries. However, normally they will be due to a combination of knee joint bending and shearing. For the vehicle manufacturer the ligament outputs will be of less help in developing their design solution, because they cannot be resolved into bending and shear components. However, this is unlikely to be a serious problem because although it is likely to be very difficult to add additional instrumentation to the real impactor it will be a relatively simple matter to add this capability to computer simulation models of the impactor.

The measurement channels on the thigh of the Flex-PLI mean that it could potentially be used to test high bumpers. However, to be realistic for this use, the Flex-PLI would need a simplified upper body mass to be added. This is discussed, in more detail, in Sections 4 and 5.6.5.

3.4 Physical and mechanical properties of the Flex-PLI legform

In the initial development of the Flex-PLI, priority was given to meeting biomechanical requirements that relate to the bending, deformation or extension of components such as the long bones, flesh and ligaments, as well as other properties such as mass, centre of gravity and moment of inertia. However, the Flex-GTα version of the legform impactor has somewhat moved away from the properties of mass, centre of gravity and, potentially, the moment of inertia, in order to improve its injury assessment capability and robustness. The authors believe that the characteristics of mass, centre of gravity and moments of inertia of the leg are important in order to obtain realistic loading of the mechanical knee. Table 3.3 shows the physical targets set by EEVC WG17, which are used in the Directive, compared with the targets set by JARI and values for the Flex-PLI GTα, estimated by JARI (Konosu, 2006a), where available.

Table 3.3: Comparison of the EEVC/EC Directive requirements compared with the latest version of the Flex-PLI, version GTα

Property	EEVC requirements	Flex-PLI targets	Flex-PLI GTα achieved values *
Total length	926 ±5 mm	921 mm	928 mm
Femur length (from knee centre)	432 mm	428 mm	433 mm
Tibia length (from knee centre)	494 mm	493	495 mm
Femur mass	8.6 ±0.1 kg	8.6 kg	6.7 kg
Tibia mass	4.8 ±0.1 kg	4.8 kg	5.7 kg
Total mass	13.4 ±0.2 kg	13.4 kg	12.4 kg
Femur centre of gravity (from knee centre)	217 ±10 mm	218 mm	189 mm
Tibia centre of gravity (from knee centre)	233 ±10 mm	233 mm	197 mm
Femur moment of inertia	0.127 ±0.01 $kg.m^{-2}$		Not Available
Tibia moment of inertia	0.120 ±0.01 $kg.m^{-2}$		Not Available

* These values have been estimated by JARI for the GTα prototype (Konosu, 2006a).

Although the values for the GTα version have been estimated by JARI they are most probably reasonably accurate outputs from the CAD system used in the design process. It can be seen that there are some large deviations from the target values for mass and centre of gravity. Although no values have been estimated for the moment of inertia of the GTα version it is thought very likely that it will be well outside the target values. This is because moment of inertia is dependent on the mass distribution which is unlikely to be correct given the deviations from mass and centre of gravity targets. Nevertheless it may be possible in a further stage of development to adjust the total mass and mass distribution to achieve either the EEVC target values or alternative targets. The EEVC targets were derived from data produced by Robbins for a 50th percentile male (Robbins, 1985), but include adjustments from the human data to take account of the impactor's simplified cylindrical shape (Lawrence and Hardy, 1993).

The Flex-PLI GTα, like the EEVC legform impactor, has 'bone' sections of a simplified shape which are larger in diameter and heavier than the thigh and lower leg of a human and the flesh in both impactors is comparatively lightweight. However, in a human the flesh (muscles) is heavier than the bones, is unevenly distributed and is only strongly attached at each end of the muscles. Differences like these are found in most if not all test devices used to represent humans for vehicle safety tests and are necessary for a number of reasons, the most important of which are simplification, robustness, repeatability, inclusion of instrumentation and the limitations of available materials.

In response to a question from the authors regarding the EEVC targets, Dr Konosu, who is responsible for developing the Flex-PLI, has stated that he is not intending to try to match the EEVC moment of inertia and centre of gravity targets, instead he will be working to produce a new specification (Konosu, 2006c). Currently he is investigating the difference between a human where the leg flesh is free to move, to some extent, independently of the bones and an impactor with the flesh more rigidly attached. From this study he is hoping to produce a revised specification in order to take account of the difference between an impactor and a human and presumably match these corrected values in the final Flex-PLI design. In the authors' opinion, establishing appropriate flesh coupling correction values will be very difficult because most of the available data are derived from PMHS which will be very different to live pedestrians who will have active muscles as they will be standing, walking or running. When appropriate new targets for mass, centre of gravity and moment of inertia values are found which include a factor for the difference in flesh coupling, it is thought likely that the Flex-PLI GTα will need significant modifications if it is to achieve these values. This is because, as already noted, the Flex-PLI GTα has most of its mass in the metal 'leg bones' whereas in the human much of the mass is in the flesh. To obtain an acceptable centre of gravity and moment of inertia with the Flex-PLI would require a significant redistribution of mass and will therefore require changes to the working parts of the flexible bone and knee joint. It may be difficult to change the legform's mass distribution sufficiently to match either the EEVC specification or a new specification whilst maintaining the mechanical requirements of the flexible bone mechanism. It should be noted that the tight tolerances on the EEVC specification are intended to restrict variation between similar impactors. Some adjustment of the nominal values, away from the human targets, may be reasonable for the Flex-PLI once it has been shown to be acceptable in other respects. However, given that any corrections for flesh coupling are thought, by the authors, to be small, further significant changes to the Flex-PLI design will be necessary to meet the revised targets.

It will be important for a new flexible legform to have appropriate moment of inertia and centre of gravity because these will have significant effect on the impactor's interactions with the vehicle structure including contact forces and kinematics during the impact. Therefore, it is recommended that a review be carried out by appropriate biomechanical experts to determine appropriate physical targets for a flexible legform impactor. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive biomechanical targets or a specification for flexible legform impactors to be developed and assessed against. The review could include considering the suitability of the anthropometric data used, including any correction factors needed to take account of simplifications in the impactor, such as straight leg bones and not representing the foot, and also any corrections needed to take account of the different mass distribution between flesh and bone and any difference in the coupling of the mass of the flesh needed. Although the authors' do not anticipate that such a review would result in any significant revisions of the targets selected by EEVC WG17 it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design.

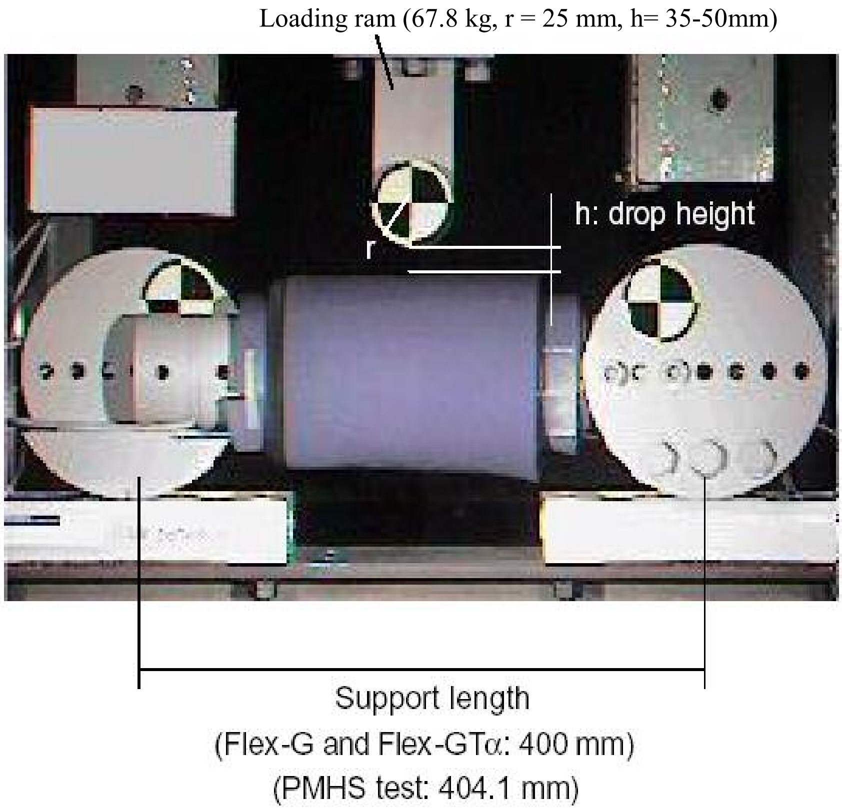
3.5 Biomechanical performance

The latest GTα version of the Flex-PLI has been assessed by Konosu (2006a) against a number of corridors derived from tests of PMHS (Ivarsson *et al*., 2004). Appropriate sub-assemblies of the legform have been tested by Konosu (2006a) in a similar set-up to that used to obtain the PMHS data so that the performance of the legform could be compared directly with the PMHS corridors. Some early dynamic PMHS test set-ups suffered from the weakness that stiffness of the bone or joint under test could not be separated from the inertial forces required to move the mass of the specimen. It should be noted that the set-up used in the PMHS tests is such that, although a dynamic test, the bending stiffness can be found independently of the energy required to overcome the inertia of the leg mass.

3.5.1 Bending stiffness of long bones

Both Konosu's (2006a) test set-up and the test results can be seen for the thigh in Figure 3.4 and for the lower leg in Figure 3.5. From these results it can be seen that the both the G and the GTα versions are within the corridor, however, the latter is towards the lower end of the thigh corridor.

It can be seen that for the thigh the corridor is tight at the lower end and that the alpha version falls slightly outside the corridor in this area but, in the authors' view this aberration is not important because it is very small and at a low level of bending moment and deflection (this is the thigh flesh deformation area).



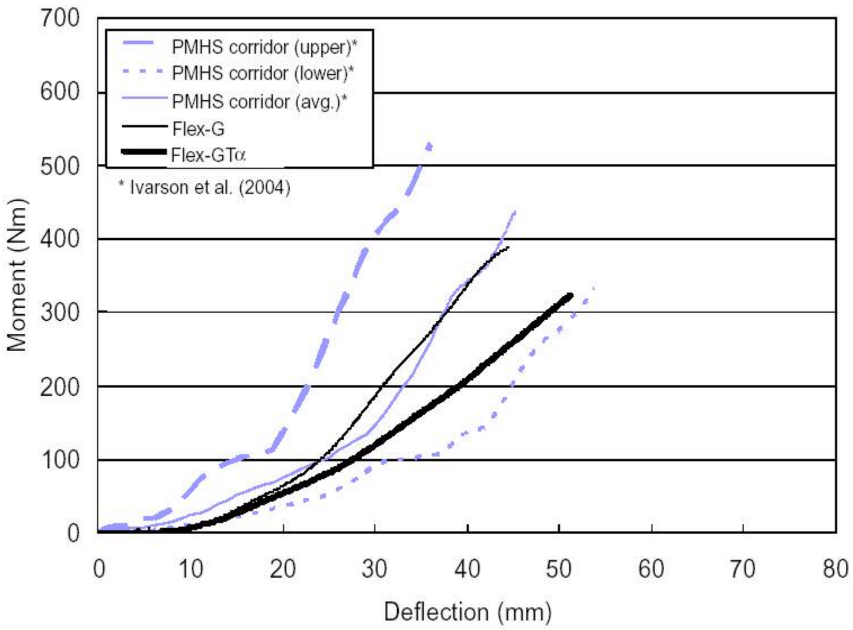


Figure 3.4. Testing of the Flex PLI thigh (Konosu, 2006a)

As with anthropometric targets, TRL recommends that both the PMHS data and the method used to derive the corridor are reviewed by appropriate biomechanical experts before the specification for a flexible impactor is finalised. Amongst other things this review could consider the suitability of the data, could adjust the corridor shape or width using the most appropriate statistical methods, widen the initial part of the corridor if necessary and take into account any effects of muscle tension in live pedestrians. Although the authors' do not anticipate that such a review would result in any significant revisions to the corridors it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive biomechanical targets or a specification for flexible legform impactors to be developed and assessed against.

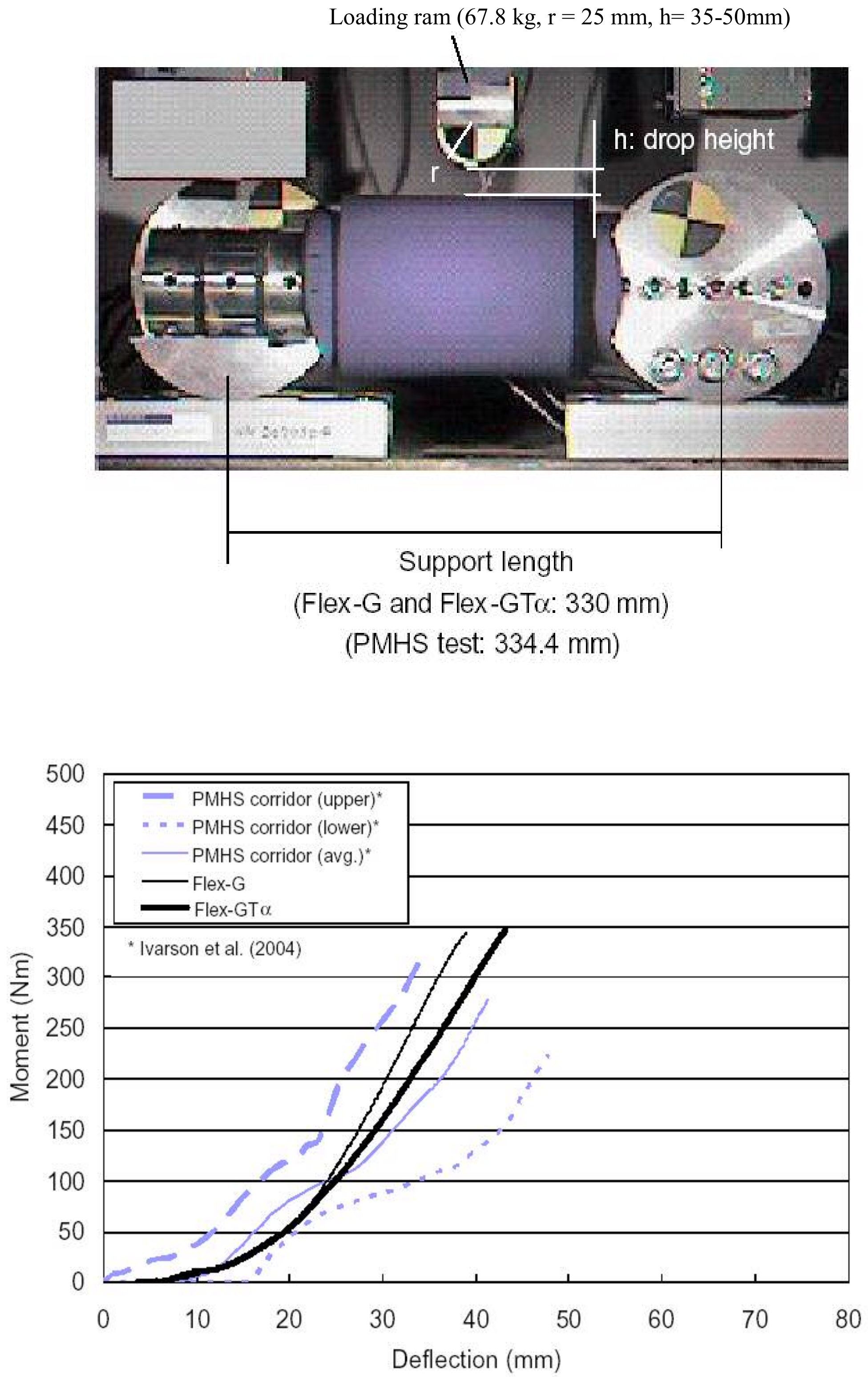


Figure 3.5. Testing of the Flex PLI lower leg (Konosu, 2006a)

3.5.2 Knee stiffness

The knee of the EEVC legform matches the EEVC corridor which has a higher lateral bending stiffness than the corridor proposed by Konosu for the Flex-PLI (Konosu, 2006a). Konosu's corridor is based solely on PMHS data.

It is suggested that the most important weakness of the data based on tests of PMHS is the lack of muscle tension. In the 1994 report of EEVC WG10 (European Experimental Vehicles Committee, 1994) biomechanical data for the knee were considered, from PMHS tests at velocities of 16 to 20 km/h, that gave a knee bending moment of 120-140 Nm. They also considered results from tests on the knees of volunteers that indicated quasi-static lateral knee bending moments of 115 to 170 Nm without injury or discomfort. They concluded that these results were in conflict because the quasi-static results are on average higher than the dynamic results and the opposite should be expected due to the visco-elastic properties of ligaments. They decided that a higher knee stiffness was needed in the impactor than shown by the PMHS tests to account for higher impact velocity and the effects of muscle force. It should be noted that the muscles and ligaments from the thigh area are positioned around the knee in such a way that they would significantly increase the stiffness of the knee in lateral loading if they were tensioned. The tendons around the knee are the tendon of the Biceps muscle, which forms the outer hamstring, and the tendons of the Semitendinosus and Semi-membranosus which with those of the Gracilis and Sartorius, form the inner hamstring (Gray, 2001), see Figure 3.6.

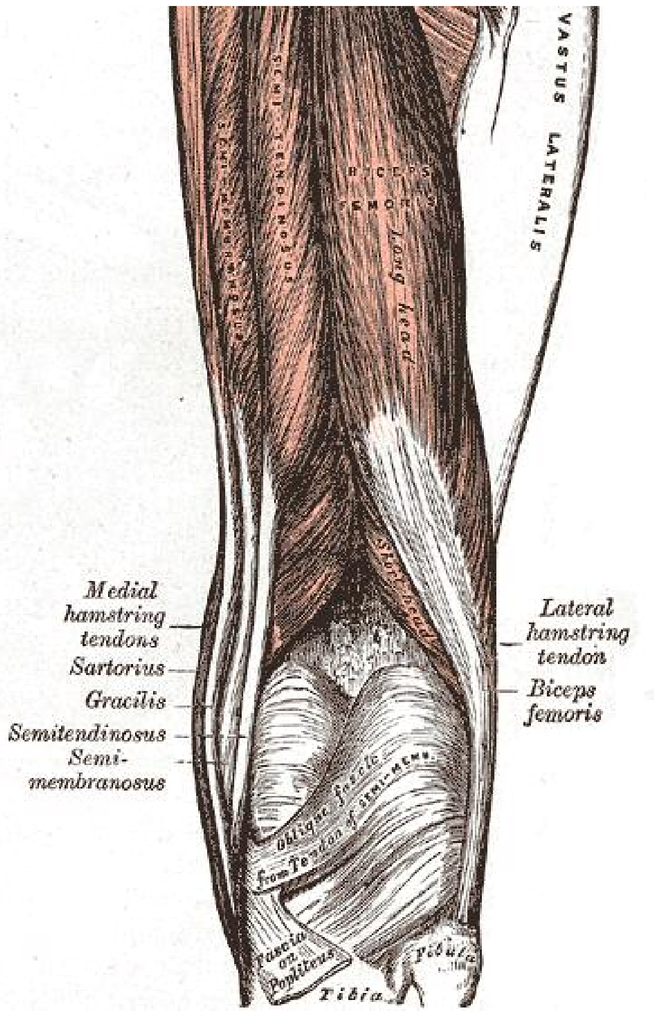


Figure 3.6. Muscles and tendons of the knee (Gray, 1918)

In their 1998 report (updated 2002) (European Enhanced Vehicle-safety Committee, 2002a) EEVC WG17 (who followed on from WG10) considered PMHS test data from tests at a higher speed

(40 km/h) carried out by Kajzer *et al.* (1997). The average peak bending moment measured in the Kajzer *et al.* bending tests was 388 Nm. Konosu and Tanahashi in their ESV paper (Konosu and Tanahashi, 2003) questioned the results of Kajzer *et al.* and concluded that there was a mistake in the calculation method used by Kajzer *et al.* to calculate the knee bending moment from the measured forces and lengths. However, there is insufficient evidence in either paper to confirm or reject this conclusion. More recently Konosu *et al*. in an SAE paper (Konosu *et al*., 2005) reported that they had received confirmation, from a co-author of the Kajzer *et al.* paper, that a mistake had indeed been made. Konosu *et al.* recalculated the Kajzer *et al.* knee bending moments using a corrected formula. This produced revised bending moments of 65 Nm for a 35 year old female, 139 Nm for a 59 year old male and 127 Nm for a 44 year old male. Konosu *et al.* also concluded that the living human muscle may increase the knee-joint stiffness and that confirmation testing and analyses need to be conducted. So the main issue for any legform is the reproduction of the correct lateral knee stiffness to represent a live human, including the effects of muscle tension.

As living humans cannot ethically be tested at potentially injurious levels, the one method available to assess the influence of muscle tone on the stiffness and bending performance of the knee and leg bones is accident reconstruction (and any other differences between living humans and PMHS data). This method was employed by Matsui (2003) when he used the EEVC WG17 legform impactor to reconstruct real pedestrian accidents. Accident reconstruction has the advantage that the measured outputs can be compared with the accident injuries to obtain injury risk curves for living humans. It is interesting to note that the injury risk curve derived from these reconstructions with the WG17 impactor shows that a knee lateral bending angle of 19.2° corresponds to a 20 percent risk of injury. As this angle is at the higher end of the range found to cause knee ligament failure in PMHS tests it would be reasonable to conclude that the current maximum lateral knee bending moment of about 460 Nm (at 15°) specified for the EEVC WG17 legform impactor is appropriate or slightly too low for live humans. Unless it is accepted that muscle tension makes a significant contribution, this inference conflicts with the far lower knee bending moment found in PMHS knee tests. The device used to reconstruct the accidents was not a perfect representation of a live human (in Matsui's case he used the EEVC WG17 impactor which has rigid bones). Therefore, the results will include a correction (transfer function) for the differences between the impactor and a live human, which in many cases can be very useful. Because the transfer function for a flexible type legform is likely to be different to that of the WG17 impactor, the results from these reconstructions cannot be transferred directly to the Flex-PLI. Therefore, if this reconstruction method is used for the Flex-PLI, it would have to be carried out with the flexible legform. Such a programme might need to start with an iterative adjustment of the knee stiffness, so that the knee outputs matched injury outcome.

Taking into account the knee geometry and ligament extension properties it seems reasonable to conclude that the lateral knee stiffness due to muscle tension is combined in a living human with the stiffness due to knee ligaments.

An alternative method of assessing the influence of muscle tone on the bending and shear performance of the knee and leg bones is to use detailed computer models of the human using realistic descriptions of bones, muscles, ligaments, tendons and their interconnections. One study using this method was reported by Soni *et al.* (2006). The authors concluded that

> 'the activation of lower extremity muscles in simulations predicts a reduction in peak knee ligament forces by a factor of two or more. Since ligament loading is predicted to be lower with muscle activation, the likelihood of ligament injury in active posture may be expected to be lower than that predicted by PMHS tests.'

Although this conclusion does not relate directly to the knee bending and shear stiffness it does suggest that the muscle effect can be significant. The authors also provide a list of limitations and suggested further improvements, so this model may be more of a good start than a definitive result.

Therefore, on the basis of the information currently available it is concluded that the EEVC WG17 knee joint stiffness is more appropriate to represent the living human than the lower stiffness selected as a corridor for the Flex-PLI legform impactor.

Lawrence *et al.* (2006) observed that

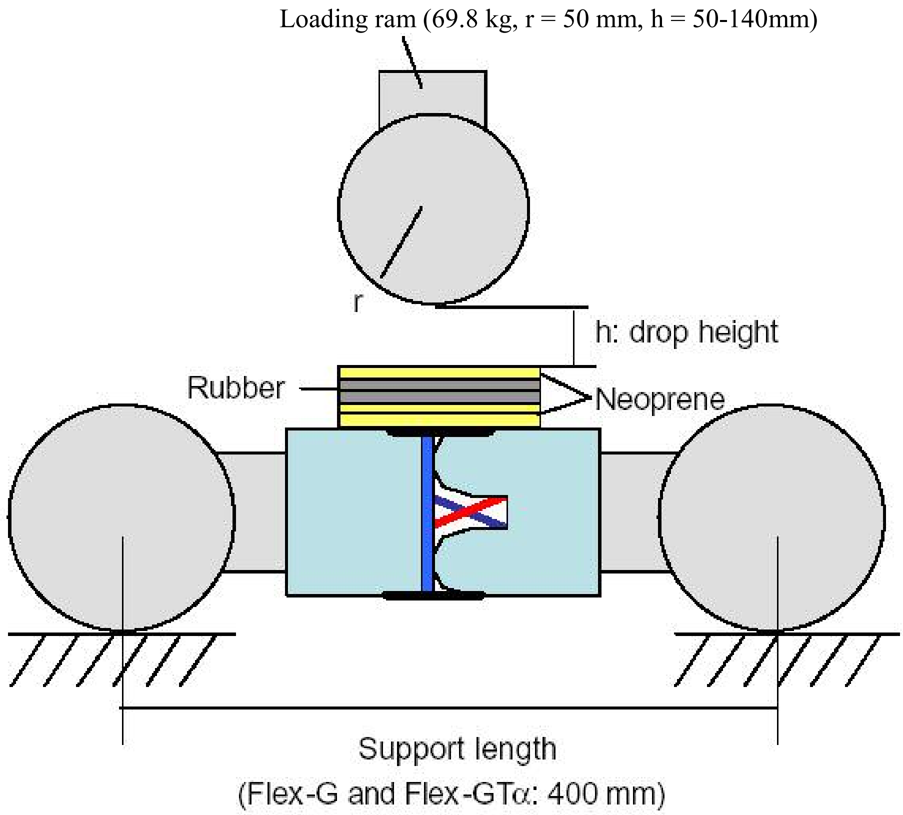
> 'increasing the strength and pre-tension of the springs acting on the wire ropes that represent the collateral ligaments in the mechanical knee of the Flex-PLI is thought likely to give similar results to the combined effects of muscle tension and knee ligaments, as both the muscle tendons and the collateral ligaments act in tandem in the human knee. However, to achieve the current EEVC WG17 knee stiffness in the Flex-PLI would require far larger springs than are currently used, which might be difficult or impossible to fit in the available space.'

It can be seen in Figure 3.3 that Flex-PLI GTα has overcome, to some extent, the difficulties predicted by Lawrence as it now has eight sets of springs and ropes to represent the collateral ligaments when the previous version had only four. It can also be seen from Konosu's paper (Konosu, 2006a) that the lengths of all the ligament springs have been doubled in this version. The test set-up used to assess the latest GTα version of the Flex-PLI can be seen in Figure 3.7.

Figure 3.7 shows the loading set-up comparison of the knee bending moments against bending angle for the Flex-GT, Flex-GTα, TRL WG17 legform (called TRL-LFI in the figure legend) and PMHS tests. It can be seen that all impactors perform above the knee bending stiffness corridors originally proposed for the Flex-PLI, not for the EEVC WG17 impactor. Konosu (2006a) states that the knee bending stiffness was increased in the Flex-GTα, to improve the injury assessment performance.

Although he does not explain how this is an improvement, the authors of this current report assume that the increase in stiffness over the earlier version is a pragmatic allowance for the effects of muscle tension. Note that the figure also shows the increase in maximum knee bending angle for the Flex-GTα which now bottoms out at about 26 degrees rather than the 19 degrees of the previous version, this compares with the 30 degree capacity of the WG17 legform impactor.

It can be seen that there is debate about the most appropriate biomechanical values to be used for the stiffness of the knee of the legform impactor. This is because in practice it is very difficult to make appropriate measurements in live subjects and PMHS. It is reassuring to note that similar debates exist about most biomechanical requirements used in safety regulations; but applying these regulations has resulted in significant improvements in vehicle safety despite these uncertainties. In the case of the EEVC WG17 legform accident reconstructions, the tests appear to confirm that the EEVC lateral knee joint stiffness is appropriate. However, as already noted, the reconstructions include a transfer function for the differences between other aspects of the WG17 legform and a human, so these results cannot be applied directly to a flexible legform which is likely to need a smaller transfer function. Therefore, before further work is undertaken to refine the Flex-PLI legform impactor it is strongly recommended that a study be carried out to determine the effects of muscle tension on lateral knee joint stiffness. Accident reconstruction using a flexible legform impactor is one method that could be used. Finite element computer models of the human body and car are very useful tools for this type of study. However, in the authors' opinion although finite element analysis is a very powerful tool to use for such a study, it has the weakness that, unless sufficiently and appropriate detailed information is used, it tends to report back, as apparent fact, what are really only estimates, due to the assumptions built into the model by its author. Detailed finite models such as THUMS will ultimately be an ideal tool for such a study as they will need fewer assumptions. Although the THUMS model is already sufficiently well developed to be used for many applications, it may not yet be ready for investigating the effects of muscle tension on lateral knee joint stiffness. This is because modelling of the muscles is still under development and work on activating the muscles is still at an early stage (Soni *et al*., 2006) in the THUMS model. Therefore it is recommended that as a first step non-injurious tests of the knees of human volunteers be carried out to establish a starting point. It is suggested that this is needed despite EEVC WG10 obtaining data of this type because the WG10 studies were of an informal nature and did not provide sufficient information for the results to be examined and accepted by others outside WG10. Such a study could determine both the maximum load that a subject can withstand without discomfort (injury) and the relationship between applied bending moment and lateral knee bending angle. These data could be used to validate computer simulation models. Alternatively, with suitable extrapolation, it could be added to the stiffness found in PMHS knee joint tests to produce a combined muscle and knee ligament stiffness.



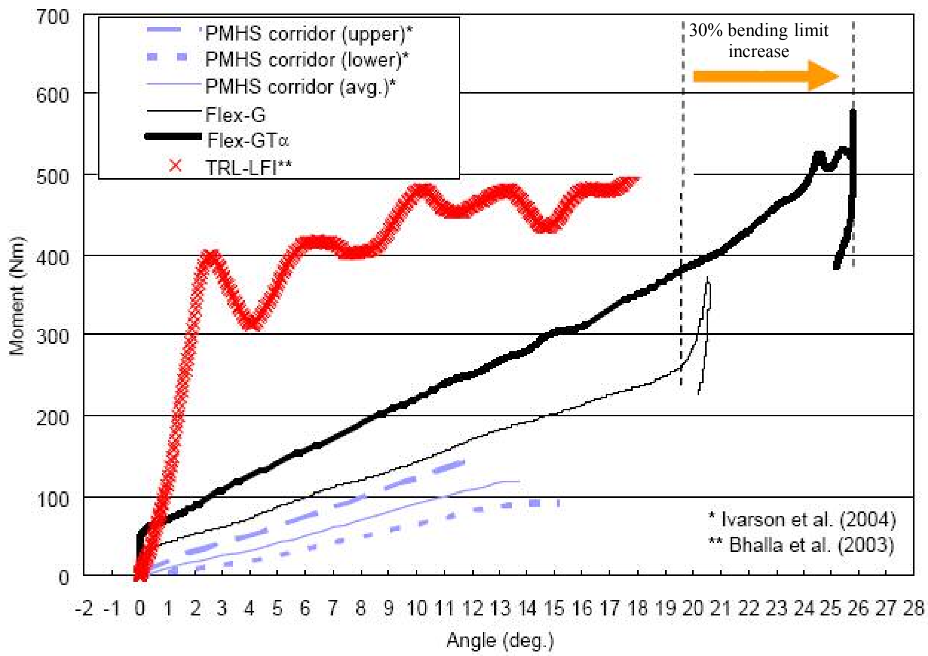


Figure 3.7. Dynamic knee joint bending relating TRL-LFI, Flex-G and Flex-GTα to PMHS corridors (Konosu, 2006a)

3.5.3 *Assessment of injury risk*

To date only some tentative protection criteria (acceptance levels) have been made by the GTR group for the tibia and knee ligaments (Imaizumi, 2005) for an earlier version of the impactor. It will be necessary to produce finalised injury risk curves for the final version of the impactor.

Much of the data available from PMHS tests for lateral knee impacts were from studies designed to provide results in terms of the global knee joint shear and bending displacement. However, within the knee joint these global displacements ultimately cause failures by extending the knee ligaments. One of the advantages of the instrumentation of the knee of Flex-PLI impactor is that it measures ligament extension directly. However, as it is not capable of measuring global knee joint shear and bending displacement much of the available PMHS data are unsuitable for deriving injury risk corridors for this impactor directly. Nevertheless, in some cases it may be possible to derive extension data from these tests by making assumptions about the knee joint dimensions and deformation modes. Alternatively, data are available from tests of individual knee ligaments and these properties can be built into computer simulation models of the knee joint to obtain data for the complete knee. One interesting study of this type used a finite element model of the human lower limb (Takahashi and Kikuchi, 2001), which analysed the human knee ligaments. They suggested that the legform impactor test injury criteria should be determined using a combination of bending angle and shearing displacement. Takahashi and Kikuchi (2001) found the acceptance limits were determined solely by the anterior cruciate ligament and the posterior cruciate ligament and therefore only these two ligaments were used in further considerations. Overlaid with the geometric performance of the ligaments were the results from dynamic simulations, which gave shearing displacements and bending moments at the time of ligament failure. From that plot, Takahashi and Kikuchi stated that the shearing displacement and the bending angle do not determine the risk of failures independently and their results were suggested as acceptance levels for knee ligament failures, although they acknowledged the need for experimental validation of their work. Although this work was aimed at the EEVC legform impactor which measures knee shear and bending displacement directly it may help to inform the debate on injury risk curves for the Flexi-PLI type of impactor which measures ligament extension directly. However, their conclusion that only the cruciate ligaments need to be considered is not supported by other studies, for example an analysis of 178 pedestrians who suffered significant knee injuries (Forward *et al*., 2001) showed that 40 of them suffered ligamentous injuries and of those 35 percent suffered injuries to the collateral ligaments. The remaining 138 casualties with significant knee injuries suffered bone fractures within or close to the knee joint.

As already noted, the Flex-PLI measures individual ligament extension and it is likely that injury risk curves will be developed for each ligament for a simplified bending or shear loading. However, real life impacts are likely to produce a combination of shear forces and bending and it is not clear if the injury risk for this type of loading will be the same as a single loading case. Therefore to measure injury risk it is recommended that the suitability of using individual ligament extension or some combination of ligament extensions is examined for the final version of Flex-PLI in order to produce and justify injury risk functions specific to that test tool.

For the long bones, much of the PMHS data are from studies intended to provide the relationship between displacement and applied force or bending moment up to the point of fracture. Therefore it should be easier to produce appropriate injury risk curves for long bone fracture. Ideally, as recommended for other biomechanical properties, both the methods used to produce the injury risk curves and the suitability of the data selected should be reviewed and confirmed by an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive injury risk curves which can then be used to select the vehicle protection criteria.

When proposing revised protection criteria for the EEVC legform Konosu *et al.* (2001) suggest protection criteria based on a 50 percent risk of injury. However, as knee injuries are likely to result in long-term disability, it is recommended that, as with phase two of the EC Directive, protection criteria for a Flex-PLI impactor be set at a 20 percent injury risk. Ideally an ‘acceptable’ level of injury risk for the knee should be selected using a cost benefit calculation. This would require detailed information to estimate the number of knee joint injuries that could be prevented and the costs to society (lost output, medical and 'human' costs) for knee joint injuries of this type. For knee joint injuries it is thought unlikely that the detailed information needed to select an injury risk value on cost benefit grounds is available.

3.6 Over-range capacity

For areas on a vehicle where providing full protection may be difficult, a concept of relaxation zones has been introduced in the pedestrian Directive 2003/102/EC. For these relaxation zones less protection is required and therefore the impactor must have some over-range capability. The bending capacity of the knee of the current Flex-GTα version has been increased to about 26 degrees when subjected to pure bending in the biomechanical tests rather than the 19 degrees of the previous version. It will not be clear until the protection criteria are finalised whether the over-range capacity of the Flex-PLI knee is sufficient. Because the bending and shear mechanisms are combined in the Flex-PLI it will be difficult to determine its reliable over-range capacity because it will be reduced in vehicle tests where the knee is subjected to a combination of bending and shear. However, it is thought to be more likely to suffer from insufficient range than the EEVC legform impactor which has a bending capacity of 30 degrees and a separate shear mechanism with a reliable displacement of about 7.5 mm.

3.7 Feasibility

For legislative use of the Flex-PLI it will be necessary to specify protection criteria based on 'acceptable' injury risks in terms of ligament extension and bending moment of the long bones. However, when considering the feasibility of achieving that level of protection it should be noted that both the protection criteria and the knee joint and long bone stiffness will affect feasibility. A sensitivity study has been carried out by a vehicle manufacturer for EEVC WG17 to determine the effect of changing the knee bending stiffness of the WG17 impactor when used to test a vehicle. The study used a detailed FE model of a real vehicle under development at the time of the study and made use of a detailed FE model of the WG17 legform impactor with a range of scaling factors applied to the WG17 knee bending stiffness corridor from 1 to 0.4. The following tables (Tables 3.4 and 3.5) have been copied from the report to WG17 (Staines, 2005).

Table 3.4: CAE knee stiffness study 'Best' location

Knee bending stiffness relative to WG17	Tibia acceleration (g)	Knee angle (deg)
100% (= WG17)	148	13.5
80%	153	16.5
60%	158	20.1
40% (approximates to JARI corridor)	163	24.6

It can be seen from the simulation results that with the WG17 knee stiffness the vehicle complied with the current phase two requirement (acceleration ≤ 150 g and knee bending angle ≤ 15 degrees) at the best location and with the phase one requirement (acceleration ≤ 200 g and knee bending angle ≤ 21 degrees) at the worst. However, changing the knee stiffness, to approximately match the JARI corridor, has a significant effect on the knee bending angle, increasing it by about 11 degrees at the best and worst locations. From these results it would appear that changing the stiffness to match the corridor produced by Ivarsson *et al*. (2004), which has been proposed for the Flex-PLI by JARI, would make it far more difficult for manufacturers to meet the protection requirements. This argument should be used with caution because the vehicle was designed to meet the Directive with the original WG17 knee bending stiffness and has not been optimised for the JARI one. Nevertheless, when considering the feasibility of meeting a proposed protection criterion based on injury risk curve for the Flex-PLI the knee and long bone bending stiffness must also be considered and for the knee it should include any allowance for the effects of muscle tension on knee joint lateral bending moment.

Table 3.5: CAE knee stiffness study 'Worst' location

Knee bending stiffness relative to WG17	Tibia acceleration (g)	Knee angle (deg)
100% (= WG17)	153	17.3
80%	144	20.4
60%	136	24.0
40% (approximates to JARI corridor)	130	28.4

At present it is not possible to come to any conclusions regarding feasibility because the protection criteria and lateral knee bending stiffness have not been finalised. There are sufficient data to be concerned about feasibility at 40 km/h due to the low knee bending stiffness of the current biomechanical corridor. However, the latest version of the impactor has a knee stiffness that is significantly higher than the current corridor and it assumed that this is in anticipation of an improved biomechanical requirement.

3.8 Robustness

The previous versions of the Flexible legform impactor, prior to the GTα version, were tested by a number of organisations. The general consensus of this testing was that the flexible legform impactor was not robust enough to be used to test vehicles at the required speed of 40 km/h. Even at speeds somewhat less than 40 km/h, these impactors were found to suffer problems with injury assessment measurement due to bottoming out of ligament extension springs.

It is important that an impactor used for regulatory testing should be robust and have accurate transducers with a suitable frequency response.

The previous versions of the impactor, the Flex-2004 and the Flex-G, were both shown to suffer from robustness issues. One of the problems was in the assessment of the injury criteria where the useful range of the instrumentation needed to be extended. In the study by Mallory *et al.* (2005), tests on the bumpers of vehicles from the North American fleet showed that, while not breaking, even the WG17 legform impactor was exceeding its limit for bending. The Canadian bumper Standard 215 uses the same equipment, test methods and similar limitations on damage as the NHTSA Part 581 regulation, but all test speeds are double that of the NHTSA requirements. Tests with the Flex-PLI, even at lower impact speeds, resulted in the impactor breaking, sometimes before it reached its bending limit.

The impactor has been improved since the G-level version, but currently the authors are not aware of any detailed results of testing with the Flex-GTα or Flex-GT legform impactors for impacts at 40 km/h. The concern that earlier versions of the Flex-PLI were not capable of assessing vehicles' aggressiveness at 40 km/h were also raised by members of the Flex-PLI Subgroup, a number of whom postponed further testing until after the development of the Flex-GT, with assurance that it was capable of assessing vehicle aggressiveness at 40 km/h.

JARI (Konosu, 2006a; Konosu, 2006b) reported, in the style of a presentation, on the progress and testing of the Flex-GTα. Dr Konosu provided information on the modifications to the legform to make it more robust. At the 3rd Flex-PLI meeting, it was discussed that the GTα had been tested at speeds of 40 km/h; however, no details of testing procedure or detailed results were produced to allow the current status of the legform's reliability and robustness to be made.

Therefore, the authors believe that currently the robustness of the latest version of the Flex-PLI at the required test speed has yet to be proven. At the next meeting of the Flex-PLI Subgroup, it is likely that these issues will be discussed and, possibly, the performance of the GTα/GT version of the Flex-PLI will be reported upon with independent assessment from other members of the Subgroup. Such a process is paramount before it could be adopted for use in any legislation.

The EEVC WG17 legform impactor was available for a number of years before it was adopted for use in a regulation and in that time, through assessment and use, it proved its robustness and the accuracy of the transducer system. However, it is likely that there will be proposals to use the Flex-PLI in regulations more quickly than with the WG17 impactor. Therefore it is recommended that before the final version of the Flex-PLI is considered for regulatory use it should be made available for sufficient time for its robustness to be assessed by the interested parties.

3.9 Repeatability and reproducibility

Good repeatability and reproducibility are important in a regulatory tool and test method because manufacturers will have to take these variations into account when designing solutions.

Dynamic three-point bending tests for the thigh, knee and lower leg components of the Flex-GTα were only reported for a very small number of tests, making it difficult to assess just how good the repeatability of the components was (Konosu, 2006b). When a similar study was conducted using the G-Level model (Konosu, 2005), a much greater number of tests were carried out and it was shown that the thigh, knee and lower leg all had very good repeatability.

BASt was tasked to assess independently both the repeatability and reproducibility of the earlier version, the Flex-G. Initial testing showed issues with the capability of the legform to assess vehicles at an impact speed of 40 km/h. The ligament extension capability bottomed out when testing vehicles with bumper systems assessed as pedestrian friendly by the WG17 legform impactor. Therefore, further testing was postponed, waiting on the outcome of the Flex-GT development, together with assurances as to its ability to be used in tests up to 40 km/h.

In the limited testing that BASt conducted with the earlier version, using the Flex-G legform on a production and modified production vehicle, they stated, in their response to TRL questions, that it had shown both good repeatability and reproducibility but only for impact speeds of up to 24 km/h.

Increasing the test speed to 40 km/h represents a significant increase in the impact severity that will impart much greater forces and stresses on the components of the impactor. It is therefore not possible to extrapolate the characteristics found by BASt at low speed to understand how it might perform at higher impact speeds.

The Flex-PLI knee shearing stiffness is produced by a combination of several factors including the joint friction, the interlocking action of knee components and the ligament tension. It may be difficult to make such a complex mechanism repeatable; however, until the flexible GTα legform has been tested it is not possible to comment further.

To date there are no data available to judge the reproducibility of the latest GTα version of the impactor. It is thought likely that the reproducibility will be acceptable provided that:

- for the impactor, the specification, manufacturing tolerance, certification test and corridors are appropriate and the final design achieves them.
- for the test, the tolerances for the test environment and for propelling the legform into the vehicle are appropriate and the equipment meets them.

3.10 Certification

For any formal vehicle assessment, whether for regulatory or non-regulatory (e.g. consumer information) purposes, it is important to make vehicle test methods and test tools reproducible in order to achieve constant standards. In order to achieve consistent test tools, both the physical and dynamic requirements should be specified. Many aspects of a legform impactor that could affect test results such as component lengths, masses, centres of gravity, etc. will be defined in the specification and with manufacturing tolerances. In general, physical aspects such as these can be confirmed by the supplier and will not change. Other important dynamic aspects may change depending on, friction, wear, aging, tuning adjustments (for example pre-tensioning of the wire ropes that limit bending), etc. Certification tests are a good method of controlling the performance of an impactor and depending on their nature they can be sensitive to all of the above variables. In addition certification tests are likely to identify faults in the transducer systems.

The dynamic certification test for the assembled upper and lower leg 'bones' and knee of the Flex-PLI (without flesh) was defined for the G-level model and remained unchanged for the GTα model (Konosu, 2006a). This consisted of the legform, without the flesh, being attached to a frame through a pin joint at the top of the impactor, and allowing it to swing freely (pendulum like) into an impact face located at the knee level. The legform is held at an angle of 15 degrees above the horizontal and released to swing into the impact face. This interface has three, 5 mm rubber sheets and two, 5 mm neoprene sheets as shown in Figure 3.8.

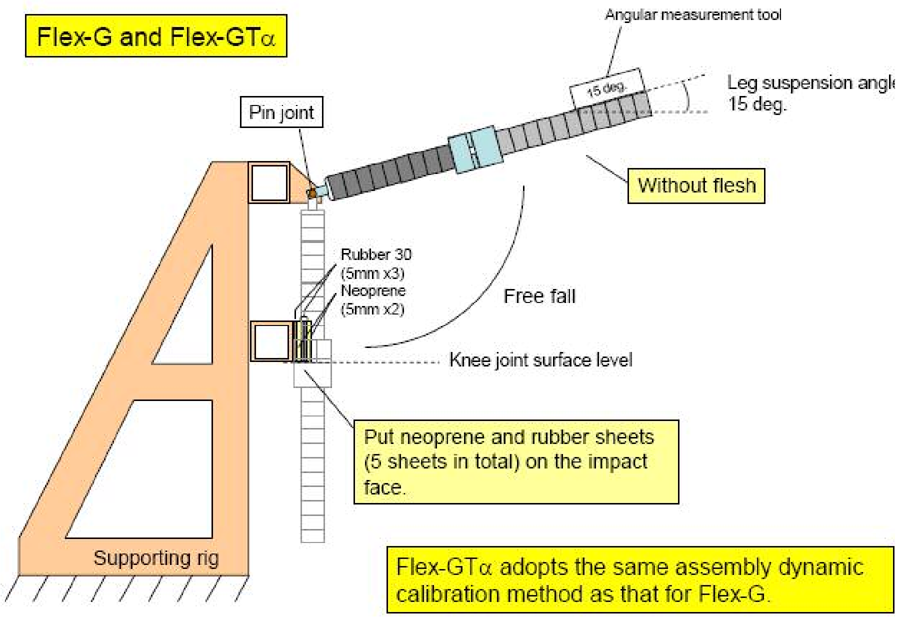


Figure 3.8. Dynamic certification procedure for the Flex-GTα (Konosu, 2006a)

The certification procedure assesses the bending moments at three different levels within the thigh, four ligament elongations in the knee and bending moments at four locations in the lower leg. These are compared with tentatively defined upper and lower corridors, which have changed slightly between the two versions of the flexible legform considered here.

The authors of this report have no first hand experience of the flexible legform impactor, but they do have some experience of the certification procedure which was first proposed by EEVC WG10 for certifying its legform. When reviewing the work of WG10, WG17 were concerned about the suitability of this method due to its the low velocity compared with the velocity used to test vehicles, the potential lost energy in the hinge joint and the need to regulate / certify the deformable arresting material. WG17 went on to adopt a TRL proposal for an alternative certification method (European Enhanced Vehicle-safety Committee, 2002a), which avoided the use of deformable arresting material and tested the leg at a velocity far closer to that of a vehicle test. With hindsight the authors think that the pendulum method was the better solution, because the WG17 method has a shorter and more violent loading action than both the pendulum test and a typical vehicle test. To overcome the two weaknesses of a pendulum test, as identified by WG17, it is recommended that:

- the test should include a specification for the design of the pin joint, about which the pendulum swings, in order to make the energy lost to friction standard and reproducible,
- a separate procedure should be introduced to control the deformation characteristics of the neoprene and rubber sheets used to arrest the impactor. The characteristics of the arrester might be tested and certified by impacting it with a rigid pendulum arm of appropriate mass, fitted to the same rig, with a performance requirement for the reaction force or pendulum acceleration.

Depending on the stiffness of the bumper system being tested, the deformation characteristics of the skin and flesh of the legform impactor will have some effect on the test results. Currently, the outer skin and flesh of the impactor are not fitted during the pendulum certification tests. One option to evaluate the characteristics of the skin and flesh would be to amend the pendulum certification procedure to include a test with the full legform including the layers of flesh and skin. Alternatively an additional certification test (or tests) could be developed to certify the skin and flesh separately. As the impactor uses different numbers of layers of flesh at various locations along its length it would appear better to develop a separate test. Stress strain plots have been provided for the impactor ‘flesh’ (Konosu, 2006a), but there is insufficient detail to show how these plots could be used in a separate biomechanical or flesh certification method.

There are individual biomechanical tests and corridors for the long bones and knee. The design of these assemblies is thought to be such that their performance can be changed or adjusted by, for example, changing the degree of pre-tensioning in the outer wire ropes of the long bone. This potential tuning of the individual assemblies should be an advantage in adjusting the overall performance of the impactor to meet the pendulum certification requirements. However, it is not clear how the performance of each part will influence the overall performance of the impactor in the pendulum test. Therefore, instead, it may be necessary to develop certification tests for the individual assemblies. These certification tests could be an adaptation of existing biomechanical tests. Assuming that the final design of the knee and long bones are deemed acceptable against the biomechanical corridors then new tighter certification corridors could be drawn up around the actual performance of the impactor. The width of the certification corridor should be set at an acceptable and achievable level of variation between similar impactors.

3.11 Plans for future development and availability for regulatory use

The final version of the flexible legform will be the Flex-GTR, which is due for production towards the end of 2007. However, based on the Flex-PLI Subgroup task scheduling, it is difficult to ascertain the current state of the legform’s development, as much testing and development reporting was not available at the time of writing.

As already noted the EEVC WG17 legform impactor was available for a number of years before it was adopted for use in a regulation which gave time for it to be assessed as suitable for regulatory use. It is likely that there will be proposals to use the Flex-PLI in regulations more quickly than with the WG17 impactor. Therefore, it is recommended that, before the final version of the Flex-PLI is considered for regulatory use, sufficient time and resources be provided to assess its suitability.

A number of recommendations have been made in the preceding sections regarding obtaining or reviewing biomechanical and anthropometric data in order to produce a specification for a flexible legform that is considered appropriate by independent experts. Ideally this specification should be produced before or in parallel with the development of the final Flex-PLI impactor design. Once the final version of the Flex-PLI is available, it can be assessed to determine if it satisfactory for regulatory use against the agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability. Due to the slippage in the development of the impactor it is not clear if the GTR Flex-PLI Subgroup will be able to complete a sufficiently thorough assessment of the final version to show if it is suitable for regulatory use. If the GTR group are not able to carry out a full assessment then it is recommended that this assessment be carried out by appropriate experts. Now that the IHRA international group are no longer formally active, the possibility of using EEVC WG17 could be considered.

The centre of gravity and moment of inertia of the current Flex-GTα version of the Flex-PLI are not considered to be acceptable. To obtain acceptable values for these properties with the Flex-PLI would require a significant redistribution of mass and will therefore require changes to the working parts of the flexible bone and knee joint. Therefore if JARI choose to correct these properties, there may be a significant delay in producing a finalised version.

3.12 Advantages of using a flexible legform

As a general rule a more biofidelic pedestrian impactor will result in protection more closely tuned to the needs of protecting pedestrians and in a more robust test method, better able to take into account future changes in vehicle design and styling trends. On the other hand, a more complex impactor is more likely to suffer robustness and reproducibility problems, making it less suitable for regulatory use. Also, it is easy to lose sight of the fact that the test procedure is intended to protect a range of statures and this often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

The main advantage of the Flex-PLI legform is its ability to represent the bending of the human long bones when struck by the front of a vehicle. It also possesses a mechanical knee joint that was designed to be a closer mechanical representation of the human knee than the current WG17 impactor.

One of the vehicle measures that help to reduce knee lateral bending is the introduction of a low load path in the bumper, early in the impact (a strong spoiler). However, potentially the contact of a strong spoiler could increase the risk of fractures at about ankle level. Ideally, therefore, a legform impactor should be able to determine the fracture risk along the full length of the bumper contact. The multiple measurement channels on the tibia of the Flex-PLI are well suited to this requirement as it makes it possible to determine the loading profile along the full length of the lower leg. This is an advantage over the EEVC legform, which has only one acceleration transducer just below the knee. EEVC WG17 has recommended that the need for an additional accelerometer, at ankle level, should be a topic for consideration / research in a document supplied to the European Commission (European Enhanced Vehicle-safety Committee, 2002b).

3.13 Cost and benefit issues

In terms of testing there will be small differences between the cost of maintaining, certifying and repairing a flexible legform compared with the EEVC WG17 legform, but, these are not considered to be significant. Overall it is thought that savings in one area are likely to balance additional costs in others.

At this stage of the Flex-PLI's development it is not possible to estimate the additional costs of producing vehicles to meet the protection requirements of a flexible legform. However, it is thought likely that the costs will be sensitive to the bending stiffness finally chosen for the knee. This is supported by the sensitivity study discussed in Section 3.7, which suggests that considerable extra crush depth will be required if ultimately a low knee bending stiffness is thought most appropriate.

A number of benefits of using a flexible legform impactor have been identified in Section 3.12 and in some cases these are likely to result in more appropriate protection which should yield additional reductions in leg injuries over the current Directive. However, compromises in the design, such as being unable to meet the centre of gravity requirement, might negate the potential benefits of the flexible legform impactor. Therefore at this stage of the impactor's development it is not clear if these benefits will be significant or realised.

3.14 Summary – Flex-PLI

The EEVC WG17 legform has been established as a regulatory sub-system test tool for many years. As such, it is specified for use in the EC Directive and draft GTR. However, the WG17 legform has some limitations and therefore there is scope for improvement with the next generation of legform test tool. The Flex-PLI is being developed as that next generation of test tool and is undergoing development and evaluation currently.

The legs of pedestrians are the most frequently injured body region in accidents with cars, so testing with an improved bumper test tool could potentially result in the prevention of a significant number of additional leg injuries.

It is clear that the flexible long bones of the Flex-PLI give it greater biofidelity than the EEVC WG17 impactor in this respect. However, providing this improvement in long bone kinematic behaviour has required some compromises in other design areas. In particular, the complex design of the latest version of Flex-PLI the GTα has meant that the mass and centre of gravity have fallen well outside of the WG17 and JARI specifications for a legform. It is expected that the moment of inertia will also be incorrect, although no information on this parameter has been made available. A number of benefits of using a flexible legform impactor have been identified in Section 3.12 and in some cases these are likely to result in more appropriate protection which should yield additional reductions in leg injuries over the current Directive. However, compromises in the design such as being unable to meet the centre of gravity requirement might negate the potential benefits of the flexible legform impactor. Therefore at this stage of the impactor's development it is not clear if these benefits will be realised or significant.

When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures and this often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

It will be important for a new flexible legform to have appropriate moment of inertia and centre of gravity because these will have a significant effect on the impactor's interactions with the vehicle structure including contact forces and its kinematics during the impact. Therefore, it is recommended that a review be carried out by appropriate biomechanics experts to determine physical targets for a flexible legform impactor. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive biomechanical targets or specifications for flexible legform impactors to be developed and assessed against. The review could include considering the suitability of the anthropometric data used, including any correction factors needed to take account of simplifications in the impactor such as straight leg bones and not representing the foot, and also any corrections needed to take account of the different mass distribution between flesh and bone and any difference in the coupling of the mass of the flesh needed. Although the authors do not anticipate that such a review would result in any significant revisions of the targets selected by EEVC WG17 it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design.

The centre of gravity and moment of inertia of the current Flex-GTα version of the Flex-PLI are not considered to be acceptable. To obtain acceptable values with the Flex-PLI would require a significant redistribution of mass and will therefore require changes to the working parts of the flexible bone and knee joint. Therefore if JARI choose to correct these properties, then there may be a significant delay in producing a finalised version.

The Flex-PLI offers little, if any, improvement in the distribution between bone and flesh mass over that of the WG17 legform.

Biomechanical corridors have been proposed for the flexible long bones. It is recommended that both the PMHS data used and the method used to derive the corridor are reviewed by appropriate biomechanical experts before the specification for a flexible impactor is finalised. Although the authors do not anticipate that such a review would result in any significant revisions to the corridor it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12, in order to provide definitive biomechanical targets or specifications for flexible legform impactors to be developed and assessed against.

For lateral knee joint stiffness it is suggested that the most important weakness of the data based on tests of PMHS is the lack of muscle tension.

- Taking into account the knee geometry and ligament extension properties it seems reasonable to conclude that the lateral knee stiffness due to muscle tension is combined in a living human with the stiffness due to knee ligaments.
- Only one paper was found which attempted to estimate the effect of muscle tension on the knee joint. The authors concluded that 'the activation of lower extremity muscles in simulations predicts a reduction in peak knee ligament forces by a factor of two or more'. The authors also provide a list of limitations and suggested further improvements, so this result may be more of a good start than a definitive answer.

The latest version of the Flexible legform has a higher knee stiffness than indicated by PMHS tests; it is assumed that this is a pragmatic estimated correction for the effects of muscle tension.

- Before further work is undertaken to refine the Flex-PLI legform impactor it is strongly recommended that a study be carried out to determine the effects of muscle tension on lateral knee joint stiffness.
- Potentially, finite element computer models of the human body and car are very useful tools for evaluating lateral knee joint stiffness (as may be done through accident reconstruction). However for complex systems, simplifications are often used to model them which require estimates and assumptions to be built into the model. The results from models of complex systems can be unduly influenced by the assumptions used in the modelling. Detailed finite element models such as THUMS will be ideal tools for studies such as would be required to investigate knee joint stiffness, as they require fewer assumptions than less detailed models. Although the THUMS model is already sufficiently well developed to be used for many applications, it may not yet be ready for investigating the effects of muscle tension on lateral knee joint stiffness. This is because modelling of the muscles is still under development and work on activating the muscles is still at an early stage (Soni *et al*., 2006) in the THUMS model.
- Therefore it is recommended that as a first step non-injurious tests of the knees of human volunteers be carried out to establish the maximum load that a subject can withstand without discomfort (injury) and the relationship between applied bending moment and lateral knee bending angle. These data could be used to validate computer simulation models. Alternatively, with suitable extrapolation, it could be added to the stiffness found in PMHS knee joint tests to produce a combined muscle and knee ligament stiffness.

To date, only some tentative protection criteria (acceptance levels) have been proposed for the tibia and knee ligaments of the Flex-PLI. It will be necessary to produce finalised injury risk curves for the final version of the impactor.

- Much of the available data from PMHS tests for lateral knee impacts are unsuitable for deriving injury risk curves for knee ligament injury for this impactor directly.
- For the long bones much of the available PMHS data are suitable for deriving appropriate injury risk curves for long bone fracture.
- Ideally, both the methods used to produce the injury risk curves and the suitability of the data selected should be reviewed and confirmed by a an acknowledged group of experts, such as EEVC WG12, in order to provide a definitive injury risk curves which can then be used to select the vehicle protection criteria.
- Protection criteria based on a 50 percent risk of injury have been proposed. However, as knee injuries are likely to result in long-term disability, it is recommended that protection criteria for a Flex-PLI impactor be set at a 20 percent injury risk.

For areas on a vehicle where providing full protection may be difficult, a concept of relaxation zones has been introduced in the pedestrian Directive 2003/102/EC for which the impactor must have some over-range capability. It will not be clear until the protection criteria are finalised whether the over-range capacity of the knee Flex-PLI will be sufficient. However, it is thought more likely to suffer from insufficient range than the EEVC legform impactor which has a larger bending capacity of and a separate shear mechanism.

It should be noted that the feasibility of providing protection to meet a flexible legform test will be sensitive to both the injury risk values selected and the knee joint and long bone stiffness. At present it is not possible to come to any conclusions regarding feasibility because the protection criteria and lateral knee bending stiffness have not been finalised. There are sufficient data to be concerned about feasibility at 40 km/h due to the low knee bending stiffness of the current biomechanical corridor. However, the latest version of the impactor has a knee stiffness that is significantly higher than the current biomechanical corridor and it assumed that this modification has been made in anticipation of an improved biomechanical requirement.

Earlier versions of the Flex-PLI have been tested and have been shown to lack robustness and knee joint deformation capacity in impact severities such as those which would be expected in regulatory test environments. Since then significant changes have been made to improve robustness, but currently the robustness of the latest version of the Flex-PLI, at the required test speed, has yet to be proven. The EEVC WG17 legform impactor was available for a number of years before it was adopted for use in a regulation and in that time, through assessment and use, it proved its robustness and the accuracy of the transducer system. However, it is likely that there will be proposals to use the Flex-PLI in regulations more quickly than with the WG17 impactor. Therefore it is recommended that before the final version of the Flex-PLI is considered for regulatory use it should be made available for sufficient time for its robustness to be assessed by the interested parties.

Many aspects of a legform impactor that could affect test results such as component lengths, masses, centres of gravity, etc. will be defined in the specification with manufacturing tolerances. In general physical aspects such as these can be confirmed by the supplier and will not change. Other important dynamic aspects may change depending on, friction, wear, aging, tuning adjustments (for example pre-tensioning of the wire ropes that limit bending), etc. Certification tests are a good method of controlling the performance of an impactor and depending on their nature they can be sensitive to all of the above variables. In addition certification tests are likely to identify faults in the transducer systems. The proposed pendulum method of certifying the complete mechanical parts of the Flex-PLI is thought to be suitable.

- It is recommended that the pendulum method should include a specification for the design of the pendulum pin joint in order to make the energy lost to friction standard and reproducible, and that a separate procedure should be introduced to control the deformation characteristics of the neoprene and rubber sheets used to arrest the impactor.
- A certification test is also needed for the skin and flesh because they are not tested (not fitted) in the pendulum test.
- The design of the long bones and knee assemblies is thought to be such that their performance can be changed or adjusted by for example changes in the degree of pre-tensioning in the outer wire ropes of the long bone or in the springs of the knee ligament. This would be an advantage in adjusting the performance of the impactor to meet the pendulum certification requirements, but it is not clear how the performance of each part will influence the impactors overall performance in the pendulum test. Therefore it is thought that individual certification tests may also be needed for the long bones and knee. These might make use of the biomechanical tests already used to assess their biofidelity and suggestions are made for how this could be done.

A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Ideally this specification should be produced before or in parallel with the development of the final Flex-PLI impactor design.

- Once the final version of the Flex-PLI is available, it can be assessed to determine if it is satisfactory for regulatory use against the agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability.
- Due to the slippage in the development of the impactor it is not clear if the GTR Flex-PLI Subgroup will be able to complete a sufficiently thorough assessment of the final version to show if it is suitable for regulatory use.
- If the GTR group are not able to carry out a full assessment then it is recommended that this assessment be carried out by appropriate experts. Now that the IHRA international group are no longer formally active, the possibility of using EEVC WG17 could be considered.

A number of benefits of using a flexible legform impactor have been identified in Section 3.12 and in some cases these are likely to result in more appropriate protection which should yield additional reductions in leg injuries over the current Directive. However, compromises in the design such as being unable to meet the centre of gravity requirement might negate the potential benefits of the flexible legform impactor. Therefore at this stage of the impactor's development it is not clear if these benefits will be realised or significant.

3.15 Conclusions – Flex-PLI

3.15.1 General

1. Although the EEVC WG17 lower legform impactor has been established as a regulatory sub-system test tool for many years it has some limitations and therefore there is scope for improvement. The Flex-PLI is being developed as that next generation of test tool and is undergoing development and evaluation currently.

2. The legs of pedestrians are the most frequently injured body region in accidents with cars, so testing with an improved bumper test tool could potentially result in the prevention of a significant number of additional leg injuries.

3. A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Once the final version of the Flex-PLI is available, it should be assessed to determine if it is satisfactory for regulatory use against the agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability.

4. Due to the slippage in the development of the Flex-PLI it is not clear if the GTR Flex-PLI Subgroup will be able to complete a sufficiently thorough assessment of the final version to show if it is suitable for regulatory use. If the GTR group are not able to carry out a full assessment then it is recommended that this assessment be carried out by appropriate experts.

3.15.2 Biofidelity

5. When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures and this often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

6. A number of benefits of using a flexible legform impactor have been identified and in some cases these are likely to result in more appropriate protection. It is clear that the flexible long

bones of the Flex-PLI give it greater biofidelity than the EEVC WG17 impactor in this respect.

7. It is recommended that a review be carried out by appropriate biomechanics experts to determine definitive physical targets for a flexible legform impactor to be developed and assessed against. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12 (Biomechanics). Although the authors do not anticipate that such a review would result in any significant revisions of the targets selected by EEVC WG17 it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design.

8. It will be important for a new flexible legform to have appropriate moment of inertia and centre of gravity because these will have a significant effect on the impactor's interactions with the vehicle structure during the impact.

    a. The centre of gravity and moment of inertia of the current Flex-GTα version of the flexible legform are not considered to be acceptable. To obtain acceptable values would require significant redistribution of mass. If JARI choose to correct these properties, then there may be a significant delay in producing a finalised version.

    b. Unless compromises in the current Flex-PLI design, such as not meeting the centre of gravity requirement, are resolved they might negate the potential benefits of the flexible legform impactor.

3.15.3 Lateral knee joint stiffness

9. For lateral knee bending stiffness the biomechanical corridor proposed for the Flex-PLI is far lower than the stiffness chosen by EEVC WG17 because WG17 included an allowance for muscle tension.

    a. Taking into account the knee geometry and ligament extension properties it seems reasonable to conclude that the lateral knee stiffness in a living human is a combination of stiffness due to muscle tension and knee ligament extension.

    b. The available data for muscle effect from mathematical simulation suggest that the effect could be significant.

    c. The latest version of the Flexible legform has higher knee stiffness than indicated by PMHS tests; it is assumed that this is a pragmatic estimated correction for the effects of muscle tension.

10. Before further work is undertaken to refine the Flex-PLI it is strongly recommended that a study be carried out to determine the effects of muscle tension on lateral knee joint stiffness.

3.15.4 Protection criteria

11. To date, only some tentative protection criteria (acceptance levels) have been proposed for the tibia and knee ligaments of the Flex-PLI. It will be necessary to produce injury risk curves for the final version of the impactor.

12. Ideally, both the methods used to produce the injury risk curves and the suitability of the data selected should be reviewed and confirmed by an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive injury risk curves which can then be used to select the vehicle protection criteria.
13. Protection criteria based on a 50 percent risk of injury have been proposed. However, as knee injuries are likely to result in long-term disability, it is recommended that the protection criteria for the knee be set at a 20 percent injury risk.

3.15.5 Feasibility

14. For areas on a vehicle where providing full protection may be difficult, a concept of relaxation zones has been introduced in the pedestrian Directive 2003/102/EC for which the impactor must have some over-range capability. It will not be clear until the protection criteria are finalised whether the over-range capacity of the Flex-PLI knee will be sufficient.

15. The feasibility of providing protection to meet a flexible legform test will be sensitive to both the injury risk values selected and the knee joint and long bone stiffness. At present it is not possible to come to any conclusions regarding feasibility because the protection criteria and lateral knee bending stiffness have not been finalised but there are sufficient data to be concerned about feasibility at 40 km/h due to the low knee bending stiffness of the current biomechanical corridor.

3.15.6 Robustness

16. Earlier versions of the Flex-PLI have been tested and have been shown to lack robustness and knee joint deformation capacity in impact severities such as those which would be expected in regulatory test environments. Since then significant changes have been made to improve robustness, but currently the robustness of the latest version of the Flex-PLI at the required test speed has yet to be proven.
17. It is recommended that before the final version of the Flex-PLI is considered for regulatory use it should be made available for sufficient time for its robustness to be assessed by the interested parties.

3.15.7 Certification

18. Certification tests are considered a good method of controlling the aspects of the impactor that could affect test results. This includes both physical aspects such as component lengths, masses, centres of gravity, etc. that are set in the specification as well as dynamic aspects that may change depending on, friction, wear, aging, tuning adjustments, etc.

19. The proposed pendulum method of certifying the complete mechanical parts of the Flex-PLI is thought to be suitable and recommendations have been made to improve its reproducibility.

    a. A certification test is also needed for the skin and flesh because they are not tested (not fitted) in the pendulum test.

    b. It is thought that individual certification tests may also be needed for the long bones and knee. These might make use of the biomechanical tests already used to assess their biofidelity and suggestions are made for how this could be done.

4 High Bumper

4.1 Introduction

Most, if not all, of the research groups who have worked in the field of pedestrian protection test methods, including EEVC (WG 10 and 17), ISO (WG2) and IHRA (PSWG), have chosen to use sub-systems type tests. Sub-system test methods consist of a set of individual tests, each representing one of the contacts that occur within a pedestrian to vehicle accident. Collectively, the family of sub-system tests represent all of the significant contacts within an accident that are likely to result in serious or fatal injuries to the pedestrian.

Test methods making use of physical pedestrian dummies might initially appear to be the most obvious test tool for assessing a car's pedestrian protection. Provided that the pedestrian dummy or dummies used have appropriate properties (such as joints, etc.) and instrumentation, then every contact likely to cause serious or fatal injuries can be assessed from bumper contact through to head impact. However, in reality, pedestrian dummy based test methods are not well suited for test methods intended for regulatory use because they would require an unrealistically large number of tests for the reasons outlined below.

Stature is the most important variable for head impact location in real life. Therefore, if a dummy based test method is intended to assess the whole area of a car that could be involved in a head impact, then a family of pedestrian dummies of different statures would be required. For the head impact area, as well as having to test each vehicle with this family of dummies, a number of tests would be required with each dummy at increments across the width of the car. In addition a pedestrian's stance and direction of motion will influence the nature and severity of each stage of the accident. For example, in one case the shoulder might make first contact reducing the severity of the head impact, but in a second case the kinematics might be such that shoulder contact is minimal giving a more severe head impact. However, some form of worst case setting of the different dummy stature head contact zones, used to contain difficult structures, might overcome the need to reproduce this range in full. Nevertheless, even if it was decided that only one stance was necessary, a dummy based test method requires that a suitable family of dummies be developed and it would need a very large and expensive test matrix to be carried out for each car model to assess the protection provided.

As discussed above, test methods using impacts between the physical car and a pedestrian dummy have a number of disadvantages for use in a regulatory type test. Sub-system tests have the following advantages over testing with dummies:

- They can easily be used to test the whole area likely to strike pedestrians.
- They can be aimed accurately at selected danger points.
- They give good repeatability.
- The tests cost less to perform.
- The test requirements are simpler to design and to model mathematically.
- They can be more easily used in component development.
- The test severity can be adjusted (e.g. by energy cap) to take account of practical design limitations.

On the other hand, although sub-system tests solve many of the problems of a regulatory test based on physical dummies, they also introduce their own problems:

- They are a simplification of the real situation.
- Appropriate test conditions and test areas must be provided for each sub-system test.
- The test conditions, test areas and any associated mark-up rules, look-up graphs or tables may become inappropriate with time, if vehicle styling goes outside the range considered or anticipated by their authors.

Since EEVC WG10 developed the lower legform to bumper test method there has been an increase in the popularity of Sport Utility Vehicles (SUV's). SUV's tend to have higher bumpers than conventional car designs, as such, the styling of the vehicle fleet has to some extent moved outside the range originally considered by EEVC WG10 and now includes many more vehicles with high bumpers. For conventional car bumpers WG10 had conducted studies to show that it was not necessary to include an upper body mass on the legform impactor. Although it would make the test tool more realistic to include an upper body mass it would make the test far more difficult to perform due to the difficulty of firing a heavy and complicated legform into the vehicle. However, when testing a high bumper with a legform without an upper body mass, if the bumper is positioned so that the main contact is above the legform impactor's overall centre of gravity the legform will tend to rotate or slide under the vehicle. This type of kinematics is unrealistic and might result in the approval of designs without effective protection. EEVC WG17, when reviewing and updating the test methods developed by WG10, noted the increasing popularity of SUV's with high bumpers and in response added a new upper legform to high bumper test method which made use of the impactor developed for testing the bonnet leading edge. The limitations of the new high bumper test developed by EEVC WG17 were that:

- They had insufficient data to determine a well justified switch between normal and high bumper test methods and tools.
- In a pedestrian accident, a high bumper is likely to cause injuries to the knee joint, the femur and/or the pelvis. However, the upper legform impactor only directly assesses the risk of femur and pelvic fracture and not directly the risk of knee joint injuries (serious joint injuries have a high risk of resulting in disablement).

Ballesteros *et al.* (2004) reviewed pedestrian injuries from the state of Maryland for the period from 1995 to 1999. They linked cases from the Maryland Automated Accident Reporting System (MAARS) database containing police reports with either the Maryland Trauma Registry or records from the Maryland Office of the Chief Medical Examiner to provide detailed injury information. Of the 2942 pedestrians in the linked database, populated by Ballesteros *et al.*, 91.2 percent had enough vehicle information in the MAARS database to determine the vehicle type. Overall, 66 percent of the pedestrians were hit by a conventional car, 9.3 percent by pick-ups, 7 percent by vans and 4.5 percent by SUVs. Ballesteros *et al.* found that pedestrian mortality varied by the type of the vehicle involved in the crash. This was statistically significant for SUVs ($P = 0.001$) and pick-ups ($P = 0.016$). When comparing non-superficial pedestrian injuries with body region by vehicle type (see Table 4.1), Ballesteros *et al.* found that there were significantly more injuries above the knee in accidents involving SUVs or pick-ups than with conventional cars.

Ballesteros *et al.* also identified that SUVs and pick-ups have a higher mass than conventional cars and in the cases they reviewed were involved in accidents within areas with higher speed limits. Therefore, to make further comparisons between the vehicle types equivalent in terms of the impact conditions, Ballesteros *et al.* controlled for mass and velocity. Once these variables had been controlled for, they found that the mortality risk and risk of sustaining an above the knee lower extremity injury was not significantly different for accidents involving SUVs and pick-ups than with conventional cars. Whilst it is important to adjust for vehicle speed in accident analyses such as this, the mass of the vehicle is not likely to be very important for pedestrian accidents as the vehicle will be slowed down by only a negligible amount during the impact. However, it may be that the heavier SUVs and pick-ups may also have stiffer bumpers and more aggressive frontal structures than conventional cars. By controlling for mass, these effects may also have been removed from the variables considered within the statistical testing. Therefore, the null result of no significant increase in above the knee injury risk in impacts with SUVs and pick-ups, after controlling for mass and speed, is not relevant for further consideration here.

The initial observation by Ballesteros *et al.* was that a greater proportion of accidents result in an injury sustained to the lower extremities, above the knee, when the accident involves a SUV or pick-up (23 percent) than when it involves a conventional car (17 percent). This indicates an important issue with SUVs and pick-ups. If the trend continues, towards an increasing proportion of the European fleet being larger SUV type vehicles, then injuries caused in accidents with high bumper vehicles could become a serious issue in Europe.

Table 4.1: Non-superficial pedestrian injuries to body regions by vehicle type (Ballesteros *et al.,* 2004)

	Lower extremity injuries		
	Above knee	**At knee**	**Below knee**
Conventional car	331	73	667
	(17.0 %)	(3.8 %)	(34.4 %)
SUV or pick-up	94	15	81
	(23.0 %)	(3.7 %)	(19.9 %)
P-value	0.004	0.936	0.001

Total *N* = 2942

4.2 Expert opinions and review of literature

For the high bumper test the expert opinions and literature obtained was reviewed in order to attempt to determine whether:

- there is evidence to revise or confirm the current high bumper definition (used to switch from the lower legform to the upper legform bumper test).
- the use of a flexible legform impactor for testing high bumpers would need modifications to the test methods or the impactor itself.
- there is any information that could be used to improve the current high bumper test tool or test method

4.2.1 High bumper definition

Within the EEVC working group (EEVC WG10) which originally developed the pedestrian test methods, the French Government research laboratory INRETS were responsible for developing the bumper test. In order to develop a test suitable for regulatory use it was necessary to produce a test tool and test method that would be simple, robust, repeatable and would represent the important aspects of a pedestrian leg contacted by a bumper. The test tool proposed by INRETS was essentially a simplified leg, without an upper body, which is fired into the stationary car. In order to determine if this simplification was acceptable, INRETS studied the influence of bumper height and of upper body mass (Cesari *et al*., 1993). However, the principal aim of this study was to determine whether the proposed test method, using a legform impactor with no upper body mass, was suitable for testing typical car type bumpers of that time. It was not to determine precisely the range of bumper heights that it was suitable for testing. The paper concluded that the legform gave comparable knee bending for bumpers at about knee level or 100 mm below the knee, but for the extremes of both low and high bumpers the results were different (200 mm below the knee and 100 mm above the knee). The cause of these differences was attributed to the position of the bumper contact relative to the centre of gravity of the leg segments and the influence of the upper body mass on the moment of inertia of the leg in terms of its resistance to rotation. As the simulated legform results matched those of the dummy for ‘normal’ car bumpers, the simplified test was deemed to be satisfactory.

As already noted, when EEVC WG17 reviewed and updated the test methods, in response to the increasing popularity of SUV’s with higher bumpers, they developed a new high bumper test and a high bumper definition (European Enhanced Vehicle-safety Committee, 2002a). However, they had limited data to help them select the bumper height at which the switch should be made. When proposing the WG17 high bumper definition, WG17 used a combination of the original INRETS simulation data (Cesari *et al.*, 1993), typical vehicle geometry (found by measuring a representative range of off-road vehicles) and also considered how those bumpers would align with the lower leg, knee and thigh of the lower legform impactor. The legform impactor emulates a 50^{th} percentile adult male; the height of the impactor's knee and the height of its overall centre of gravity are 494 mm and 553 mm respectively.

The INRETS study showed that an upper body mass was not necessary for vehicles where the bumper impact occurred at or below the knee joint, but would be necessary for bumpers that impacted 100 mm above the knee (it is not clear from the paper, but the bumper height probably refers to the centreline of a comparatively narrow bumper cross-section). It was suggested by the GTR group (Informal Working Group on Pedestrian Safety, 2006) that WG17 misinterpreted the original INRETS simulations. Lawrence, one of the authors of this paper, was a member of WG17 during these discussions and in his opinion this was not the case. However, it would have been better if more data had been available to WG17 for them to choose the high bumper definition. This is because there will be a bumper height at which the legform contact will be high enough to cause it to rotate under the bumper in a manner that clearly is not realistic. As this will affect the transducer outputs obtained, particularly the knee bending angle, it is important that the acceptable to unacceptable transition height for the lower legform test is found more accurately.

A number of studies were found in the literature search relating to high bumpers. Unfortunately, although they provide data that show that the lower legform impactor behaves realistically with normal car type bumpers and unrealistically with certain high bumpers, they are not suitable for finding the transition bumper height where the lower legform performance passes from acceptable to unacceptable. A particularly interesting study was that of Sakurai *et al.* (1995), where the performance of two legform impactors with and without upper body mass was determined in full scale experiments, using a vehicle representation on a sled to strike the legform. However, only two bumper heights where examined (centreline height of 300 and 400 mm). For these two heights, little difference was found in the with and without upper body mass tests indicating that the two prototype legforms used, without an upper body mass, were suitable for 'normal height' car bumpers but the results give no guidance on the transition height were the impactor becomes unsuitable. The two prototype impactors used in this study were similar in principle to the final WG17 legform used in the EC Directive 2003/102/EC.

The method of drawing the Lower Bumper Reference Line is shown in Figure 4.1. The current high bumper definition in the EC Directive is that high bumper vehicles are those with a Lower Bumper Reference Line at 500 mm or more. This definition means that many 'off-road' vehicles, with bumpers higher than those typically found on cars, are still classified as being within the 'normal' height range and therefore must pass a lower legform test. For vehicles intended to have some off-road capacity this causes a feasibility issue because most bumper designs intended to meet the knee bending criteria have a deep bumper face which extends too close to the road surface to permit normal off-road use (off-road vehicles typically have a larger ramp angle than cars). This issue was discussed in a presentation given to the GTR pedestrian safety group (OICA, 2006) which provides data on the upper and lower bumper reference lines for a range of existing vehicles. It shows that the bottom edge of the bumper of a typical SUV must be set at around 440 mm to achieve the ramp angle necessary for off-road use (depending on the distance the bumper overhangs in front of the wheels and the minimum off-road ramp angle deemed acceptable) and that the typical range found for SUV's was from 340 mm up to 500 mm. Therefore, even if the lower legform test is confirmed as being suitable for testing those off-road vehicles with bumpers slightly below the current high bumper definition, if off-road capability is to be retained, it may be necessary to adjust the high bumper definition on the grounds of feasibility. This view was accepted by the GTR group and their draft test method allows the option of using the upper legform impactors to test vehicles with bumpers with a lower bumper reference line height of between 425 and 500 mm.

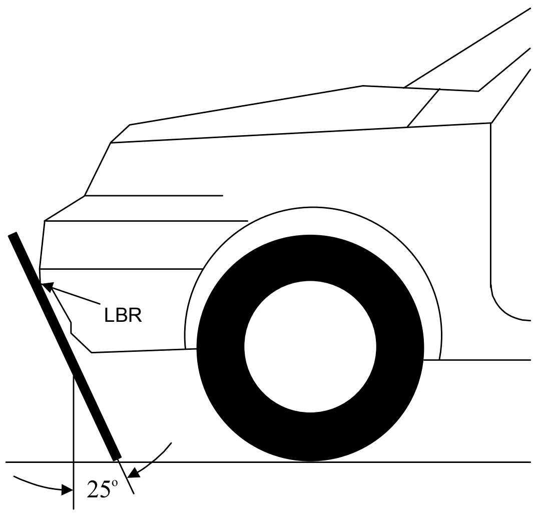


Figure 4.1. Method of drawing Lower Reference Bumper Line (Commission of the European Communities, 2004a)

Permitting manufacturers to switch to the upper legform test at a lower height will mean that vehicle ramp angle will not be compromised and as discussed in Section 4.2.3 meeting the upper legform test will protect the femur and pelvis and in addition it will provide some protection to the knee and lower leg.

Nevertheless, a study specifically designed to identify the transition point where a switch between the two tests is justified would be of benefit. Depending on its scope, such a study may well show that certain high bumpers might offer best protection if they are designed to meet both tests, or that permanently adding a simplified upper body mass would make a legform impactor suitable for testing all bumper heights. Ideally the study, as well as looking at the effect of bumper height, should also look at bumper depth (top to bottom), bumper shape and possibly also the influence of using different knee bending stiffnesses.

Based on the currently available data it would appear that there are two options for a high bumper definition:

- Continue with the EEVC WG17 high bumper definition, as this appears to be the most relevant opinion (noting that the recommendation to raise the foot end of the impactor 25 mm for a shoe allowance will increase the transition height by the same amount, making it better suited for testing bumpers at the higher end of the current 'normal height' bumper definition).
- Taking into account the feasibility issues for off-road vehicles permit some flexibility for the manufacturer to nominate whether to use the lower or upper legform test for bumpers at the higher end of the 'normal height' bumper definition as proposed in the draft GTR.

It should be noted that both JARI and ACEA experts, in their responses to specific questions from this project, agreed that there was a conflict between providing the necessary low load path for passing the lower legform test and the high bumpers needed for vehicles intended for off-road. They both suggested that this was sufficient justification for revising the WG17 high bumper test, as proposed in the draft GTR, to allow the option of using the upper legform impactors to test vehicles with bumpers with a lower bumper reference line height of between 425 and 500 mm.

4.2.2 Flexible legform impactor for high bumpers?

For high bumpers the JARI flexible legform, like the WG17 legform, suffers from the simplification (weakness) that it has no upper body mass. However, it has the advantage that both lower and upper leg bending moments are measured directly on the instrumented flexible bone cores (as well as measuring knee ligament extension). The EEVC WG17 legform is not instrumented to measure the risk of upper leg fracture and the femur section would be difficult to modify to do so (it measures the risk of knee joint injury and the accelerometer below the knee is used to measure the risk of lower leg fracture). Therefore, potentially, if a suitable upper body mass were added to the flexible legform it could be used to assess bumpers of any height or alternatively it could be used without an upper body mass for normal height bumpers and with an upper body mass for testing high bumpers. However, first the issues identified in Section 3 would need to be addressed.

Adding an upper body mass that correctly represents the human upper body is likely to require a comprehensive research and development programme in itself. The simplest solution would be to attach the upper body of a suitable side impact dummy through a simplified central hip joint, but propelling such an impactor into a car would be difficult. The alternative of driving the car into the impactor may be more feasible but it would lose some of the advantages of the current simple sub-systems test.

The following comments with regard to this matter were received from the experts consulted:

- ACEA response:
    - With respect to the Flex-PLI with additional upper body mass, ACEA is not in a position to give answers on a test tool which does not yet exist.
    - ACEA agrees to the procedure proposed in the draft GTR. This procedure is considered to be feasible.
- JARI response:
    - Basically, to determine the best method of testing high bumpers, a careful study is needed. One method is probably to use a Flex-PLI with an 'upper body'; however, several issues will occur.
        - From a viewpoint of testing issues, we cannot use current sub-system test system (cannot propel a Flex-PLI with an 'upper body'); sled test system or car running system will be required, i.e. the sub-system merit will be lost.
        - From a viewpoint of technical feasibility issues, SUV does not have any load path to the lower part of leg; therefore, probably it would be very difficult to pass such a test.
- BASt response:
    - High bumpers should be tested with impactors with adjacent, proportionally effective masses (i.e. torso, pelvis).
        - Further research is needed, but as long as no appropriate test tool is available, for bumpers > 500 mm tests with the upper legform impactor might be useful.

As discussed in Section 3 there are a number of outstanding issues regarding the Flex-PLI impactor; however, if these are resolved, then fitting it with a suitable upper body mass would appear to offer the best solution for testing high bumpers. Not only does the Flex-PLI have the potential to offer a more biofidelic performance, it also has the capacity to measure the bending moments caused by the vehicle contacts in both lower leg and thigh, in addition to the knee instrumentation. Additional instrumentation between the upper body mass and the joint where it is attached to the legform 'hip joint' might also be used to assess the risk of fractures within the pelvis. This combination would make it very suitable for testing a wide range of bumper heights from very low to very high.

If the Flex-PLI proves to be unsatisfactory for use as a regulatory tool then the possibility of further developing the WG17 impactor to be suitable for testing high bumpers could be considered.

4.2.3 Improvements to the current high bumper test

As discussed in Section 4.2.1, one change that might be made to improve feasibility would be to permit vehicle manufacturers to switch to the upper legform to high bumper test at a lower bumper height than currently specified by WG17. It remains to be shown at what bumper height a switch to the upper legform is desirable in terms of suitability of the lower legform impactor, but this change would be a pragmatic solution to the feasibility issue where the low load path needed to meet the lower legform knee bending conflicts with the large ramp angle required for off-road use. It should be noted that both phase one of the EC Directive and the draft GTR have some allowance for switching to the upper legform tests for bumpers below the high bumper definition to address this issue (phase one of the Directive permits, in exceptional cases, manufacturers may apply for a derogation for bumpers below the 500 mm high bumper definition and the draft GTR has 75 mm zone below the 500 mm definition where manufacturers can opt to use either the legform or the upper legform to test the bumper).

A further feasibility issue that has been raised by vehicle manufacturers is that the bumper crush depth needed to meet the EEVC WG17 high bumper test is too large to be easily accommodated. For this reason both phase one of the EC Directive and the draft GTR have reduced the protection requirements for high bumpers, increasing the force from the WG17 recommendation of 5 kN to 7.5 kN and the bending moments from 300 Nm to 510 Nm. However, it should be noted that this increases the risk of injury from the 20 percent risk chosen by WG17 up to about 68 percent (Lawrence *et al.,* 2006). Lawrence *et al.* (2006) proposed a method of estimating the necessary crush depth for the legform impactor. This method took into account the fact that energy-absorbing depth provided for pedestrian protection would also contribute towards meeting vehicle damage mitigation regulations, meaning that, overall, less crush depth is required than implied when considering pedestrian protection on its own.

There are three regulations relating to bumper performance: Economic Commission for Europe (ECE) - Regulation 42 (Economic Commission for Europe, 1980), National Highway Traffic Safety Administration (NHTSA) - Code of Federal Regulations 49, Part 581 (NHTSA, 1999), and Canadian Motor Vehicle Safety Regulation (CMVSR) - Standard 215 (Transport Canada, 1978).

Both ECE Regulation 42 and NHTSA Part 581 include a pendulum test of the bumper face and corners (or equivalent) with a velocity of 4 km/h (2.5 mph) for the face and 2.5 km/h (1.5 mph) for the corners, but NHTSA Part 581 also includes 2.5 mph barrier test to the front and rear. In both regulations the pendulum mass must equal that of the car under test and both require that after the tests the lights must work, the bonnet, boot and doors operate in the normal manner and all of the essential features for safe operation of the vehicle must still be serviceable.

When the requirements of the European 4 km/h bumper damageability test (Regulation 42) are combined with the high bumper pedestrian protection requirements, then the overall bumper depths required to meet both pedestrian protection and damageability can be calculated. Using a similar method and again assuming an energy-absorbing efficiency of 65 percent, but assuming a more realistic residual crushed depth of 20 percent, for both pedestrian protection and vehicle protection phases, it can be calculated that:

- For a high bumper test with a force criterion of 7.5 kN
    - the total bumper depth required, including the remaining depth of crushed energy-absorbing materials, is about 120 mm (this would be about 55 mm more than a Regulation 42 bumper without pedestrian protection)

This compares with the 120 mm depth suggested in the OICA presentation to the GTR pedestrian safety group (OICA, 2006).

- For a high bumper test with a force criterion of 5.0 kN
    - the total bumper depth required, including the remaining depth of crushed energy-absorbing materials, is about 190 mm (about 125 mm more than a Regulation 42 bumper without pedestrian protection)

It should be noted that the Canadian bumper damageability requirement is far more demanding than the European (Regulation 42) and US (Part 581) tests and if the requirements of this test were substituted in the calculations, then a total bumper depth of about 160 mm would be required to meet a 7.5 kN high bumper test and about 230 mm would be required to meet the 5 kN criterion. The authors understand that the Canadian authorities are considering revising their bumper test because of concerns that it encourages pedestrian unfriendly bumper designs.

To account for feasibility issues it has been proposed that the protection criteria for the high bumper test within phase one of the Directive be retained for use in phase two. It has been shown by Ballesteros *et al.* (2004) that non-superficial injuries to the lower extremity above the knee (femur fractures) occur in a higher proportion of pedestrian accidents with vehicles having high bumpers (SUVs and pick-ups) than in those with conventional cars. In addition Matsui (2004) has found a link between the force found in the high bumper to upper legform test and the injury risk to the lower leg and knee (discussed below). Based on the observation of Ballesteros *et al.* and the injury risk link found by Matsui, it is evident that a high bumper test could be important for controlling lower extremity injuries in the real world. The importance of such a test would increase for each region as the proportion of vehicles with high bumpers in the vehicle fleet increases, as has been the recent trend in Europe. It is recommended that the importance of the high bumper test (based on the vehicle fleet) and the potential for reducing the severity and incidence of above the knee (and to a certain extent knee and lower leg) lower extremity injuries are considered alongside the feasibility issues. Retention of the EEVC WG17 high bumper protection criteria would reduce the risk of injury.

Matsui (2004) conducted impact tests with the Polar dummy and tested the same vehicles with the EEVC WG17 lower and upper legform impactors. He noted the problems with the legform rotating unrealistically under the high bumpers when the impact was above the overall centre of gravity of the impactor. He analysed the combined data to determine if tibia acceleration outputs from the lower legform impactor could be related to the risk of femur fractures and concluded it was feasible to use it as an alternative injury criterion for SUV bumpers. Likewise, he analysed the data to determine if the upper legform force measurement could be related to the risk of knee injury due to bending or shear loading. He concluded that it was feasible to use the upper legform impactor force measurement as a criterion for determining the risk of knee shear displacement but not for knee bending angle, however, for both knee bending and shear there was a reasonable correlation between the measured force and the two knee injury mechanisms. In the authors' opinion, these data should be used with caution because the knee of the Polar dummy is designed to meet different biomechanical corridors and in Matsui's analysis he compares injury risk ratios for the two measures that are based on different levels of injury risks. Ideally, comparisons of this type should only be made when the test tools and criteria area a closer match. However, the relationship found between injury risks for injuries not directly measured by each impactor suggests that for high bumpers meeting the protection criteria of either test will improve protection (but not necessarily meet a specific 'safe' speed target).

A presentation given to the GTR pedestrian safety group (OICA, 2006) provides before and after test results for a SUV bumper modified to meet the upper legform to bumper test protection criteria of 7.5 kN and 510 Nm (with a manufacturing allowance of an extra 20 percent). Before and after lower legform test results are also provided in the paper for the standard and modified bumper and these show a significant improvement in tibia acceleration and knee joint shear displacement and a small improvement in knee bending angle from 33.5 degrees to 30.9 degrees. It should be noted that the lower legform impactor hits mechanical stops at 30 degrees and results in excess of 30 degrees would be far higher had the stops not been contacted. It should also be noted that Lawrence *et al.* (2006) proposed that the bending criterion should be not to exceed 19 degrees. Although these test results support the conclusion that can be drawn from Matsui's work (2004), that whichever test is used the countermeasures will improve protection to some extent, it suggests that it may only save all serious bumper injuries at lower speeds than intended. Therefore it can be concluded that reducing the high bumper transition point, as permitted in the draft GTR high bumper test, is reasonable in response to feasibility issues for off-road vehicles, although the actual level of the transition height requires further consideration with respect to biofidelity.

4.3 High bumper conclusions

Based on the currently available data it would appear that there are two options for a high bumper definition:

a. Continue with the EEVC WG17 high bumper definition.

b. Permit some flexibility for the manufacturer to nominate whether to use the lower or upper legform test for bumpers at the higher end of the 'normal height' bumper definition as proposed in the draft GTR. This is to take account of the off-road use ground clearance feasibility issue.

   i) However, although reducing the high bumper transition point, as permitted in the draft GTR high bumper test, is reasonable in response to feasibility issues for off-road vehicles, it would be safer for pedestrians to place the transition height where biofidelity considerations require it.

   ii) The relationship found by Matsui (2004) between injury risks for injuries not directly measured by each impactor (lower or upper legform) suggests that for high bumpers meeting the protection criteria of either test will improve protection (but not necessarily meet a specific 'safe' speed target).

Use of a Flexible legform impactor for testing high bumpers:

a. An upper body mass must be added that correctly represents the human upper body, but it should be noted that adding a suitable upper body mass is likely to require a comprehensive research and development programme in itself.

b. The JARI Flex-PLI has the advantage over the EEVC WG17 legform that both lower and upper leg bending moments are measured directly on the instrumented flexible bone cores (as well as measuring knee ligament extension). However, there are a number of outstanding issues regarding the Flex-PLI impactor. If these issues are resolved, then fitting it with a suitable upper body mass would appear to offer the best solution for testing high bumpers.

c. Instrumentation between the upper body mass and the joint where it is attached to the legform 'hip joint' might also be used to assess the risk of fractures within the pelvis. This combination would make it very suitable for testing a wide range of bumper heights from very low to very high.

d. If the Flex-PLI proves to be unsatisfactory for use as a regulatory tool then the possibility of further developing the WG17 impactor to be suitable for testing high bumpers could be considered.

Improvements to the current high bumper test and feasibility issues:

a. The EEVC WG17 high bumper definition is such that the lower legform test applies to many off-road vehicles.

b. Vehicles intended for off-road use need to allow for a greater ramp angle in order to negotiate rough terrain. This ramp angle constraint means that off-road vehicles have high bumpers, which give rise to a feasibility issue because this is in conflict with the protective measures needed to pass the lower legform to bumper test.

c. Changing test methods to permit vehicle manufacturers to switch to the upper legform to high bumper test at a lower bumper height than currently specified by WG17 would resolve the feasibility problem. It remains to be shown at what bumper height a switch to the upper legform is desirable in terms of suitability of the lower legform impactor, but this change would be a pragmatic solution to the feasibility issue.

d. It should be noted that both the EC Directive and the draft GTR have some allowance for switching to the upper legform tests for bumpers below the high bumper definition to address this issue.

e. A further feasibility issue raised by vehicle manufacturers is that the bumper crush depth needed to meet the EEVC WG17 high bumper test is too large to be easily accommodated.

f. Taking into account the link that Matsui found between the force found in the high bumper to upper legform test and the injury risk to the lower leg and knee, retaining the EEVC WG17 high bumper protection criteria would reduce the risk of knee joint injury.

5 Bonnet Leading Edge

5.1 Introduction

The contact between a pedestrian and the bonnet leading edge of a car is one of the principal contact phases and potentially one of the injury causing contacts. The bumper will normally make the first contact and will push the pedestrian's legs forward. This contact low on the pedestrian will both rotate the legs about the hip and start to rotate the whole body. As the pedestrian's leg rotates, the upper leg (thigh) of an adult pedestrian will typically contact the bonnet leading edge of the typical car. Shorter pedestrians, including children, will be contacted higher up the body; similarly, higher vehicles such as SUVs will typically contact adult pedestrians on the pelvis or higher. The contact will continue as the pedestrian rolls around the bonnet leading edge.

When sub-system pedestrian test procedures were proposed in the mid 1980's (Harris 1986), the bonnet leading edge test was one of the three areas addressed on the car. The sub-system tests were developed by some of the members of EEVC WG10, under a contract for the EC. The bonnet leading edge test was developed by the then TRRL, now TRL (Lawrence *et al.*, 1991; Lawrence *et al.*, 1993). TRL also developed the upper legform impactor that is used in this test, see Figure 5.1. The front member is a simplified representation of the femur. The front member bending moment and the loads between the front and rear members are recorded in an impact test; these can be related to the risk of femur fracture and pelvis injury by injury risk curves.

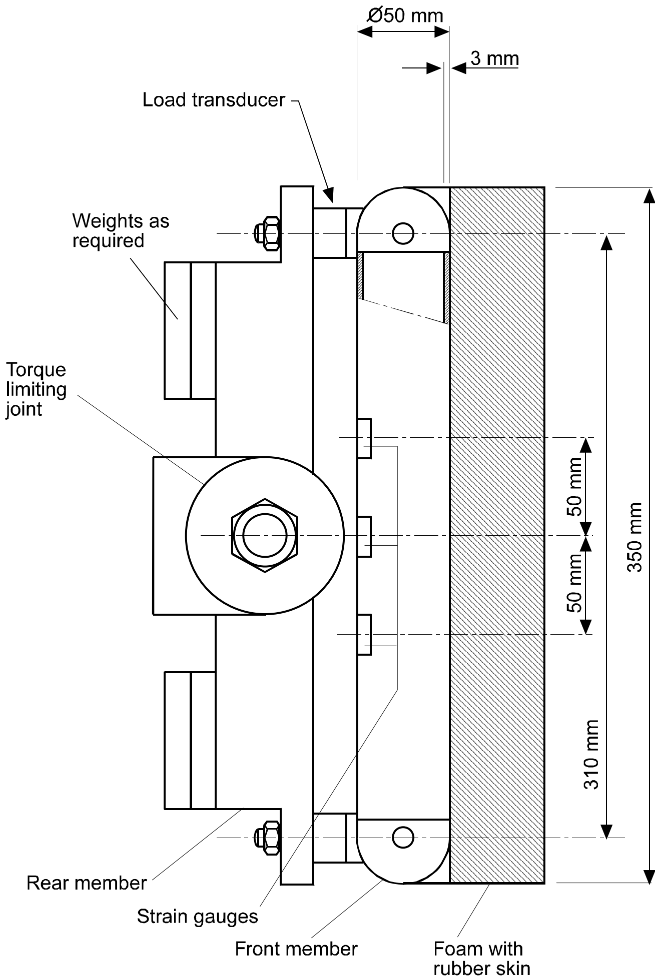


Figure 5.1. Upper legform impactor

The real world impact conditions for this contact phase are highly dependent on the front end geometry of the car. Key parameters of vehicle shape were identified by TRL and a set of look-up graphs were provided to determine the impactor energy, impact velocity and impact angle. Acceptance criteria were also proposed by TRL.

A first draft of an EC Directive was produced in 1992. The pedestrian test methods were gradually refined by WG10 and then by WG17, with much of the focus being on developing the lower legform and headform impactors. However, a number of accident studies in this period reported that the bonnet leading edges of the latest car designs were causing far fewer injuries than previously. Moreover, it was reported that these designs were still failing the bonnet leading edge test. These problems were partially addressed with changes to the test parameters and the acceptance criteria.

The EC Directive to protect vulnerable road users was published in 2003. This specified two stages of pedestrian protection, popularly referred to as part one and part two. Under part one the bonnet leading edge test is a ‘monitoring only’ test, i.e. the test has to be carried out but manufacturers are not required to meet the target criteria. Part two required the acceptance criteria to be met but this was subject to a feasibility review. This review (Lawrence *et al*., 2004; updated in Lawrence *et al*., 2006) made proposals for further changes to the test parameters and acceptance criteria, but, in addition, recognised that the test would continue as a ‘monitoring only’ test, so as to allow updated information to be collected for further consideration of requirements.

There were discussions within UNECE between 2002 and 2006 on a global technical regulation (GTR). The upper legform to bonnet leading edge test was not accepted by the group developing this regulation. The group was however favourable to including an improved bonnet leading edge test at a later date.

At the current time a formal proposal is expected to be made by the EC to the European Parliament for an EC Regulation with revised phase two requirements. It is understood that this is likely to include the upper legform to bonnet leading edge test as a ‘monitoring only’ test.

In this section the development of the current test is reviewed. Then accident data and other comments are reviewed, using published literature. However, within the resources of this study it has not been possible to review all that has been published on this test. Options for improvements to or replacing the current test are then considered.

5.2 Development of the current bonnet leading edge test

Before discussing options for a future bonnet leading edge test it is useful to review the development of the existing test. As well as covering the current EEVC WG17 test and the EC Directive phase two test here, the proposals made by TRL in the feasibility study (Lawrence *et al*., 2006) will also be covered.

EEVC WG10 was given the mandate of developing sub-system tests rather than dummy based tests. Hence, TRL was required to develop a sub-system bonnet leading edge test. Sub-system tests have a number of advantages such as better repeatability, ease of aiming at ‘hard points’ on the vehicle and a lower test cost. However, without the whole system the test parameters are not obtained automatically. There is therefore a need to reproduce realistic impact conditions in some other way. These also need to take account of the influence of the rest of the body during the impact.

It is worth noting that the test development started in 1989, so vehicles then on the road would have ranged from mid 1970’s to late 1980’s designs. The programme included accident reconstructions, but given the limited number of suitable cases available many of these were of car designs that were old at the time. The cars that the impactor was designed to test would generally have had a prominent bonnet leading edge, with a marked and abrupt change in front end angle, typically at the front edge of the bonnet or a crease line in the bonnet. However the test programme did include tests to a Ford Sierra, which had a modern rounded shape. At this time SUVs were much less common than they are currently; little consideration was therefore given to the problems of testing this vehicle type.

The two main injury modes that the impactor was designed to measure injury risk for are femur bending fractures and pelvis fractures, such as those of the pubic rami, that are typically caused by loading through the femur. The front member consists of a steel tube, representing the femur, that is strain gauged to measure bending moment (see Figure 5.1). Two load transducers measure the load between the front member and the rear member.

Had the impactor been allowed to rotate it would have been very difficult to control it to rotate in a realistic manner. Without an upper body mass there would be nothing to force it to rotate in the correct direction, so it would have frequently rotated in the opposite direction. Also, the impactor has a very small moment of inertia compared with a complete live pedestrian or pedestrian dummy, so any rotation that occurred would probably have been unrealistically rapid. To have forced the impactor to rotate in a controlled manner would have required a complex test apparatus, which would have lost many of the benefits of a sub-system test. Hence the impactor was designed to be guided to move in a fixed direction and not to rotate during the impact. While it was known from dummy tests that there was considerable rotation during the bonnet leading edge contact it was also known that the peak forces occurred during the early part of the impact, with the later impact being a ‘leaning on’ phase. Also, good correlation of vehicle damage was obtained between dummy tests and impactor tests.

The severity of the bonnet leading edge impact is far more dependant on the shape of the car than either the bumper or bonnet top contacts. For streamlined car shapes the impact will be of low severity and for tall upright shaped cars the impact will be of higher severity. It was therefore necessary to vary the impact conditions by vehicle shape. The test parameters were derived from a number of sources. The most important parameter is the impact energy. Computer simulation results by TNO and Calspan were used by TRL to produce the energy look-up graph. As part of this process, TRL decided that it was possible to use two car shape parameters, bonnet leading edge height and bumper lead, and ignore bumper height as that had less influence. Impact velocity and impact angle were derived from TRL dummy tests and again look-up graphs were produced. The mass of the impactor varies; this is obtained by a simple formula from the energy and velocity. The velocity graph was adjusted so that the impactor mass would not be impractically low.

The acceptance levels proposed at this time, 4 kN sum of loads and 220 Nm bending moment, were based on accident reconstruction tests carried out as part of the project. As these are based on impactor readings these relate to the impactor and not directly to values for live pedestrians, so they have any necessary transfer functions built in.

A further benefit of the protection required by the bonnet leading edge test is that although it is aimed at protecting 50th percentile adult males it could also be effective in providing some protection for smaller adults and children.

The development work was reported in detail to the EC (Lawrence *et al.*, 1991) and in less detail to the following ESV conference (Lawrence *et al.*, 1993). Some of the decisions taken, particularly concerning the lack of rotation, were further explained later in a WG17 committee paper (Lawrence, 1998).

After the end of the development project some details of the impactor were changed to produce a production version. The strain gauges used were changed to avoid errors due to local strain effects and improvements were made to the flesh and skin mounting and to the mountings of the weights used to adjust the impactor mass. A new certification test was introduced in 1994, involving an impact with a suspended steel tube. After BASt reported a load path through the foam flesh, the dimensions of the foam were changed in 1996 to avoid the problem. Since then the design of the hardware has remained virtually unchanged.

The main changes to the bonnet leading edge test since it was first proposed have been to the test parameters and the acceptance criteria.

TRL developed an FE computer model of a pedestrian to simulated car impact and used it to simulate impacts with a matrix of car shapes. From these a revised energy graph was produced. The work was reported to WG17 (Lawrence and Hardy, 1998) and with minor adjustments the energy graph was used by WG17 in their 1998 revision of the pedestrian test procedures (European Enhanced Vehicle-safety Committee, 1998). This led to a reduction in test energy for most car models.

TRL continued to improve the computer model to make it more biofidelic and less like a model of a pedestrian dummy. Recommendations were made to revise the WG17 test energy graph based on this more biofidelic pedestrian model and an improved vehicle model (Neale *et al.*, 2001).

However, it was also noted that these energy curves required higher energies for many car shapes than the previous ones. WG17 discussed the appropriateness of the test energies when compared with the comparatively low injury rates for bonnet leading edge impacts found in accident studies and the high failure rates seen when current cars are tested. It was therefore agreed that whilst the trends of the latest energy curves (Neale *et al.*, 2001) were more appropriate, some adjustment of their absolute values may be needed.

The energy graph proposed was examined to see if the new curves were more consistent in terms of required test energy when typical errors in measured bumper lead and bonnet leading edge height were introduced (Staines, 2004a & 2004b). It should be noted that the straight edge method used to mark vehicles for the EEVC test methods will be sensitive to errors where the surface of the vehicle is relatively flat in the area where the straight edge makes contact. It was concluded that the new curves were far less sensitive to these marking-up errors and were therefore more robust.

These energies were considered further in the feasibility study for phase two (Lawrence *et al*., 2006). The study by Neale *et al.* (2001), also included some tests of the sensitivity of the energy predictions in terms of energy for one vehicle shape with a 700 mm high bonnet leading edge and a 150 mm bumper lead. For this vehicle shape it was found that some improvements to the pedestrian and vehicle models resulted in an increase in energy and one reduced it, resulting in a net increase in bonnet leading edge energy. A rational explanation could be found for each change with, for example, a more natural walking stance lowering the pelvis and upper body height by 20 mm and thereby increasing the effective mass seen by the bonnet. However, for the larger vehicle shapes the changes to give the pedestrian model greater biofidelity produced a reduction in test energy of about 30 percent. It therefore seemed reasonable (to Lawrence *et al.*) to assume that further changes to give the pedestrian model greater biofidelity by for example introducing more joints in the spine and connecting the mass of the muscle, internal body organs, digestive system, etc. more loosely to the skeletal frame would reduce the bonnet leading energy by a further similar amount. It was therefore proposed that the Neale *et al*. test energies be adjusted, as agreed in principle by WG17, by introducing a 30 percent reduction. Some additional minor adjustments were also made. The most significant adjustment was that, instead of making a fixed allowance for the energy absorbed in the flesh of the impactor, the allowance was progressively reduced for the more streamlined car shapes, where the test energy is too low to fully crush the impactor flesh.

With the above 30 percent reduction and other adjustments, most of the car shapes on the energy graph would be tested at a lower energy than with the current EEVC WG17 test procedure. However, because the two sets of energy curves differ significantly, particularly in the slope of energy against bonnet leading edge height, there are some car shapes where the test energy would be higher under the new proposal. These are car shapes with a relatively low bonnet leading edge height of less than 700 mm and a relatively short bumper lead. (On the grid of car shapes used in the computer model there are three shapes: 600 mm BLE height / 50 mm bumper lead, 650 / 50 mm, 650 / 100 mm.) Most of these would not require a test with the EEVC WG17 test procedure (i.e. calculated energy <200 J) but would require a test with the new proposal.

The upper legform energy cap of 700 J was introduced by EEVC WG17 on the grounds of feasibility based on their decision that 150 mm of crush was the maximum crush depth that it was feasible to provide. This was reconsidered by (Lawrence *et al*., 2006) in the light of information received from manufacturers. Based on this and considerations of the practical minimum crush depths needed to absorb energy it was thought that an energy cap of 500 J would be an improvement. Therefore, an energy cap line set at 500 J was included in the proposed new energy look-up-graph.

Returning to the issue of acceptance criteria, Matsui *et al.* (1998) had conducted upper legform tests on 15 production cars. These were evaluated against the EEVC WG10 performance criteria of having a total force of less than 4 kN and a bending moment of less than 220 Nm, and used the WG10 test parameters (European Experimental Vehicle-safety Committee, 1994), which for most cars require higher test energies than the WG17 test parameters. With their review of pedestrian accident data, Matsui *et al.* observed that the number of severe femur and/or pelvis injuries caused by the bonnet leading edge is smaller than that of the other severe injuries caused by the bonnet or bumper. This led to the suggestion that when considering the priority of the pedestrian test procedure, the upper legform impact test should be the lowest among the three subsystem tests. To validate the injury criteria for the legform impact test, Matsui *et al.* used the upper legform impactor and numerical simulations to reconstruct pedestrian accidents selected from the Japan Automobile Research Institute (JARI) database. In order to understand the relationship between measured physical values and injury severity, the best 12 cases were selected from the accident reconstruction tests. Initially, the impact force was plotted against the bending moments and it was concluded that the indication was that the current injury criteria gave a 0 percent possibility of causing an injury of AIS 2+ severity. A Weibull cumulative frequency curve was made from the accident reconstruction tests to establish the injury criteria for femur or pelvis AIS 2+ injuries, for both impact force and bending moment. These curves set the 0 percent frequency limits to be 4 kN and 220 Nm, as these probabilities had been determined earlier in the paper. The revised impact force and bending moment levels corresponding to a 50 percent chance of sustaining an AIS 2+ femur or pelvis injury were then determined to be 7.5 kN and 510 Nm and for a 20 percent level, 6.3 kN and 417 Nm, respectively.

The method used and the assumptions made to produce the upper legform injury risk curves by Matsui *et al.* (1998) were considered by EEVC WG17. They had several concerns about the approach used by Matsui, the two most important concerns were that the Weibull analysis produced an injury distribution rather than an injury risk curve and that the values selected to set the zero injury risk were too high.

Therefore, Rodmell and Lawrence (European Experimental Vehicle-safety Committee, 2002a) conducted a further 23 upper legform accident reconstructions and combined these with the original 12 Matsui (JARI) tests and a further 4 newer reconstructions by Matsui to produce a larger dataset. Normal and logistic injury risk analysis was carried out to produce the injury risk curves used by EEVC WG17 to select the values currently in the second phase of the Directive. As Rodmell and Lawrence were able to match the damage (dents) in the vehicles concerned, these results are not dependent on the accuracy with which the investigators could determine impact velocity. They also include a transfer function for any differences between the impactor and its instrumentation and a living human. Due to these factors and the comparatively large sample size these injury risk curves are regarded as the best currently available data. From these injury risk curves, the current WG17 acceptance criteria, of sum of forces not to exceed 5.0 kN and bending moments not to exceed 300 Nm, were obtained.

Feasibility adjustments to the acceptance criteria or targets were also proposed (Lawrence *et al*., 2006). These were increased from 5 kN to 6.25 kN and from 300 Nm to 375 Nm, to take account of the manufacturers' 20 percent approval / conformity of production allowance. In addition a lower protection zone was proposed, i.e. a manufacturer nominated part of the width with higher acceptance criteria or targets, to make it more feasible for manufacturers to meet the requirements or targets in difficult areas.

These proposals were made in the feasibility study (Lawrence *et al*., 2006) to allay feasibility concerns by the use of changes in test energy (reductions for most car shapes), increased protection criteria and the proposal to change the energy cap from 700 to 500 Joules. However, it has not been proven that the changes proposed are sufficient to remove the conflict between low injury rates observed and current car designs failing the original Directive's phase two bonnet leading edge test.

Matsui and Takabayashi (2004) reported that the effect of relative humidity on the Confor™ foam flesh of the lower legform was a major cause of variation in the lower legform's certification test. As the upper legform impactor uses the same foam, Lawrence *et al*. (2004; 2006) proposed the same relative humidity tolerance for the upper legform that they proposed for the lower legform. This is that the relative humidity be controlled to 35 ±15% for vehicle tests and 35 ±10% for certification tests.

5.3 Accident and injury studies, and comparisons with test results

A paper by Cesari *et al*. (1996) was one of the first to point out that while accident studies showed a low rate of adult femur fractures with modern cars, almost none of the then current cars fulfilled the proposed requirement. They concluded with respect to the bonnet leading edge test that “its application may require car modifications not linked with the improvement of pedestrian protection”.

EEVC WG17 considered the rate of injury caused by the bonnet leading edge as part of its review of the test procedures developed by WG10. In its 1998 final report, updated in 2002 (European Enhanced Vehicle-safety Committee, 2002a), it gives accident data from Germany, France and the UK. The German study, involving accidents between 1985 and 1995, compared new models introduced from 1990 onwards with those introduced before 1990. AIS 2+ upper leg and pelvis injuries caused by the bonnet leading edge fell from 11 to 7 percent, with none in the 1990+ design group occurring at or below 40 km/h. The French study didn’t identify the part of the car causing the injuries. Car models from 1990 on were compared with an earlier study that ended in 1983, thus containing cars models up to 1983. Femur fractures decreased substantially in all three age ranges: for <12 years they fell from 38 to 8 percent, for 12-49 years from 20 to 0 percent, and for >49 years from 19 to 2 percent. For pelvis fractures the picture was less clear, but again injuries to the 12-49 year range fell to zero (from 21 percent). Pelvis fractures for <12 years rose from 8 to 12 percent and those for >49 years rose from 22 to 25 percent, with both rises being non-significant. The UK data were from a database of hospital in-patients, so the average severity was greater. Over the period 1980 to 1994, the proportion of pedestrians injured in the upper leg and pelvis region (AIS 2+ and AIS 3+) fell by about a third. However, at the end of this period there were still about twice as many AIS 3+ injuries to the upper leg and pelvis region than there were to the lower leg and knee region.

WG17 also reported a summary of Euro NCAP results. No bonnet leading edge tests were passed, compared with 7 to 37 percent for the other tests. Only 1 percent of upper legform tests passed or were within 25 percent of passing, compared with 14 to 54 percent for the other tests. These were results using the WG10 test procedures, so the impact energies and acceptance criteria would not be the same as those of the current WG17 test procedures. For most car shapes the WG10 impact energies were higher, often much higher. Also the WG10 acceptance criteria were lower, 220 Nm bending moment and 4kN sum of forces, against WG17’s 300 Nm and 5 kN. It was anticipated that these changes would considerably increase the pass rate in Euro NCAP bonnet leading edge tests.

A paper by DEKRA and VDA at the 18th ESV conference (Berg *et al*., 2003) compares recent German data (GIDAS data from accident years 1999 to 2001) with the older German data in the IHRA database (1985-95). The data used were AIS 2+ injuries from frontal impacts of passenger cars to pedestrians. ‘Passenger car’ here is understood to exclude SUVs. The recent data were quite a small sample, 116 AIS 2+ injuries from 53 accidents. Injuries caused by the bonnet leading edge appear to have reduced from 10 percent to 3 percent of the total AIS 2+ injuries between the two samples. However, data are also provided for a ‘front panel and headlamps’ area, and this as well as the bonnet leading edge is regarded as a tested area only in phase two. It therefore seems that ‘bonnet leading edge’ as used by Berg *et al*. does not mean the area defined as ‘bonnet leading edge’ in the pedestrian test procedures; it is therefore presumably closer in meaning to being the leading edge of the opening bonnet. Not all of the injuries caused by the front panel and headlamps will be due to the defined bonnet leading edge area, but the majority of these are probably ‘bonnet leading edge’ injuries. If these are included, the change appears to be a reduction from 13 percent to 8 percent of total AIS 2+ injuries. Estimates are then made of the potential for injury reduction. With respect to the IHRA data the authors say “The result is a very low potential of 7.1 % for the bonnet leading edge, the front panel and the headlamps. With 11.5 % the bumper system seems to have a reasonable potential.” On the numbers given their comment seems a little harsh. The respective numbers based on the GIDAS data are 3.2 percent and 11.3 percent. Later, with respect to the bonnet leading edge the authors comment “In light of this remarkable change of significance, any specific test on this part of the car is no longer suited to effectively reduce the number of pedestrian injuries in the future and should be deleted from any planned test procedure.”

Daimler Chrysler (Buerkle *et al*., 2003) used GIDAS data up to January 2003. They also selected AIS 2+ injuries in (non-SUV) car frontal impacts, but then further filtered the data to include only accidents with impact speeds in the range 0-40 km/h (the range covered by the pedestrian test procedures). This gave a small sample of 124 AIS 2+ injuries from 74 accidents. Of these, only six injuries (4.8 percent) were caused by the bonnet leading edge (three to the pelvis, one to the lower leg, one to the abdomen and one to the spine) with another three (2.4 percent) caused by the headlamps (all to the lower leg). They estimate the potential of the test procedures by assuming that only the injuries that the tests are intended to prevent would be prevented (i.e. to body regions simulated by the impactor). (This may seem a pessimistic assumption, but conversely to assume that other body regions would benefit equally would be too optimistic.) The potential of the bonnet leading edge test was estimated to be only 2.4 percent (presumably of injuries from car frontal impacts at impact speeds $\leqslant$40 km/h). The potential of the bumper test was estimated to be 23.4 percent on same basis but the child headform was also 2.4 percent and adult headform test only 0.8 percent.

The Japan Automobile Research Institute (JARI) (2004a), in their feasibility study, reported that the Euro NCAP phase 12 bonnet leading edge tests in 2003 on 16 cars (48 tests) gave no test passes. These were carried out to a protocol that uses the WG17 test energies and acceptance criteria. JARI also reported injury data from the IHRA database. The proportion of AIS 2+ injuries that were to the pelvis and femur were 7.5 and 3.5 percent respectively compared with 23 percent for the lower leg and 31 percent for the head. They say that “the EEVC/WG17 upper legform to bonnet leading edge test, which all cars failed, is apparently contradictory to the actual situation in a real-world pedestrian accident”.

The current authors checked the Euro NCAP phase 11 and phase 13 results and found four and two passes respectively, so phase 12 may be unusually poor for the bonnet leading edge test. Nevertheless, there is clearly a much lower pass rate than might be expected from the injury data.

A paper by Okamoto *et al*. (2001) shows the distribution of AIS 2+ injuries caused by the bonnet leading edge by body region, for automobiles and utility vehicles, using data from the NHTSA Pedestrian Crash Data Study and the Hannover Medical University Accident Research Unit (from the USA and Germany respectively - see Figure 5.2). Pelvis injuries dominate the body regions injured by the bonnet leading edge of conventional cars. Femur injuries are comparable in number with abdominal injuries. For bonnet leading edge of utility vehicles, abdominal injuries are the most frequent, followed by the pelvis and then the thorax. PCDS data for utility vehicles show that most of the pelvis injuries are AIS 3.

5.3.1 Possible reasons for the disparity between recent accident data and test results on current cars

The EEVC WG17 bonnet leading edge test, as used by Euro NCAP, will fail most vehicles, yet, as was shown in Section 5.3, the risk of injury from this part of the impact is much lower than it used to be. Where other experts have suggested a reason, it is often simply a lack of biofidelity. One specific reason given has been the lack of rotation to mimic the rolling action of a pedestrian around the bonnet leading edge. However, the current authors are not aware of any research carried out to identify the reason. It is likely that there is more than one contributory factor. It would be useful to identify these contributory factors before starting on the development of a revised or replacement test, firstly to avoid repeating the ‘mistakes’ and secondly to avoid making unnecessarily radical changes from the current test that might compromise the replacement test.

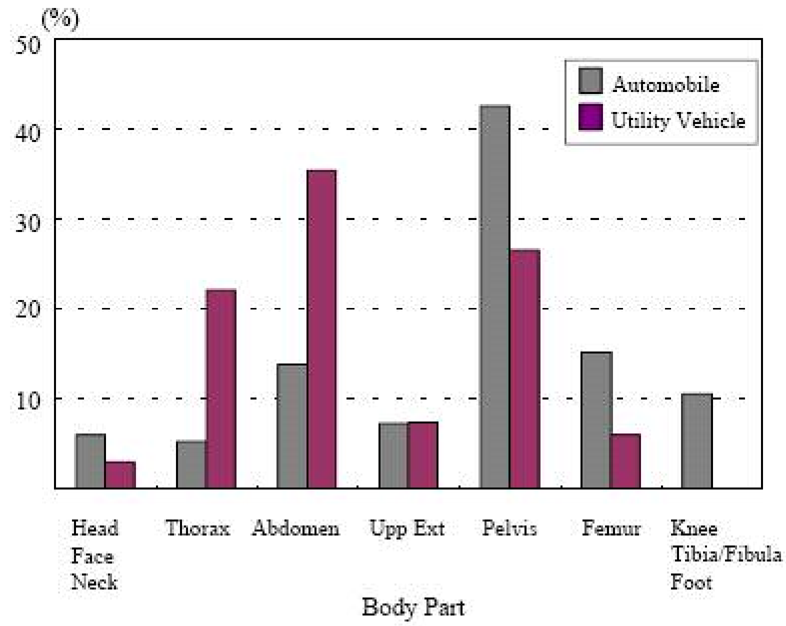


Figure 5.2. AIS 2+ injuries caused by the bonnet leading edge - distribution by body region, for automobiles and utility vehicles (Okamoto *et al*., 2001)

If the current test itself, the interactions between a live pedestrian and a car, and the research under-pinning the current test are all considered, then there are many possible factors that might have contributed to the current problem. The following list is provided but is unlikely to be complete:

- The WG17 impact energies were derived from an FE computer model of a pedestrian and simulated car (Lawrence and Hardy, 1998). Some of the deficiencies of the model (relative to the live pedestrian) could have caused the impact energies to be too high. A more biofidelic version of the model (Neale *et al*., 2001) gave different results, illustrating the sensitivity of the impact energies to these details of the model. Making the leg more flexible reduced the severity of the bumper impact, which led to a higher velocity bonnet leading edge impact and hence increased impact energies. However, it was noted that there was more that could be done to make the model even more biofidelic, in particular modifications to make the spine more flexible. Such modifications would be likely to reduce the impact energies considerably, by reducing the effective mass involved in the impact.
    - The impact angle and impact velocity will also affect the realism of the impact and these might change significantly if determined using a biofidelic model.
- In a number of ways the 'worst case' is built into the test procedure. It is of course debatable as to whether this should be so, but given this worst-case approach the current upper legform test would not be expected to estimate the injury risk seen by the whole population.
    - In around half of fatal and serious accidents the vehicle is braking before impact. This will mean that the attitude of the vehicle under braking would justify a lower test energy than that specified in the test procedure, based on the normal ride attitude.
    - The energies are based on a model of a 50th percentile male pedestrian. The average pedestrian involved will be shorter and lighter than this. The impact energy for a lighter pedestrian would be less, though with a shorter pedestrian being hit higher on the body it is possible that more of the body will influence the impact, increasing the energy.
    - The upper legform is centred on the bonnet leading edge, which will maximise the bending moment. Live pedestrians will have their thighs contacting the bonnet

leading edge in different positions, most of which will give lower bending moments than a mid-femur impact.

- Most bumpers on cars appearing in the accident data will not be as safe for pedestrians as bumpers that have been designed to meet the pedestrian bumper test. These unsafe bumpers will on impact push the legs away more rapidly, reducing bonnet leading edge impact severity, compared with the safe simulated car that was used to set the impact parameter curves. However, the limited comparative modelling data that are available suggests that this effect is quite small.
- If the bumper impact causes a tibia fracture then the effective mass of the femur impact with the bonnet leading edge will be reduced, reducing the impact energy and the potential for injury by the bonnet leading edge. This effect would not be easily proven using accident data as it would be masked by another effect. A positive correlation would be expected between tibia fractures and femur / pelvis fractures as a given individual may be stronger or weaker than the average, and also the specific speed of the accident would influence both injury risks.
- The WG17 acceptance levels may still be too low. The injury risk curves used by WG17 were obtained by carrying out accident reconstructions with the upper legform impactor (Rodmell and Lawrence, 1998a; Rodmell and Lawrence, 1998b). The sample size available was barely adequate for the purpose. Because of the limited sample size the two main injury types, femur fractures and pelvis fractures, were combined. This means that some of the injuries used to obtain each injury risk curve were for the wrong failure mode, as the impactor's bending moment outputs are intended to measure the risk of femur fracture and the load transducers to measure the risk of pelvis fracture. This was particularly a problem for the bending moment injury risk curve as the majority of the injuries were pelvic fractures.
- The impactor doesn't rotate about the bonnet leading edge and slide rearwards in the way that a pedestrian does:
    - Modelling to obtain impactor energies may have included energy for crushing parts of a car that the impactor does not crush.
    - On modern cars, with larger radius bonnet leading edges, the rotation may be more important than it was or appeared to be at the time the test was developed. Lawrence *et al.* (1991) reported, from dummy tests and simulations, that the change in femur angle was small during the short duration of the peak force to the bonnet leading edge. However, live pedestrians are less rigid than the dummy and simulations used. Both the larger bonnet leading edge radius and the less rigid pedestrian may extend the main impact duration and hence the degree to which the pedestrian rotates during it.
    - The femur rotating over a curved surface may cause a lower energy impact. It allows the upper femur and pelvis to move towards the car, with a contact force acting, without necessarily requiring the car to deform and absorb energy.
    - For a given crush volume / energy a rolled impact would penetrate less deeply, so it would tend to see lower and therefore less injurious forces.
- The impactor has a fixed mass in any given impact whereas the pedestrian's effective mass would probably increase during the impact. It is likely that in the early impact the impact mass is higher than the pedestrian's effective mass would be.
- The impactor front member ('femur') is very rigid compared with the human femur.
    - With more rounded bonnets, the femur contact area could be greatly extended as the femur bent, whereas it would make little difference with an old-style 'sharp' bonnet leading edge.
    - Bending would soften the initial impact, spreading it out more in time.

- The impactor flesh (i.e. Confor™ foam) is much lighter, softer and more compressible than human flesh.
    - As a more rounded bonnet will contact a larger area of flesh, both real flesh and foam 'flesh' this may make the foam characteristics compared with real flesh more critical for rounded bonnets.
    - The force-deflection profile may be important.
    - Dynamic effects such as pressure waves may be important. The attachment of flesh at the far side of the bone may be important, as interaction with the bone would then be to both push and pull.
    - The ability of the flesh to transmit shear loads may be important.
- While there clearly has been a very large decline in injuries caused by the bonnet leading edge, accident data may over-state this decline.
    - Does the 'bonnet leading edge' used in the data correspond to the definition in the test procedure, i.e. including the wing leading edge and any headlamp induced injuries that are bonnet leading edge type injuries?
    - Do the data include the full vehicle scope or are some vehicles such as SUVs (up to 2.5 tonnes) excluded?
    - Some studies have selected only the type of injuries that the upper legform to bonnet leading edge test is designed to simulate, such as upper leg and pelvis injuries. Accident data include many injuries to body regions that would not be expected from the typical accident scenario. To assume zero benefit for these other body regions is unduly pessimistic, though conversely it is accepted that assuming the same benefit for these other body regions is unduly optimistic.
    - Where only impact speeds below the equivalent car speed of 40 km/h are selected, an over-estimate of impact speeds would reduce the reported number of lower speed injuries.
    - By selecting data for the latest car designs some studies may have selected a higher proportion of newer cars. Newer cars will on average have a different involvement in accidents that may affect the road types and speed limits involved, as well as being driven by a different sample of drivers. It's possible that this could have affected the proportions of injuries attributed to different parts of the car and to the ground.

5.4 Other comments on the current test

Matsui *et al*. (2002) tested a compact car and an SUV with the Polar dummy and then performed comparison tests using the WG17 impactors and test procedures. For the bonnet leading edge tests, the impactor test was positioned where the dummy impacted, and the residual deformations (dents) were compared to judge how similar the impacts were. For the compact car the sub-system impact energy from the WG17 look-up curves was less than 200 J, and so wouldn't normally be tested, but for the comparison the test was carried out anyway. The dents obtained from the dummy and sub-system tests were similar. For the SUV, the sub-system impact energy was capped at 700 J, as specified in the test procedure (it would otherwise have been 1100 J), but the dent obtained still clearly exceeded that observed with the dummy. The suggested reason was that impactor doesn't rotate so that more energy is applied to the area. They recommended decreasing the impactor energy for SUVs. Matsui *et al*. (2005) adds to the previous study by testing a mid-sized sedan car. The residual deformation of the bonnet leading edge was also in agreement between the dummy and impactor tests for the medium-size sedan. The finding that impact energies for SUVs are too high is consistent with the modelling work by (Neale *et al*., 2001) that was mentioned in Section 5.2.

JARI's feasibility study (Japan Automobile Research Institute, 2004a), mentioned in Section 5.3, also looked at vehicle design measures that would be necessary to comply with the bonnet leading edge test requirements. They calculated the stroke / crush depth required from the specified WG17 impact energy. While they failed to allow for the upper legform impact force being greater than the measured force (because part of the impactor is in front of the load transducers), which would reduce the stroke, they also didn't allow for the manufacturers' margin (manufacturers typically design to get 80 percent of the acceptance criteria) or the depth of the crushed material, which would increase it. For a typical car shape they then went through a theoretical design exercise. They made the bumper much deeper to increase the bumper lead and hence reduce the impact energy. They then increased the bonnet leading edge height to gain the required crush depth. Because increased height increases the impact energy, their design was iterated upwards until they had a tall vehicle for which the 700 J energy cut off was reached. This increase in height would increase fuel consumption. This approach of JARI's can be criticised firstly because this extra crush depth was obtained solely by adding to the external profile, whereas manufacturers would in the first instance try to generate it internally by moving components away from the bonnet leading edge. Secondly, they algebraically added the increase in height to the existing crush depth, ignoring the difference in direction. Thirdly, by extending the bumper they assumed an increase in vehicle length; this increase in length would probably be better utilised to extend the bonnet leading edge forwards as well as upwards, to maximise the increase in crush depth along the impact direction.

JARI (Japan Automobile Research Institute, 2004a) also refer to the work by Matsui *et al*. (2002) that was mentioned above, but it isn't stated by JARI that only with the SUV was the dent much bigger with the WG17 impactor test than with the dummy test. They then compare the rigid upper legform front member with the way the femur can flex during the impact. They then refer to tests by Matsui *et al*. (2004) where the thighs of complete cadavers were impacted, and the impact force was correlated with femur fractures to derive an injury risk curve. The 20 percent injury risk value was 8.84 kN. JARI use this value to obtain an equivalent tolerance for the upper legform of 7.40 kN, by allowing for the impactor mass in front of the load transducers. They say that a more biofidelic upper legform would measure lower forces, and with their higher criteria many more vehicles would have passed the force requirement in the Euro NCAP tests. They conclude that, "The test poses serious problems in terms of the impact energy, the test tool in relation to biofidelity, and the injury acceptance levels." The current authors point out that the impactor force measurement is designed to measure the risk of pelvis fractures rather than femur fractures; any revision of the acceptance criteria would have to consider both injury modes.

Okamoto *et al*. (2001) also compared Polar dummy tests with upper legform to bonnet leading edge tests. Two crash tests were conducted using the Polar pedestrian dummy, one with an automobile and one with a utility vehicle. For the automobile it was observed that the bonnet leading edge mainly contacts the femur and the pelvis rides on the bonnet. However, with the utility vehicle the bonnet leading edge hits the pelvis directly with the femur contacting the front grill and the bumper. They then tested the utility vehicle using the EEVC upper legform impactor, with the impactor weight and velocity modified to match the vehicle deformation obtained with the dummy tests. Model runs using a numerical simulation of the Polar dummy were used to assist with finding the correct test parameters. They estimated the required impact energy to be about 400 J whereas the WG17 look-up graph value is 1095 J (capped at 700 J). They suggest that the protection criterion relating to femur injury is not necessary for tests with utility vehicles as the pelvis is the main part injured, and recommend that the WG17 look-up energies need to be reviewed.

5.4.1 Feasibility

As with any such test, a vehicle can in theory be designed to meet the requirements by providing a structure of appropriate stiffness with sufficient crush depth to deform to absorb the test energy. The current EEVC WG17 test, however, often needs a crush depth that is difficult to accommodate alongside the other functions of this area, such as providing a cross-member to support the bonnet catch.

Lawrence *et al*. (2004; 2006) discussed feasibility issues with many of the European manufacturers. Their comments related to the EEVC WG17 requirements that were specified for the second phase of the pedestrian Directive (European Parliament and Council, 2003). All of the manufacturers spoken to, who made vehicles of such a shape that an upper legform to bonnet leading edge test was required, were unanimous in expressing concern about the feasibility of meeting the protection criteria in this area, mainly due to a lack of crush space, rigidity and packaging issues. Increasing the bonnet leading edge clearance from underlying structures by raising it requires greater impact energy, according to the current look-up tables in the test procedure and therefore does not offer an easy solution. Reduction of the impact severity through lowering the bonnet leading edge and increasing bumper lead, which results in reduction of the test energy, is another strategy being considered by some manufacturers. Although this will aid compliance with the Directive phase two requirements, it will restrict the space available for cooling and the upper front cross-member, etc. Weakening bonnet latches would lead to other problems such as durability issues. It was apparent from discussions with manufacturers that they believed that the requirements of phase two of the Directive were not feasible in this area.

There were no new technological developments to aid the protection of pedestrians in the bonnet leading edge area that were at such a stage of development so as to be available for use before the introduction of phase two of the Directive. However, over a longer time scale it is likely that active systems could be available. Systems such as air bags could provide protection from the bonnet leading edge impact. In order to deploy them at the right time, however, it would be necessary to have pre-impact sensors to detect the imminent pedestrian impact. These are likely to be available within a few years. It should be pointed out, though, that the cost of such active systems might be difficult to justify in cost benefit terms, given the generally low injury risk provided by current car designs. However, for a small proportion of large vehicles presenting a higher injury risk it might be cost effective.

The intention would be that any future revision of the bonnet leading edge test, such as the concepts discussed later, would mean that the revised test was better able to estimate real-world injury risks. This should therefore mean that the test would be less demanding and therefore that feasibility concerns would be eased. Nevertheless, it may be necessary to consider such feasibility measures such as possible lower protection zone or an energy cap.

5.5 Options for improving the current impactor and test method

Whereas the bonnet leading edge test is expected to be a ‘monitoring only’ test in the EU’s revised phase two, the intention of this section is to make proposals that could allow it at some time in the future to be a test with mandatory requirements. In this section changes that could be made to the existing test by improving the current impactor and test method are considered; more radical changes will be considered in the section following.

The main problem facing the existing WG17 test and its acceptability is that the results of testing cars predict injury risks that are not compatible with the accident data. There are two ways that this can be addressed while essentially retaining the existing test: by reducing the impact severity (i.e. test energy) or by increasing the acceptance criteria. Both of these were proposed in the feasibility study (Lawrence *et al*., 2006). This may or may not have addressed the conflict between the test results and accident data. However, the changes proposed to the test energy were pragmatic adjustments that were not based on research data. Also, the change of acceptance criteria was not based on a revision of the injury risk curve, so it doesn’t help to resolve the discrepancy between predicted injury risk and the accident data. There is therefore a need to carry out further work to put both the impact energies and the injury risk curve on a firmer basis.

One paper (Snedeker *et al*., 2005) has been found and reviewed that proposes changes to the current test method. Their proposals would retain the upper legform impactor and much of the test procedure, but would require some changes to reduce the impactor mass below its current minimum. Snedeker *et al*. used the THUMS FE pedestrian model (of which more below) to model pedestrian impacts with three types of simulated vehicle: sedan, SUV and van / 1 box. For each type the bumper height, bumper width, bumper lead, bonnet leading edge height, bonnet pitch and windscreen position were kept constant while the bonnet leading edge was set to five different values (0, 50, 100, 250 and 500 mm). They also performed five PMHS tests to simulated car shapes (sheet steel bonnet supported on steel frame; bumper was PVC shell over steel plate) and compared the results with the modelling results. They proposed a package of changes to the current test method:

- The bonnet leading edge should be determined by rotating a line from the upper bumper reference line and taking the point of first contact as the bonnet leading edge
- Two different tests are proposed for vehicles with a bonnet leading edge (as defined above) at or below 900 mm and above 900 mm
- The ≤900 mm test should measure only bending moment for femur fracture risk and the >900 mm test should measure only force for pelvic fracture risk
- A geometric method is proposed to determine the impact velocity
- The ≤900 mm test should be at an impactor mass of 7.5 kg and the >900 mm test at 11.1 kg
- The ≤900 mm test should have a failure criteria of average bending moment >320 Nm and the >900 mm test a failure criteria of peak average force > 10 kN

They assessed their proposed changes by using an upper legform FE model to compare their proposals with the current test and found that the bending moments obtained with their proposal were better correlated with the THUMS model and PMHS tests than were those obtained with the current test procedure. However, their proposal didn't require a test for pelvic injury risk in some cases where THUMS had predicted pelvic fractures and in a case with a pelvic fracture in a PMHS test. They suggest that perhaps both outputs should be monitored near the 900 mm threshold.

This study by Snedeker *et al*. warrants a more thorough consideration than there is time for within the current study. It may have some advantages over the current test. However, the current authors have the following initial comments:

- The method determines the bonnet leading edge as the first contact above the bumper. What, however, is needed is to obtain the correct position so as to centre the impactor where the most severe part of the pedestrian impact, with the greatest injury potential, occurs. As the impactor does not rotate during the impact an upper legform impact point somewhere between the first and last pedestrian contact points is desirable.
- Having two tests with a transition height is not desirable as the 'wrong' injuries will still occur within a given zone. In particular, vehicles in the femur injuries zone may cause pelvic injuries to shorter adults and children. Test conditions should be varied as the type of impact varies, but gradually with increasing bonnet leading edge height to reflect the gradual change as pedestrians of different statures move from receiving femur impacts to receiving pelvis impacts.
- The impact velocity and impact mass should be determined using computer simulations of pedestrian impact, not by the rough assumptions used. Proposals for doing this are made below.
- The criteria proposed have been taken from the literature with no considerations of the need for transfer functions. Impactor devices often need these as the forces, etc. measured are not the same as those that would be obtained in a real human pedestrian impact. This is particularly true when the device has poor biofidelity. The value proposed for bending moment was not adjusted to take account of the shorter length of the front member compared with the adult femur. While injury risk curves from reconstruction tests are difficult to obtain, as the accident cases available are very limited, they are still seen as the best option for the upper legform.

The impact energies used in the current test procedure have been based on a succession of computer models, as was explained in Section 5.2. The best model to date was the FE model of Neale *et al.*

(2001). This had a number of improvements to make the pedestrian part of the model more biofidelic, as well as improvements to the simulated vehicle. Nevertheless, it was recognised that further work was needed to make other parts of the model more biofidelic. In particular, it was recognised that a more biofidelic and therefore more flexible spine would be likely to reduce the estimated impact energies by reducing the effective mass of the pedestrian in contact with the bonnet leading edge. One option would therefore be to carry out further development of the existing model, until such time as it was adequately biofidelic.

Toyota Central Research and Development Labs, in collaboration with Wayne State University, have developed an FE model of the human called THUMS (Total HUman Model for Safety) (Oshita *et al*., 2002). This has been made available to other groups and seems to be a well regarded model. The model, particularly the lower extremities, has been validated for use as a pedestrian (Maeno and Hasegawa, 2001). The model is available in several sizes / ages; for instance Yasuki (2005) gave a presentation on the use of the 50th percentile male, 5th percentile female and 6 year old child as pedestrian models to compare with the lower legform impactor. THUMS has a very detailed skeleton. Development is continuing to refine the internal organs and muscles. The level of detail in THUMS is much greater than in the model used by Neale *et al*. THUMS is roughly a factor of 10 larger in terms of the number of nodes and elements. With such a detailed model it is in some ways easier to achieve biofidelic behaviour, as much of the behaviour is determined by the skeletal structure. It is still necessary, of course to, set the correct material properties.

Another option for determining the upper legform test energies would therefore be to use THUMS. If used at its current level of development it is likely to be more biofidelic for the purpose than anything that could be developed with reasonable effort by starting from the model used by Neale *et al*. An additional advantage may be that the results will have greater weight when being considered by experts in the field, than had a proprietary model been used.

While THUMS may be the best model currently available, there is still scope for further development. One issue that is likely to be important is that of muscle tension. Ideally, the model should represent a live human. However, much of the available data come from PMHS tests, where the muscles would not be tensioned. As was discussed in Section 3.5.2, Soni *et al*. (2006) modified THUMS to provide some muscle tension for the major muscles around the knee. This made a significant difference to the knee ligament response. The impact energy of the bonnet leading edge impact is likely to be affected by the muscle tension in several parts of the model. Ideally muscle tension would be provided throughout the body but key areas are likely to be muscles around the knee that affect the knee lateral rotation, the thigh or other muscles directly impacted by the bonnet leading edge, muscles around the hip that affect the hip lateral rotation, and muscles in the torso including those around the spine that affect the stiffness of the torso as a whole.

As part of a project to improve the test parameters it would be useful to reconsider how best to determine the shape of cars. Ideally the characteristics chosen should be those that have the greatest influence on the test severity. Conversely, the test energies should not change significantly as a result of minor changes in front end profile. The current test is overly sensitive to some minor changes in profile, particularly on vehicles with a large radius of curvature at the point where the straight edge touches. The correct balance needs to be made between having a simple test and a test that provides realistic test energies in all cases. As was mentioned in Section 5.2, at the end of the original development of the bonnet leading edge test it was decided to drop the bumper height and only use bonnet leading edge height and bumper lead to determine the test parameters. However, as the model used has changed the bumper height has had more or less influence, and with the higher proportion of SUVs in the car fleet, bumper height may need to be included. Another possible variable would be the radius of curvature of the bonnet. Yet another would be to use the angle between the upper bumper and bonnet leading edge reference lines. The angle of the straight edge used to determine the bonnet leading edge should also be reviewed. A change from 50° to the vertical to 40° has previously been proposed in order to identify more accurately the centre of the upper leg impact (Neale *et al.*, 2001; Lawrence *et al*., 2006). Another possibility would be to measure bonnet height and bumper lead for contacts with a straight edge held in turn at a number of different angles, and then obtain a contribution to the total impact energy for each pair of values. This is intended to reflect the rolling action of the pedestrian in the bonnet leading edge contact.

Some of these options could result in a look-up system that was more than two-dimensional. This might be beyond the capabilities of look-up graphs similar to those used currently, depending on the complexities of the relationships. This need not be a problem as it would be possible to build the relationships into a software program. Even if the system remains two-dimensional it might be worth changing to using a defined program, to avoid the reproducibility errors and potential mistakes of the current look-up system. TRL has developed such a program (BLEtest) and supplies it with the upper legform impactor, but it currently has no official status.

The model of Neale *et al*. used only a representation of a 50th percentile adult male. Ideally, a range of statures should be used to represent those likely to be injured by the bonnet leading edge, or perhaps those likely to be injured on or below the pelvis by the bonnet leading edge. The test parameters could then be determined either by averaging the results or by using some degree of 'worst-casing'.

The current impact velocities and angles are still essentially those proposed when the test was first developed. While the test energy is the most important parameter, any new modelling should also be used to revise the test velocity and angle look-up graphs.

The simulated car used for the modelling described above should also be tested with an FE model of the upper legform, using the test parameters obtained. This would allow a direct comparison of the performance of the upper legform impactor with that of a complete pedestrian. This comparison should include the pattern of vehicle crush and the crush depth. If the simulated car is too simplified this comparison could be carried out with an FE model of a real car. The comparison could give an indication of whether the changed test parameters were adequate to solve the basic problem of the test failing cars that were causing few injuries, or whether more radical changes were required, such as those in the section following.

The current test was developed for conventional car shapes and sizes. The application of all the pedestrian tests to vehicles outside the current scope (not more than 2.5 tonnes, M1 or N1 derived from M1) will be considered in Section 7. Proposals will be made there for marking-up for, and performing, the bonnet leading edge test procedure on vehicles with angled or flat fronts and vehicles with a very high bonnet leading edge. Most angled or flat fronted vehicles should be outside the current scope but some may be within the current scope. The changes proposed to deal with vehicles of these shapes could therefore be applied also to vehicles of these shapes that are within the current scope.

The current injury risk curves are based on accident reconstruction tests using the upper legform impactor (European Enhanced Vehicle-safety Committee, 2002a). The number of tests used was much less than was desirable. In particular, the limited number of injury cases meant that both femur and pelvis injuries were combined when estimating the force and bending moment injury risk curves. Ideally, further reconstructions should be carried out so that the injury risk curve for each test output could be determined using only the relevant injury type (femur fractures for the bending moment and pelvic fractures for the sum of forces). However, this analysis would need some care as the occurrence of either fracture could have the effect of reducing the load acting to cause the other fracture. Based on the number of cases used previously, it is roughly estimated that to separate the injury types would need a minimum of about 20 cases of each type (pelvis fracture, femur fracture and neither fracture type). This would require about 20 additional fracture cases, with most of them needing to be femur fracture cases. However, a larger number of cases than this would be highly desirable, to improve confidence in the result. Given the reported marked decline in injuries caused by the bonnet leading edge, it may not be possible to obtain a sufficient number of adequately documented cases with an injury caused by the bonnet leading edge, and for which a vehicle of the model involved can be obtained for the reconstruction.

The foam used for the flesh material could be reviewed. The Confor foam was chosen primarily for its energy-absorption (i.e. low rebound) properties (Lawrence *et al.*, 1991; Lawrence *et al.*, 1993), but at the time it was not appreciated that its properties were highly sensitive to temperature and humidity. However, any change should be made with caution as a change could lead to other problems. These Confor foam properties have less effect on the upper legform than they do on the lower legform, as the thickness is greater and the certification test less severe. It is suggested that this option is not actively pursued, but it could be considered if a suitable alternative material comes to notice.

The length of the front member could be increased to reduce the risk of the ends of it contacting the vehicle on vehicles with a large radius of curvature. The current length of the front member is 350 mm but 50 mm of this is the hemispherical end caps, leaving 300 mm at constant radius. This is roughly two thirds of the typical femur length. However, increasing the length would add to the mass in front of the load transducers, particularly if a thicker wall thickness was required to maintain adequate strength. A longer and heavier rear member would also be required so the minimum test mass would be considerably increased. The acceptance criteria would then need to be modified for the revised impactor. Overall, there would be considerable effort and consequences involved for a very small benefit, so this option is not recommended.

Recommendations:

- The test parameters of energy, velocity and angle should be reviewed using the THUMS FE model
    - The model used should preferably include muscle tension for key parts of the body. If these do not become available as an integral part of the THUMS model then it might be possible to add them as part of this work.
    - The model should be used to identify the car shape parameters that best relate to the impact severity
    - The model should then be used to obtain test parameters for a matrix of vehicle shapes
    - The modelling should include a range of pedestrian sizes, as a minimum a 5th percentile female as well as a 50th percentile male
    - Modelling should be used to make a direct comparison between upper legform and pedestrian impacts
- Additional accident reconstructions should be carried out to improve the injury risk curves
    - Ideally, each injury risk curve should be based on the appropriate type of injuries. This would need a minimum of about 20 cases of each type, preferably more.

5.6 Options for replacing the current impactor and test method

As was mentioned earlier, there have been criticisms about the lack of biofidelity of the upper legform impactor in the bonnet leading edge test. One of the main criticisms concerns the lack of a rolling action to simulate the movement of the pedestrian around the bonnet leading edge. However, the authors are not aware of evidence to show what the essential features of a replacement test should be. If biofidelity can be achieved with little disbenefit it would be sensible to develop a highly biofidelic test. However, the bonnet leading edge impact is inherently complex and the impact point on the pedestrian is such that a large part of the pedestrian’s body will influence the impact. It is probably impossible to design a replacement bonnet leading edge test that is significantly more biofidelic while remaining as simple and easy to use as the current test. Increasing biofidelity would be obtained at the cost of increased complexity.

Before any of the options below or any alternatives are developed it is strongly recommended that some effort be made to establish what the essential characteristics of a replacement bonnet leading edge test are. Understanding the deficiencies of the current test would be a useful start.

It should also be established which injuries are being considered in terms of injury type, pedestrian stature and impacting vehicle, and if possible decide which vehicles would be within the scope of a legislative test. The original test was designed for typical cars, which would mostly impact adults on the femur. Now, however, these vehicles are causing far fewer injuries while there is great concern about injuries caused by high vehicles. The typical injury-causing impact is thus likely to be at a significantly greater height than before. Also, it should be established whether injuries to children are significant, and if so whether they need a specific test or whether they would be adequately protected by a vehicle that had been optimised to protect a different body region in adults.

Pedestrian sub-systems tests were proposed by Harris (1986). As was mentioned in Section 5.2, EEVC WG10 was later given the mandate to develop sub-system tests as opposed to a dummy test. It is useful to review the benefits of these two basic options:

Sub-systems:

- More repeatable, as the equipment and kinematics are less complex
- Can accurately aim at desired test points
- Don't need many dummy sizes to test whole area likely to strike pedestrians
- The impactors are cheaper than dummies
- Lower cost (and quicker) to perform test and to repair car
- Can test more locations on a vehicle than might be practical with dummies
- Requires less space and energy, because the impactor is moving instead of the car, though it should be possible to propel a whole dummy into a stationary car
- Need not use a complete car; can use sub-assemblies instead
- Quicker and easier to develop sub-system impactors and test procedures than a generally accepted pedestrian dummy
- The test requirements are simpler for the car manufacturers to design to and to model mathematically
- They can be more easily used in component development
- Easier to re-test part of a vehicle that has been modified or worst-case test variants of a model
- Can if required use different severities of test (equivalent car speed, pedestrian age & size, energy cap for feasibility) on different parts of the car
- The test severity can be adjusted (e.g. by energy cap) to take account of practical design limitations
- They can include corrections in the impactor's test conditions to compensate for limitations in the biofidelity of the pedestrian dummies used to develop them. (With a dummy these limitations would cause errors in the latter stages of the impact.)

Dummy tests:

- More realistic i.e. more like a human, though they can never completely reproduce the response of a live human
- Don't need to specify so many test parameters
- Impact conditions between body components and vehicle components are generated automatically
- Fewer problems when testing deployable devices such as airbags – not only with timing of deployment, but also the presence of other body parts would affect the pressure in the airbag, etc.

- They can give proper weight to the effect of all parts of the human on the vehicle (an issue even for passive systems). For instance, the pedestrian thorax might deflect the bonnet before the head impacts.
- Could easily test the vehicle in the under-braking condition
- May be less affected by trends in car design (for example, the rolling action of a pedestrian around the bonnet leading edge may be more important for rounded car shapes than for the older, squarer designs)
- Take more vehicle characteristics into account. For instance the rebound characteristics of a vehicle at the first impact might be advantageous or disadvantageous later in the impact or at ground contact, but a sub-system test would probably not discriminate. This could be important with active safety devices.
- Could indicate mismatches between different areas. With sub-system tests a soft area optimised for one impactor might allow greater penetration than a harder area optimised for a different impactor; this might cause bending and or shear loads on a real pedestrian. A dummy test with appropriate requirements could maintain a more consistent intrusion profile.

If these points are considered in relation to the three areas of the car to be tested, the balance of advantage and disadvantage for using sub-system tests will be different for the three areas. For the bonnet top there is little alternative to a sub-system test, because of the difficulty of impacting the desired impact point with a dummy, However, dummy tests for the bonnet leading edge could be much more attractive as the impact conditions in that area are determined automatically from the initial impact speed, lateral location, etc. A bonnet leading edge test using a dummy could be combined with the bumper test as a front end test. This would be particularly attractive for testing vehicles with high bumpers.

The choice of using a sub-system test or a dummy test for the bonnet leading edge test is not necessarily an either / or choice, as there are a number of options of increasing complexity ranging from the current sub-system test to a full dummy test where the characteristics of a simple sub-system test are gradually replaced by those of a dummy test. The options considered in this section start with the options closest to the current test. Successively more dummy-like tests are then considered. Finally, a third top-level option of using computer modelling is considered. It should be noted that the list is not exhaustive; there are likely to be a number of worthwhile options that haven't even been thought of for this list.

Lawrence (2005) on behalf of EEVC WG17, considered future options for pedestrian protection test procedures. Some of the options considered here are taken from that paper. However, several others are presented here probably for the first time. It must be pointed out that most or all of these ideas have not been developed in any way and are just concepts. As such, some may on further consideration be found to have fundamental flaws which would make them incapable of being developed into a workable test. Within each main option there would also be a number of subsidiary choices that should be evaluated if the basic idea were to be taken further. As mentioned above, the starting point should be to establish the essential requirements of a new test. Once this is done it may be possible to eliminate several of the concepts below from further consideration.

5.6.1 Option 1: Upper legform with secondary mass

When the current upper legform test was being developed one of the options considered was to increase the effective mass of the impactor during the impact. This was to reflect the way the pedestrian 'leans on' after the initial impact with more of their mass acting through the bonnet leading edge impact. At the time this complication was not taken further as the current impactor seemed to be adequate. This concept could be achieved by having additional masses that were initially set back from the rear member so that they would slide into contact at the appropriate time. A simple way of doing this would be to have a tube or box with a sliding weight and to fill the gap with foam to prevent a harsh impact with the main impactor. This is shown in Figure 5.3. A variation on this would be to have several weights in line in the tube, with foam spacers between them. The minimum change would be to have a single central tube or box, or two symmetrically about the torque limiting joint. However, the offset option shown could be used, if the torque limited joint were also slackened or released, to generate or encourage a rotation to reflect the pedestrian's rolling action. This option to generate rotation should extend the contact area and make it more similar to the real-world pedestrian impact.

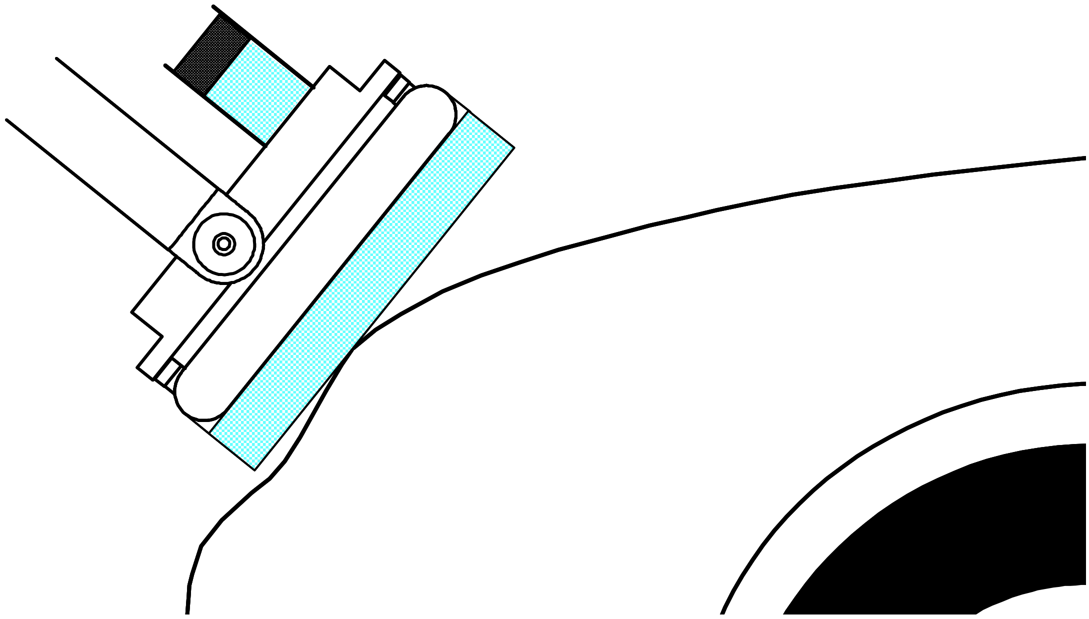


Figure 5.3. Upper legform with secondary mass concept

With such an impactor the test parameters and particularly the test energy would have to be reconsidered, preferably in a similar way to the suggestions made in Section 5.5. The additional weights don't necessarily have to be fixed; they could be adjusted according to the size and shape of the vehicle under test. Energies might need to be higher to keep the mass of the fixed part similar, or the standard bonnet leading edge energies might be about right, in which case the mass driving the early part of the impact would be reduced. The acceptance criteria might also need to change.

The advantages of this 'upper legform with secondary mass' concept would be:

- that it only makes limited changes to the current impactor and test
- that it would be easier to propel into the test vehicle than some of the other options

The disadvantages would be:

- that it may not do enough to solve the problems of the current test
- that there may be a preference among experts for a test that does not involve the current impactor

5.6.2 Option 2: Upper legform with additional section

Another of the closer options to the current upper legform impactor and test would be to add one or more additional sections at the front of the impactor, above and possibly also below the front member; see Figure 5.4. These would have perhaps several kilogrammes of weight and be covered with the same flesh and skin material as the main section. They would also impact the vehicle, extending the contact area and providing some aspects of the 'rolling pedestrian' action, though the timing would not be realistic. The dent created in the vehicle with this extended impact could be more realistic than with the current impactor. The impactor could just be a hinge at the joint(s) but a flexible link that could transmit a bending moment may be better. This impactor would impact differently according to the profile of the car, in a way that should be more biofidelic than with the current test. With a large radius bonnet leading edge, both parts would impact almost independently, so the loads and bending moments measured at the main section would reflect only the impact of the main part. However, on vehicles with a squarer profile the secondary section would be well clear of the bonnet when the main section contacts, and would drag the main section forward, increasing the loads and bending moments measured. The basic concept doesn't require that the secondary section be instrumented but that could be an option. With the additional section, the overall moment of inertia of the impactor would be higher so it may be possible to slacken or release the torque limiting joint and allow the impactor to rotate, to provide some rolling action without it rotating too rapidly. Another option would be to make the impactor a free-flight impactor; this could be particularly attractive if the weight had to be reduced to keep the combined impactor at a similar weight to the current upper legform.

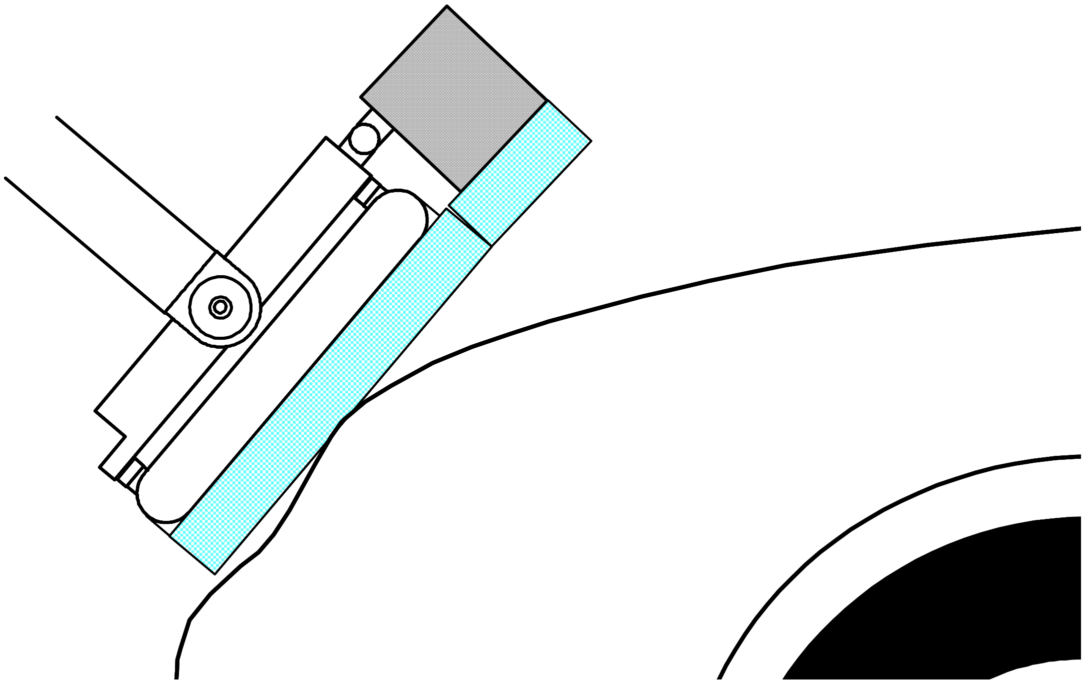


Figure 5.4. Upper legform with additional section concept

Note that the concept was to provide elements of the impact that are later or are further up the bonnet due to sliding effects. With the two parts as shown it would be tempting to regard the main section as the femur and the secondary section as the pelvis. However with the impact located at a defined bonnet leading edge, on high vehicles they will be at the wrong height for this interpretation. As with the current test, the impact should be centred on the main section even when the height of the vehicle means that it is at a typical pelvis height. As with the previous concept, with such an impactor the test parameters and particularly the test energy would have to be reconsidered, preferably in a similar way to the suggestions made in Section 5.5. Energies might be higher to keep the main section similar, or the standard bonnet leading edge energies might be about right, in which case the energy driving the load and bending moment readings would be reduced. Acceptance criteria may also need to change.

The advantages of this 'upper legform with additional section' concept would be:

- that it only makes limited changes to the current impactor and test
- that it takes some account of the bonnet radius
- that it would be easier to propel into the test vehicle than some of the other options

The disadvantages would be:

- that it may not do enough to solve the problems of the current test
- that there may be a preference among experts for a test that does not involve the current impactor

5.6.3 Option 3: Upper legform with forced rotation

A third option based on the current upper legform would be to control the rotation in some manner so that it moved in a more biofidelic manner. There could be many ways of doing this. For the current purpose little thought has been given to the specifics of doing this. Figure 5.5 shows a generic pusher that could be operated in a controlled manner. This could be a stored-energy device, or it could be a hydraulic or pneumatic ram with an external energy store and connecting pipes to bring in the fluid or air. A completely different approach to generate the rotation would be to use a lever system connected to the propulsion mechanism or that contacts an external buffer. Whatever system is used, it would be difficult to maintain controlled rotation, within a specified corridor, that was independent of the impact forces. This difficulty would probably mean that larger components would be needed to overcome resistance, in which case it would be very difficult to keep the minimum impactor weight acceptably low. The torque limiting joint could be replaced with a simple pivot to save some weight.

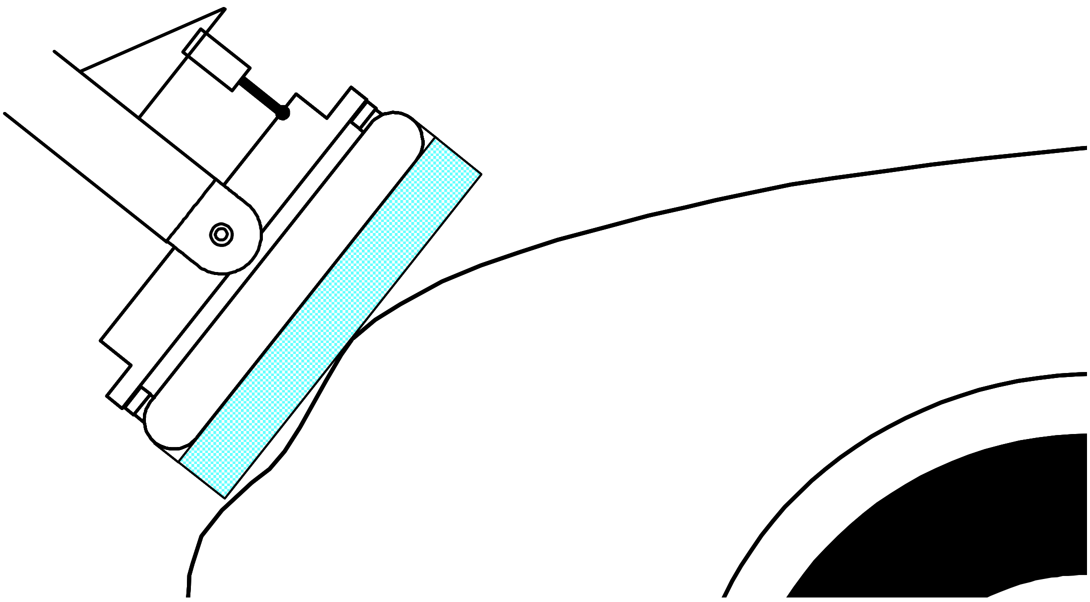


Figure 5.5. Upper legform with forced rotation concept

This concept should provide the most realistic rotation of the upper legform based concepts. As with the previous concepts the test parameters and acceptance criteria would have to be reconsidered. The rotation corridor would have to be obtained; this could potentially be a function of the vehicle size and shape, if this was considered to be necessary.

The advantages of this ‘upper legform with forced rotation’ concept would be:

- that it only makes limited changes to the current impactor and test
- that it should generate realistic rotation
- that it would be easier to propel into the test vehicle than some of the other options

The disadvantages would be:

- that it may not be practicable to generate the required rotation while maintaining an acceptable impactor weight

- that it may not do enough to solve the problems of the current test
- that there may be a preference among experts for a test that does not involve the current impactor

5.6.4 *Option 4: Flexible femur-form*

One of the differences between the bonnet leading edge test and the lower legform to bumper test is that the lower legform simulates a specific pedestrian stature whereas the bonnet leading edge test makes a priority of testing a specific part of the vehicle. A specific pedestrian stature is not built into the design of the upper legform, though the current test parameters are derived from simulations of a specific stature. The bonnet leading edge may occur on different vehicles over a wide range of heights, but in all cases there would be the potential to cause injuries to pedestrians of various statures (although with some vehicles this risk may be low). Over a certain height range the test will simulate the femur impacts that it was designed for, even though the stature at greatest risk may be somewhat different from the 50th percentile male. Beyond this range the body regions at risk may be different but the impactor may still provide some protection. The way that the bonnet leading edge test targets this (normally) prominent feature, with a relatively high potential for injury compared with the flatter surfaces immediately below and behind it, can therefore be regarded as an advantage.

The concept shown in Figure 5.6 therefore attempts to combine some of the better features of the bonnet leading edge test with some of the better features of the Flex-PLI. This would consist of a segmented, flexible femur-form, similar to the long-bone design of the Flex-PLI. However, it would be launched in free-flight at a specified velocity and angle, using simulation-derived look-up tables similar to those of the current test. It would use bending moment and possibly acceleration as the outputs that would have to meet given acceptance criteria. The design details, such as the number of segments, segment mass, flexibility (i.e. minimum radius of curvature) and bending stiffness, should be chosen for this test and not necessarily copied directly from those of the Flex-PLI. Some segments, particularly at the top end of the impactor, would need to be massed up to include a contribution to an upper body mass. Contributions to a lower leg mass may also be necessary. It may be difficult to make such an impactor sufficiently robust as the tensile and shear forces between segments could be quite high. This is because the impact would be to the centre of the femur-form, whereas in a bumper test the main impact is close to the knee; also the extra masses mentioned would potentially increase the stresses on the centre segments. The impactor would certainly wrap around the bonnet leading edge to the extent that it was capable of and, with the correct choice of impact parameters, it could impact initially just below the bonnet leading edge reference line and then rotate around in an approximation to the pedestrian's rolling motion. Obviously, it would be necessary to expend considerable effort in developing the test parameter look-up graphs, and the injury risk curves from which the acceptance criteria would be obtained.

The advantages of this 'flexible femur-form' concept would be:

- that it retains a focus on the required test area
- that it takes advantage of on-going developments to provide a more realistic bending response than the current rigid front member
- that it would avoid the complications of a guided impact
- that it should generate realistic rotation
- that it would be easier to propel into the test vehicle than some of the other options

The disadvantages would be:

- that it may not be possible make it sufficiently robust
- that it may be very difficult to obtain injury risk curves for the test outputs

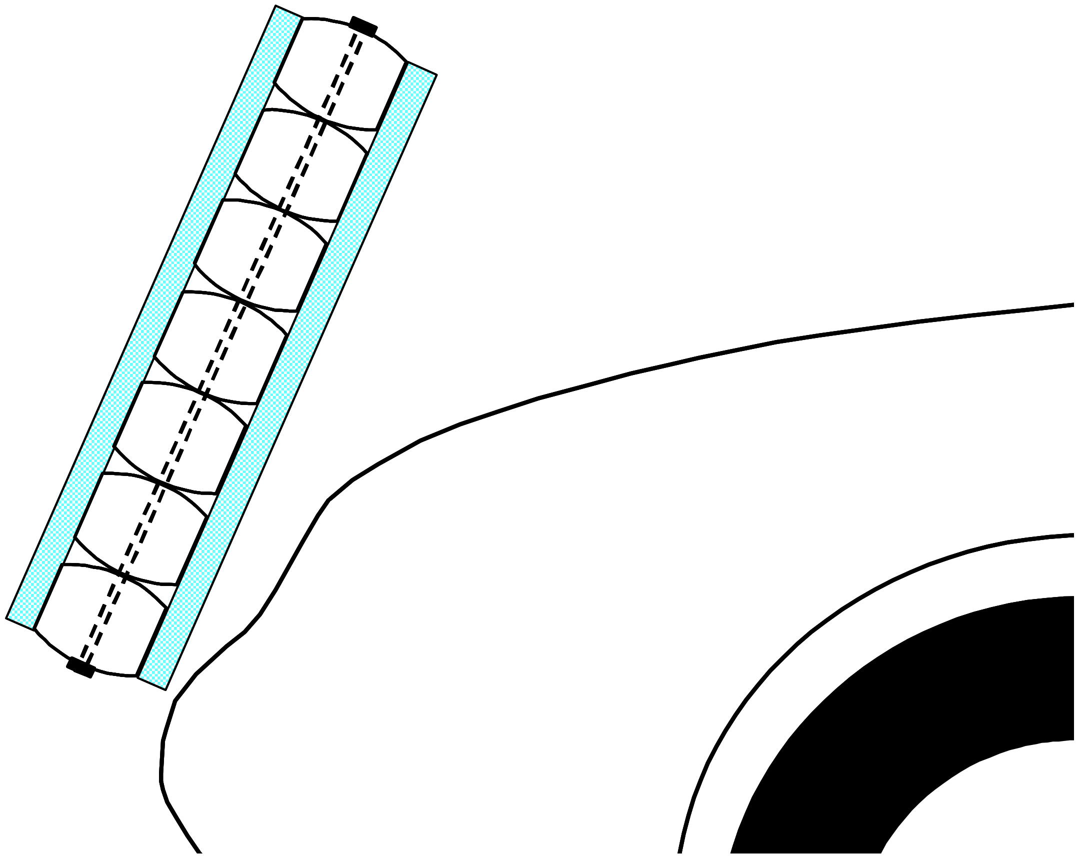


Figure 5.6. Flexible femur-form

5.6.5 Option 5: Lower legform with upper body mass

The next concept is to use a lower legform with an added upper body mass to test the bonnet leading edge, see Figure 5.7. This concept is also being considered for the high bumper test, see Section 4.2.2. There would be little point in testing the front of a car with two different lower legforms so the logical extension would be to make this a combined front of vehicle test combining the bumper (both low and high) and bonnet leading edge tests. The main difference between this and all the previous concepts would be that the impactor would be launched horizontally to simulate the initial impact between vehicle and pedestrian. Therefore, the properties of the impactor would have to be such that the correct bonnet leading edge impact conditions were generated automatically from earlier interactions with the vehicle (i.e. the bumper impact) and internal interactions within the impactor. However, by doing so the impactor would be able to use the same initial impact conditions for all vehicles. There would be no need to use vehicle shape parameters to simplistically describe the vehicle. All aspects of the vehicle shape that determined the bonnet leading edge impact would be automatically taken into consideration. Also, vehicle stiffness would be automatically taken into consideration whereas the current method does not distinguish between, for instance, a stiff steel panel and a weak plastic part that would effectively change in shape during the early impact. Any debate about the derivation of look-up parameters from modelling, and the biofidelity of the model used, would also be avoided.

As was discussed in Section 4, the standard lower legform has a reasonably realistic trajectory when it impacts conventional car bumpers, but it doesn't rotate sufficiently when high bumpers are impacted. The problem is that the pedestrian's legs are effectively pulled round, in this case, by the motion and inertia of the pedestrian's body. Thus, removing the body, to create a lower legform impactor, means that the trajectory is not realistic when the impact with the bumper is too high in relation to the impactor's centre of gravity. Adding an upper body mass has been discussed as a way of getting the legform to behave in a similar way to a pedestrian's leg when hit by a high bumper. Such a high bumper test would require significant development. It is thought that an upper body mass would have to be of the order of 15 kg to provide the required benefit in the high bumper test. This could be a compact mass attached to the hip end of a lower legform impactor through a ball joint.

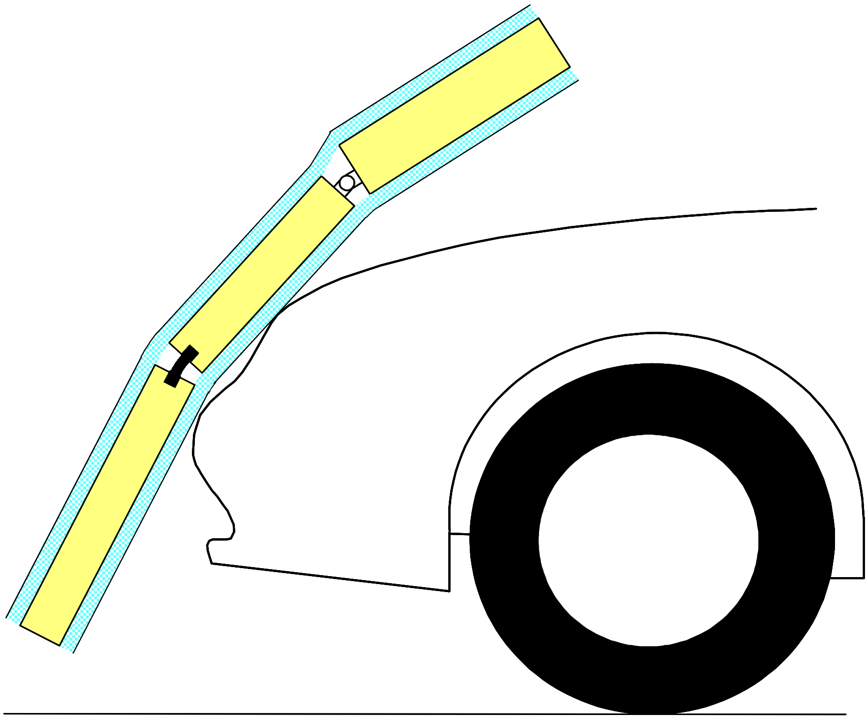


Figure 5.7. Lower legform with upper body mass concept

Lawrence (2005) extended the concept by suggesting using a lower legform with an upper body mass to combine the bumper and bonnet leading edge tests. Clearly, in order to generate a realistic bonnet leading edge impact such an impactor would need to:

- have a realistic trajectory into and preferably throughout the bonnet leading edge impact
- have the correct effective mass when in contact with the bonnet leading edge
- have a reasonably realistic pelvis section to contact the vehicle with, for vehicles of such a height that the pelvis contacts the bonnet leading edge

Such an impact device would need a considerable development programme. As a first step the scope of vehicles that would be tested should be decided, as the maximum height of bonnet leading edge for which such a device would be expected to work will determine the upper body mass required. For a bonnet leading edge impact much more than a compact mass will be required; the mass, centre of gravity and moment of inertia of the upper body mass are all likely to be important parameters. The upper body mass required is likely to be much more than that needed for a high bumper test. Having a single, rigid upper body mass may not be adequate; it may be necessary to have more than one upper body segment or to have a flexible link to the femur section. The final version might require a much larger upper body mass than that shown in Figure 5.7.

The starting point in terms of hardware should be the best available lower legform impactor. The development project might also have to strengthen the lower legform to withstand any additional stresses from adding the upper body mass. The Flex-PLI (see Section 3) is still being developed, but if its development is ultimately successful (see Section 3.11) it would probably be the best impactor to use. The device's instrumentation would be that required for the bumper test with the addition of a load cell at the hip joint, maybe a pelvis accelerometer, and transducers to measure femur bending (already provided in the Flex-PLI).

The advantages of this 'lower legform with upper body mass' concept would be:

- that it automatically takes account of vehicle size, shape and stiffness
- that it provides a relatively biofidelic impact including the pedestrian's rolling action
- that by combining with the bumper test it may reduce the number of tests required for a vehicle
- that as a combined bumper test it would avoid the need for special treatment of high bumpers

The disadvantages would be:

- that it may have to be very large and heavy to work, particularly for the larger vehicles, which would make it difficult to launch
- that it could be difficult to simulate the correct stiffness and behaviour for a live human
- that one device probably couldn't correctly simulate a single leg impact into a low car and a combined legs and/or pelvis impact into a high car
- that it would only represent one specific pedestrian stature
- that there would be a limit to the height of vehicles that could be properly tested
- that the increased complexity and difficulty of a combined test would be needed even for vehicles that would not need testing with a bonnet leading edge only test

5.6.6 Option 6: Partial or full dummy

The previous option might have to be nearly as heavy as a dummy to work properly for the bonnet leading edge, so an alternative would either be to use a full dummy or to use a partial dummy. A concept for a partial dummy is shown in Figure 5.8. This would be simplified to remove unnecessary parts (for this purpose) such as the head, neck and arms. It might be necessary to add mass to the torso to compensate for the mass thus removed. Though two legs are shown a possible simplification would be to use only one central leg. However, using two legs and a realistic stance is probably the best way of handling the gradual transition from two distinct leg to bonnet leading edge impacts with low cars, to a combined impact onto the bonnet leading edge with higher cars where the top of the femur or the pelvis is impacted.

The advantages of the 'partial dummy' concept would be:

- that it automatically takes account of vehicle size, shape and stiffness
- that it provides a relatively biofidelic impact including the pedestrian's rolling action
- that by combining with the bumper test it may reduce the number of tests required
- that by starting with an existing dummy less development effort may be required
- that it would be cheaper and easier than using a full dummy

The disadvantages would be:

- that it would be so difficult to launch into a car that it may be easier to run the car into the standing dummy
- that it would only be as biofidelic as the original dummy
- that it would only represent one specific pedestrian stature
- that the greater complexity is likely to give poorer repeatability and reproducibility
- that there would be a limit to the height of vehicles that could be properly tested
- that the increased complexity and difficulty of a combined test would be needed, even for vehicles that would not need testing with a bonnet leading edge only test

- that it would cause more damage to the vehicle than the previous options, thus increasing test costs

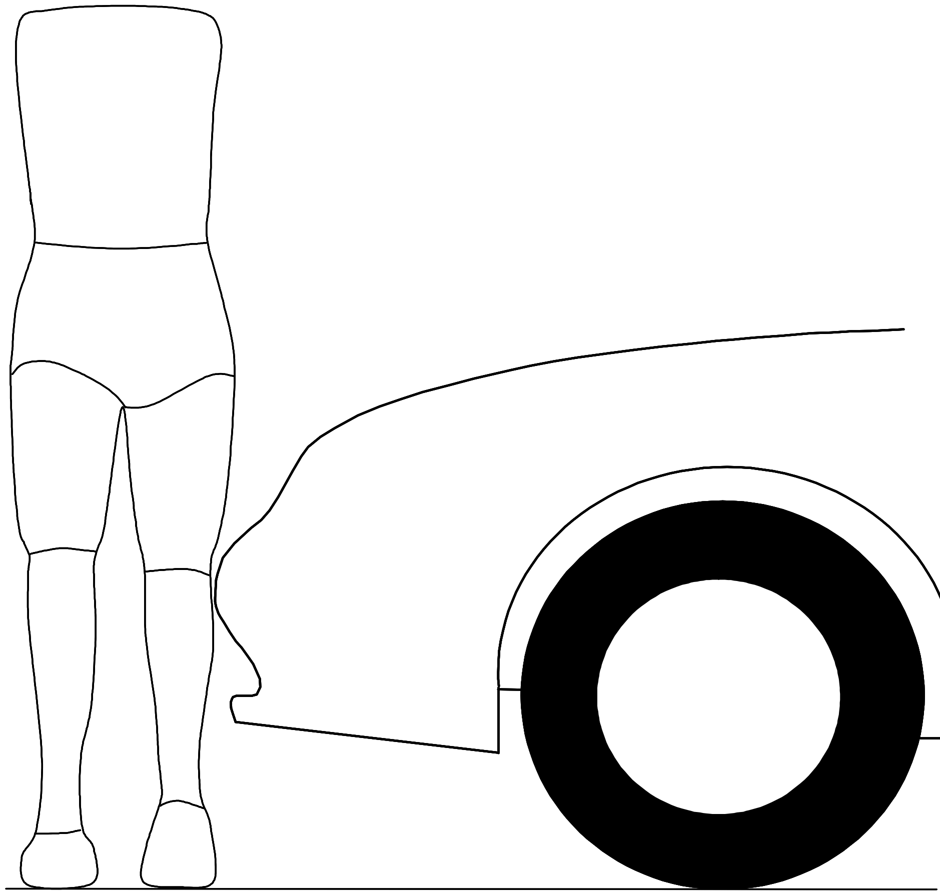


Figure 5.8. Partial pedestrian dummy concept

The advantages and disadvantages of a full dummy would be similar. It would cost more per test and repeatability and reproducibility would probably be worse because more components would be involved, but if a suitable pedestrian dummy was available the development effort would be minimised, and a full dummy may be more easily accepted. The best pedestrian dummy at the present time is probably the Polar II dummy. However, even this may not biofidelic enough to simulate the bonnet leading edge impact accurately. It would need to be confirmed that factors such as the flexibility of the spine were adequately biofidelic for this purpose. The SAE Pedestrian Dummy Task Group is currently developing specifications for a more advanced pedestrian dummy. However, this is intended for research rather than legislative use.

5.6.7 Impactors for other parts of the body

Most or all of the previous options have effectively assumed a single, adult pedestrian stature. There has also been a focus on impacts to the femur and pelvis. However, younger pedestrians may be hit higher up the body by the bonnet leading edge, particularly with the larger vehicles that are of particular concern for this impact area. It may therefore be worthwhile developing additional sub-system impact tests using new impactors, to protect against injuries not covered by the current or possible replacement sub-system tests. One possibility is a test using a thorax impactor. A series of child thorax impactors of different ages was developed by Hamilton (1988), but were not taken up in legislation. These or similar devices may have a place for testing the bonnet leading edge of large vehicles. An abdomen impactor might be another possibility, though for protecting this body region feasibility could be a difficult issue. It should be noted that many of the existing injuries to children may be prevented if the bonnet leading edge meets requirements to protect the adult. There would be considerable resistance to having two different tests to the same part of the car, on feasibility grounds, because these would be likely to require different bonnet leading edge stiffnesses. Meeting both requirements would require a greater crush depth than either test alone. If having two tests for different statures on the same part of the car were to be accepted at some future time, then consideration should be given to testing the bonnet leading edge with the child headform impactor on vehicles where the bonnet leading edge is beyond the 1000 mm wrap around distance. (On conventional cars the child headform test zone starts at 1000 mm wrap around distance but on high vehicles, for feasibility reasons, it currently starts a specified distance behind the bonnet leading edge reference line.)

5.6.8 Virtual testing using computer simulation

One common requirement with all the test options considered previously, even if it wasn't specifically mentioned above, would be to make the test hardware and test method sufficiently biofidelic. Biofidelic here means simulating a live pedestrian, not a PMHS. All anthropometric test devices are compromised to some degree because simplifications have to be made and also because other requirements compete, such as being durable under loads that would cause injuries. In recent years, finite element (FE) computer models have been developed to the point where they can in some respects provide a more biofidelic representation of the live human than can a hardware device. The THUMS model was mentioned in Section 5.5 and represents the current 'state of the art'. However, as was discussed, there is still scope for further improvements to THUMS such as the addition of muscle tension to represent better the live pedestrian. Nevertheless, in the future, using an FE model may be the most biofidelic way of testing the bonnet leading edge. Such an option would have considerable problems though. The pedestrian model would have to be controlled so that the same model was always used and so that results did not depend on the system that it was run on. The greatest difficulty would be that an FE vehicle model would also be required for each vehicle tested (though most manufacturers would have created one as part of the normal development process) and this would have to be validated to ensure that it was adequately representative of the real-world vehicle. One possibility for validating the vehicle model would be to carry out hardware and software (FE) tests with the existing impactors, with the requirement that the results should be the same to within a specified percentage. However, the cost of this could be comparable with carrying out normal legislative sub-system tests. There would be considerable initial resistance to the use of FE modelling for legislative testing purposes. It would be inadvisable to start with an impact as complex as the bonnet leading edge impact, so this is probably not an option to pursue at this time.

The advantages could be:

- improved biofidelity
- improved repeatability and reproducibility
- reduced costs
- greater ease of testing different pedestrian statures

The disadvantages could be:

- need to produce and validate the FE model of the vehicle
- the need to develop, validate and control the use of the specified pedestrian model(s) and costs of doing so

5.6.9 Other groups working on the bonnet leading edge test

Groups other than EEVC WG17 have also considered a bonnet leading edge test. The IHRA PSWG initially gave priority to developing the headform and lower legform tests. They intend next to consider the high bumper and bonnet leading edge tests. For the bonnet leading edge they are likely to start by studying their options for the test; a Flex-PLI with an upper body mass is likely to be one of the options considered. However, this assumes that the PSWG is able to carry on despite the recent disbandment of the IHRA Steering Committee.

In Europe, the APROSYS (Advanced PROtection SYStems) project's pedestrian and pedal cyclist sub-project is also considering next-generation tests including tests for the bonnet leading edge.

5.7 Discussion

The current upper legform to bonnet leading edge test was developed on the basis of accident data and reconstruction tests involving vehicles that generally had much squarer profiles than the more rounded profiles of current car designs. Not long after the test was developed there were studies reported that showed that the injury risk from the bonnet leading edge impact was much less with modern cars than with older car designs. However, more recently there have been reports of a higher injury risk with tall vehicles in the US fleet. The SUV vehicle type in the European vehicle fleet is generally intermediate between conventional European cars and these tall US vehicles. As SUVs are not common enough to appear in the European accident data in large numbers, the extent to which they pose an increased risk of causing bonnet leading edge injuries is not known.

Not withstanding the decreased injury risk with modern cars, EEVC WG17 (European Enhanced Vehicle-safety Committee, 2002a) took a decision to retain the bonnet leading edge tests, as future influences on the shape and stiffness of the car front could not be foreseen and the test methods should be applicable to future car designs as well. However, the European Commission proposed test procedures in two phases. The first phase included the bonnet leading edge test only as a 'for information' test. The European Commission is expected to propose that the second phase would again only use it as a 'for information' test. The draft global technical regulation (GTR) developed within UNECE does not include a bonnet leading edge test. The current impactor and test method were described by the GTR group as having a "serious lack of biofidelity". An improved impactor and test method could however be accepted at a future date.

Any development of an improved impactor and test method has to be considered in the above context. Vehicle regulations are becoming increasingly global. It seems unlikely that a legislative bonnet leading edge test (i.e. one with mandatory requirements) would be introduced in any country or region in the future unless it formed part of a UNECE regulation. Therefore, when considering the options for a future test it would be prudent to consider both purely technical issues and the degree to which it might be found acceptable within the UNECE. There would be little point in developing an improved test if it were also considered to be unacceptable. The GTR group is looking towards the IHRA PSWG to lead the work on a future bonnet leading edge test. The PSWG is intending to continue meeting and working despite the disbandment of the IHRA Steering Committee. If the PSWG were to disband also there would be other possible forums for this work, such as ISO WG2 or EEVC WG17. It would therefore be preferable for those working on an improved test to work within PSWG (or alternative forum) rather than attempting to work independently.

One of the bases for future developments should be a thorough understanding of the bonnet leading edge impact dynamics. This is an exceedingly complex impact because of the way different parts of the pedestrian influence the impact. These interactions are also likely to be sensitive to the differences between dummies, PMHS and live pedestrians. It will therefore be very difficult to reproduce a live pedestrian, because of the limited data available. It is suggested that computer models could be a useful tool for understanding the impact and attempting to link back to the live pedestrian. However, truly adequate validation of the computer models would never be possible as there will never be enough data of the right kind. In the authors' opinion a complex but realistic FE model is likely to give a better answer than a relatively simple lumped-mass model. The adequacy of the simplifications in a model should be checked by validation. With a lumped-mass model both the structure and the material properties are simplified. A complex model such as THUMS will be inherently much more realistic in terms of its structure and the behaviour arising from it. Material properties would still be simplified, however, compared with the real-world. It is also recommended that the model used should include muscle tension effects to simulate, to the extent possible, the live pedestrian.

It would be useful to use the above modelling to understand why the current test predicted injury risks in excess of those seen in the accident data. Understanding this would mean that unexpected problems with a replacement test would be less likely. Also, many of the alternatives to the current test have serious disadvantages, so such an understanding may help to avoid the unnecessary exclusion of workable solutions.

Any project to develop an improved bonnet leading edge test should start by considering the scope of vehicles in terms of size and shape that should be tested. Large vehicles and those of different shapes can cause difficulties with the bonnet leading edge test, and in particular with the determination of the bonnet leading edge reference line. These issues will be discussed, in relation to the current test, in Section 7. However, if and when a new test is developed it would be important to ensure that the new test would work with the full range of vehicles that should be tested. This is likely to be particularly true of the lower legform with upper body mass, as taller vehicles are likely to require larger and heavier upper body masses. It should be remembered that while the taller vehicles are a relatively small proportion of the vehicle fleet, it seems likely that they are contributing disproportionably to injuries caused by the bonnet leading edge.

A number of concepts that could be used for a future bonnet leading edge test were presented and discussed previously. These could be divided into four categories.

The first category, in Section 5.5, was improvements that keep the existing impactor and the basic test but that change the test parameters and review the acceptance criteria. These measures might or might not be adequate to solve the basic problem of the high predicted injury risks. However, even if they were adequate it would probably be difficult to persuade the IHRA PSWG to accept them.

The fourth category, a test using computer modelling, is also unlikely to be accepted at the current time, though it might considered in time as techniques improve.

The second and third categories, in the order presented, were tests involving a targeted bonnet leading edge impact and tests involving a combined bumper and bonnet leading edge test. It is worth considering the characteristics of these two categories, as the choice between them represents the ‘top-level’ choice that has to be made:

The tests that target the bonnet leading edge:

- Would involve impactors of similar weight to the current legform impactors, and which could therefore be delivered in a similar manner with the same propulsion systems
- Would require some means of specifying the impactor parameters according to the characteristics of the vehicle, and with the possibility of errors in the derivation of the look-up data
- Would only take account of those parameters of vehicle shape that were built in to the method, and would not take account of the vehicle stiffness at earlier contacts (e.g. bumper, grille)
- Would only require a test for those vehicles that, on the basis of their size and shape, were determined to present a significant potential for injury. Given the recent accident data and assuming the test specified realistic impact energies, with no test below a lower energy limit, most vehicles would probably not be tested.
- Would aim the test onto the prominent bonnet leading edge irrespective of height and thereby represent to some extend the statures and body regions that would be at a higher risk of injury
- Would be able to test very tall vehicles without the kinematics becoming unrealistic

The combined bumper and bonnet leading edge test:

- Would involve much heavier and larger impact devices that would be much harder to deliver and might therefore require the vehicle to be propelled into a stationary device. The cost of repairing the vehicle between tests would probably also increase.
- Would not require complicated impact parameters that varied from test to test, and the correct velocity could not be disputed
- Would automatically take account of the shape and stiffness of the vehicle
- Would have to test the whole front end even if the bonnet leading edge had little potential for causing injury
- Would represent one specific stature that might have a relatively low injury risk at certain bonnet leading edge heights
- Would start to produce unrealistic kinematics on vehicles outside the test's design envelope

It is suggested that at least one option from each category be considered in greater depth before this decision is taken. It could, for instance, be useful to have an estimate of the minimum weight of impactor that would be necessary for the legform with upper body mass option. In view of the difficulties with the current test, the combined test option may have the greater support, as it differs more greatly from the current test. However, this option would also have significant disadvantages such as the difficulty in impacting the test device into the car, or vice versa. No preference between those two categories is expressed here, and neither is a preference expressed for any option within either category.

Lawrence *et al*. (2006) estimated the benefits of the test procedures after the changes proposed by the EC to the phase two requirements of the pedestrian Directive, separately for the changes to each test procedure (see their Table 13.25). For the bonnet leading edge test this represented the complete removal of the EEVC WG17 bonnet leading edge test, as no benefit was assumed from a 'for indication only' test. If the effect of the changes to each test procedure are compared with the effect of changes to all three test procedures together it can be seen that there is little interaction between the estimates, so the potential financial benefit from reintroducing the bonnet leading edge test can be estimated to be about €630 million p.a. in the EU25. However, the changes to the other tests were feasibility adjustments, such as lower protection zones to cover areas where it was difficult to provide higher levels of protection. If similar feasibility adjustments are assumed, and a future improved bonnet leading edge test developed, it might be expected to provide benefits of the order of €500 million p.a. This estimate is based on the accident data used by Lawrence *et al*., which would have included vehicle designs over quite a wide range of years. However, if the trends considered in Section 5.3 are recalled, it is likely that the bonnet leading edges of the latest car designs are causing fewer injuries than those in the accident data, in which case this estimate of potential benefit is likely to be a considerable over-estimate. The increasing proportion of SUVs on the roads of Europe may also have the potential to increase future injuries or lessen the reduction in injuries, with corresponding effects on the potential benefits.

5.8 Conclusions

1. A number of accident studies have reported a considerable reduction in the injuries caused by the bonnet leading edges of cars of modern design.
2. Studies have also reported that the EEVC WG17 upper legform to bonnet leading edge test fails most current cars, effectively predicting high injury risks that are inconsistent with the accident data for recent car designs.
3. The upper legform impactor and the bonnet leading edge test have been criticised by experts for their lack of biofidelity. However, it has not been demonstrated whether poor biofidelity is the cause of the high predictions of injury risk.

4. Proposals were made previously for changes to the upper legform impact energies and to the acceptance criteria. However, it has not been demonstrated that these would be adequate to bring the test results into line with data from accidents involving recent car designs.
5. A number of concepts for a replacement impactor and bonnet leading edge test procedure have been identified and the advantages and disadvantages of each have been discussed.
6. Any replacement bonnet leading edge test should ideally be accepted by international experts, particularly those within IHRA PSWG and the UNECE Informal Group on Pedestrian Safety, before it is used in legislation. Given the difficulties and high cost of developing any alternative impactor or even of revising the test parameters and acceptance criteria, the issue of acceptability should be borne in mind when deciding which option to develop. The relevant working groups should preferably be involved in selecting the option(s) that are further developed.
7. The option involving the least change to the current test would be to review the test parameters and acceptance criteria, while retaining the current upper legform impactor.
   a. Computer modelling should be used to determine the required parameters.
   b. The pedestrian model used should be a very detailed and biofidelic FE model such as THUMS. Ideally this should be further improved by adding muscle tension effects, to simulate live pedestrians, in key parts of the model.
   c. The model should be used to find out which parameters of car shape are best correlated to the impact severity and these should then be used in the test procedure.
   d. The modelling should include a range of pedestrian sizes, as a minimum a 5^{th} percentile female as well as a 50^{th} percentile male.
   e. Modelling should be used to make a direct comparison between upper legform and pedestrian impacts, to check that the new test parameters should give more realistic estimates of injury risk.
   f. Additional accident reconstructions should be carried out to improve the injury risk curves. Ideally, each injury risk curve should be derived using data concerning the appropriate type of injuries.
   g. Changes to the test parameters and acceptance criteria based on such a study may still not be adequate to bring the test results into line with data from accidents involving recent car designs, as the impactor has an inherent lack of biofidelity in certain respects. Also, a test procedure that retains the current impactor may obtain limited support from experts.
8. A number of concepts have been suggested for a replacement and more biofidelic sub-system impactor to test the bonnet leading edge. These options would require a look-up method to obtain the test parameters, similar to the current method; the values would be obtained from computer modelling. These concepts would retain many of the benefits of a sub-system test, such as using a relatively compact and light-weight impactor that can easily be propelled into a vehicle. These concepts could be used to test the prominent bonnet leading edge to protect those statures at greatest risk for any given vehicle height.
9. A number of concepts have been presented for combining the bumper and bonnet leading edge tests, using impact devices ranging from a lower legform with an upper body mass to a full pedestrian dummy. These would impact the vehicle front horizontally at a fixed speed and would then simulate the initial impact in a biofidelic manner to generate automatically the correct impact into the bonnet leading edge. These would all involve a large and heavy impact device such that it might be easier to propel the vehicle into the test device rather than the test device into the vehicle. The test device would represent one specific stature of pedestrian.
10. Another option considered for the bonnet leading edge was a legislative test using computer modelling instead of an impact device. This option is considered to be premature for this test at this time, though it could be an option for the future once such methods have been used in less complex legislative tests.

6 Improved Procedures for Protecting the Head

The IHRA Pedestrian Safety Working Group report (2001) includes pedestrian accident statistics taken from Europe, Australia, Japan and the USA. The report shows that the head is the second most frequently injured body region after the combined region of 'legs', at the AIS 2 to 6 injury level, and accounts for 31.4 percent of the injuries. The bonnet top and wing (17.6 percent), windscreen glass (14.7 percent) and windscreen frame and A-pillars (9.0 percent) together accounted for 41 percent of the injury causing contacts for the 3,305 AIS 2 to 6 injuries from pedestrian accidents that were reviewed by the group. The IHRA report goes on to state that, 'The head is the most common site of fatal injuries to a pedestrian struck by a passenger car, either alone or in combination with one or more fatal injuries to other body regions. For example, in a sample of 145 pedestrians who were fatally injured when struck by a car, 56 percent sustained a fatal brain injury.' Based on this it can be concluded that protection for the head should be given the highest priority for reducing serious and fatal pedestrian accident injuries as very few injuries to the legs are likely to be life threatening.

6.1 Existing test methods

6.1.1 EEVC

The European Enhanced Vehicle-safety Committee (EEVC) pedestrian test methods were first developed by Working Group 10 (EEVC WG10) and then further refined by Working Group 17 (EEVC WG17). The EEVC methods form the basis of the European Directive 2003/102/EC. Essentially the test concerning the level of protection for the head consists of firing a child headform into the front part and an adult head into the rear part of the bonnet top (including the wing tops). The child headform has a mass of 2.5 kg and is fired at a velocity of 11.1 m/s and at an angle of 50 degrees (relative to the horizontal) into the child zone see Figure 6.1. The adult headform has a mass of 4.8 kg and is fired at a velocity of 11.1 m/s and at an angle of 65 degrees (relative to the horizontal) into the adult zone see Figure 6.1. For both the child and the adult, the head protection criteria are for the Head Injury Criterion (HIC) to be ≤ 1000.

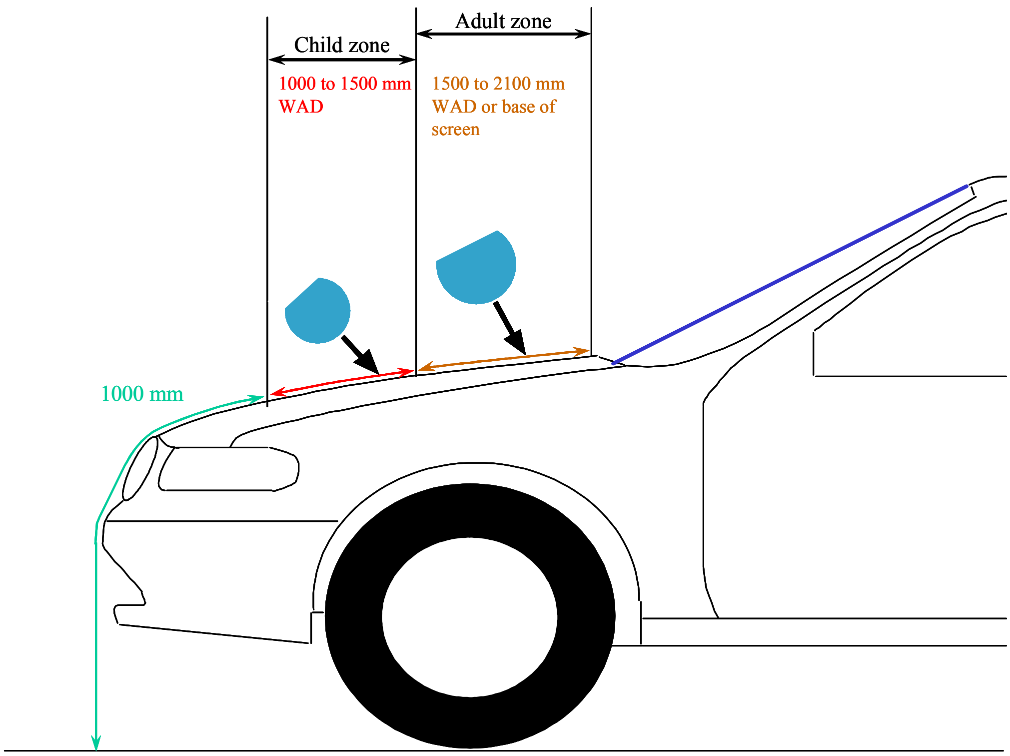


Figure 6.1. The EEVC (WG17) headform test method

The mandate for EEVC WG10 followed by WG17 was to develop test methods suitable for use on the bonnet top, up to the base of the windscreen with a vehicle impact speed of 40 km/h. The windscreen and windscreen frame was deliberately excluded from their mandate despite being the part contacted in many serious and fatal pedestrian head injuries accidents. The reasons for limiting the mandate included:

- The central area of the windscreen was considered safe.
- At that time it was not considered feasible to make the windscreen frame (particularly the A pillars) safe.
- Research had shown that protection effective at 40 km/h vehicle speed was feasible.

6.1.2 ISO, IHRA and Japan MLIT

ISO WG2 has also produced sub-system head test methods which are an adaptation of the EEVC test methods. These ISO headform specifications were used as the basis of the draft International Harmonised Research Activities – Pedestrian Safety Working Group (IHRA PSWG) head test method and the IHRA specification for the 3.5 kg child and 4.5 kg adult headforms is essentially the same as that of ISO, although the test method is different. The Japan Ministry of Land, Infrastructure and Transport (MLIT) with the help of IHRA, the Japan Automobile Manufacturers Association, Inc. (JAMA) and the Japan Automobile Research Institute (JARI, who are also members of the ISO and IHRA working groups) have developed a pedestrian head protection requirement. The Japanese requirement is based on the ISO / IHRA headform specifications.

6.2 Options for improving test methods

To be of benefit, improved test methods must save more pedestrians (prevent injuries or reduce injury severity) than current legislation and to achieve this saving the test methods must be suitable for use in a regulation.

Options to save more pedestrians by providing vehicle based protection (suitable crush depth and stiffness, etc) are to:

- extend the scope
- protect at higher accident speed
- improve the test methods
- improve the test tools
- improve protection criteria

Of the alternative test methods discussed in Section 6.1.2 the approach of the IHRA pedestrian working group is of most relevance to improving savings. This is because they were formed after the work of EEVC WG17 was essentially complete and their aim was to build on and improve existing test methods.

6.3 Scope

Options for extending the scope to cover more types of vehicles are discussed in Section 7. Increasing the scope to cover vehicles not covered by the pedestrian Directive (2003/102/EC), using either the test method specified in the Directive or new improved test methods, will obviously result in additional savings. The potential for additional savings can be seen by reference to Figure 7.1, in Section 7.2.

A further option to increase the scope, not discussed in Section 7, is to require protection on more of the injury-causing areas of vehicles. Currently protection for the head in the European and Japanese regulations starts at the front of the bonnet and finishes at the rear with no protection required behind the rear bonnet reference line. Therefore the windscreen and windscreen frame (including the A-pillars) are not required to have pedestrian protection. However, as can be seen from Table 6.1, out of the total of 824 head injuries in the IHRA sample, 512 or 62 percent are caused by contact with the windscreen glass and windscreen frame (IHRA Pedestrian Safety Working Group, 2001). It is clear that providing protection in these areas could be very effective in reducing serious and fatal head injuries.

Table 6.1: IHRA pedestrian injuries by body region and vehicle contact source – all age groups, AIS 2-6

Contact	Body Region	Head	Face	Neck	Chest	Abdomen	Pelvis	Arms	Legs					Unknown	Total
									Overall	Femur	Knee	Lower Leg	Foot		
Part of the Vehicle	Front Bumper	24	2		3	5	3	6	19	59	76	476	31	1	705
	Top surface of bonnet/wing	223	15	2	139	44	43	86	23	3	1	1	2	1	583
	Leading edge of bonnet/wing	15	2	4	43	78	85	35	50	40	6	30	1		389
	Windscreen glass	344	56	12	30	5	12	23	2			1	1	1	487
	Windscreen frame/A pillars	168	28	5	35	7	14	31	5	1				2	296
	Front Panel	5	1		9	13	7	6	9	14	11	35	3		113
	Others	45	7	1	38	12	13	15	15	9	5	39	18		217
	Sub-Total	824	111	24	297	164	177	202	123	126	99	582	56	5	2790
Indirect Contact Injury		13		17	1	1	7	1		3		1	2		46
Road Surface Contact		171	22	2	22	2	9	42	6	4	3	5	15	1	304
Unknown		27	6	3	19	10	16	25	1	7	9	32	3	7	165
Total		1035	139	46	339	177	209	270	130	140	111	620	76	13	3305

These areas were excluded from the EEVC WG10 and WG17 mandate because no feasible protection measures for the area as a whole were ready for use at the time of introducing the European Directive. However, it is already potentially feasible to provide some improved protection for the top and bottom windscreen frames and the dashboard top; the dashboard top is often the ultimate cause of head injures once the windscreen glass has failed. Even for difficult areas such as the windscreen A-pillars, prototype airbag systems have been shown to be effective. Currently A-pillar airbag systems are not thought to be sufficiently well developed for use. However, rapid progress is likely to be made in resolving the remaining issues which include packaging, coverage, and the development of triggering systems which are reliable and can discriminate between the types of object with which collisions may occur. Therefore consideration could given that test methods for these areas be developed both to aid development of the systems and to be ready for regulatory use when the time is appropriate.

The central area of laminated windscreen glass away from the support frame and underlying structures is normally considered safe at vehicle speeds up to about 40 km/h; however, a test to confirm this would be of benefit. Such a test would also be of benefit for testing underlying components such as the dashboard top. However, before a protection requirement could be placed on the glass itself it would be necessary to show that the properties of the laminated glass are repeatable and that there is a feasible method of adjusting its failure properties to provide the necessary protection.

It should be noted that scope for pedestrian test methods has significant implications on the complexity and possibly the number of tests and test tools needed in a test method. The EEVC pedestrian working group (WG17) in their paper discussing the way forward for pedestrian protection (Lawrence, 2005) discussed a number of pedestrian accident scenarios which could be included in the scope of a test method. For example, side swipe pedestrian accidents might be included as these can result in the head contacting the windscreen frame. As the head impact conditions are influenced by the accident scenario it is important that the scope be decided first and then suitable test methods and tools can be developed to meet it. It can be seen from Figure 7.1 in Section 7.2 that N2 and N3 vehicles cause a disproportionately high number of pedestrian fatalities compared with the number of serious injuries. For these vehicles, although the absolute number of casualties that could be saved might appear comparatively small, a cost-benefit ratio might show protection on these vehicles to be worthwhile. Therefore, it is recommended that a more detailed analysis of accidents statistics should be carried out with weighting applied for the number of vehicles in each category in order to determine a well-focussed scope. In the following sections 6.4, 6.5 and 6.6 it has been assumed that the scope for future test methods would include the windscreen and frame, and would be applied to all M1 vehicles and possibly to all N1 vehicles.

6.4 Protect at higher accident speed

A protection speed can be selected to save the desired proportion of accident casualties using data found in detailed accident studies. It should be noted that this protection or vehicle speed is not necessarily the same as the sub-system headform test speed, as pedestrian kinematics can cause body parts to impact at higher or lower speeds than the initial vehicle speed. The cumulative injury distributions plotted against car impact speed has been found from the IHRA pedestrian accident dataset and is shown in Figure 6.2. The number of casualties that could potentially be saved by a selected protection speed is dependent on a number of factors including the proportion of injuries caused by the tested areas, the injury risk chosen for the protection criteria and the degree of bottoming out of vehicle deformation at speeds in excess of that used in the test. Nevertheless, it is likely that the simplified assumption that all current injuries caused by parts of the car that will be protected in future will be saved in accidents up to, or slightly in excess of, the protection speed required in the test, will produce a reasonable estimate of the potential savings in casualties. Using this assumption the potential injury reduction can be estimated from the IHRA pedestrian accident dataset or similar accident data for cars without pedestrian protection.

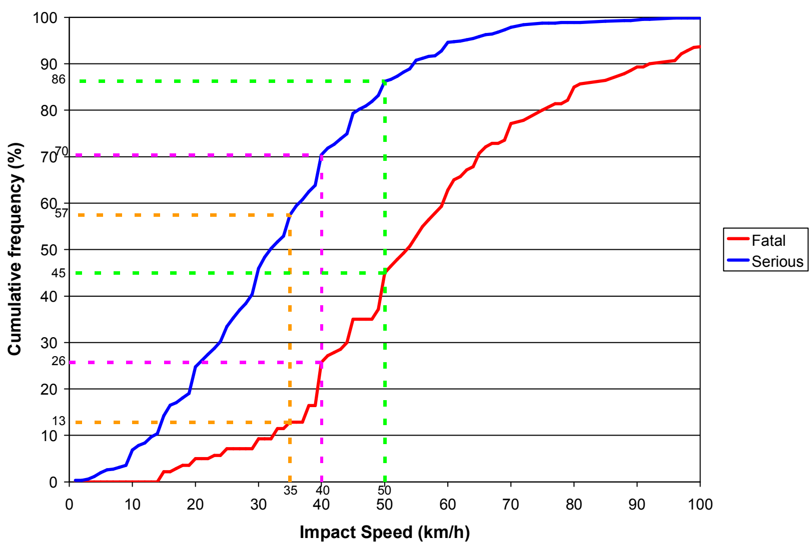


Figure 6.2. Cumulative impact speed distribution, from the IHRA pedestrian accident dataset, by casualty severity, with values for specific vehicle speeds

Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. From Figure 6.2 it can be seen that increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be saved.

6.5 Improved test methods and tools

For regulatory use it is important that the test methods and tools are simple, accurate, repeatable and robust. To achieve this normally requires some simplification and compromise in reproducing the accident conditions in both the test method(s) and tool(s). There are three fundamental approaches that can be used for pedestrian protection test methods:

- physical dummies
- sub-system tests

- mathematical modelling (of pedestrian or impactor and car)

These three methods can be used separately or in combination.

In real life each pedestrian accident is unique in some way so that there are an almost infinite number of real accident situations. For the bumper and bonnet leading edge it might be feasible to use physical or mathematical pedestrian dummies in test methods across the front of the vehicle. The number of dummy statures required for this could probably be limited by considering which were most vulnerable to injury (worst case). When the range of pedestrian statures and other accident variables are taken into account, it can be concluded that the area of the car that can potentially be contacted by the head is so large that that the only feasible test method is one that is based on a sub-system test approach (real or mathematical).

In the EEVC pedestrian test methods, physical headform sub-system tests are required, but mathematical simulation was used by their experts to derive impact conditions for the tests. Similarly a combination of real and computer simulated dummy tests were carried out to obtain impact conditions for the bonnet leading edge test, which were transferred to the test by means of look-up graphs. In the future, a more direct inclusion of mathematical models in regulations is thought to be possible. In a first instance simulation could be used to derive vehicle specific test conditions for each vehicle tested. Later, simulation might be suitable for virtual approval without the need for a physical approval test. However, WG17 has concerns about the feasibility of specifying the necessary expertise needed for this kind of modelling within a robust procedure. It is the view of WG17 that the current standards of simulation and data for validating the models are not yet suitable for virtual approval methods to replace physical testing (Lawrence, 2005).

It is thought very likely that, at some time in the future, virtual testing techniques will have developed to such a standard that they could be used in regulations. However, even then there will be problems over confidentiality of manufacturer's car models, controlling improvements and versions of the pedestrian models and auditing the approval process. Taking both this and the concerns of WG17 regarding virtual approval into account the following sections of this report have been written using the assumption that the next generation of test methods will use physical headform tests, but that the impact conditions used will be based to some extent on computer simulation.

6.5.1 Head impact speed

The impact of a pedestrian with the front of the car (bumper, bonnet leading edge) affects the head trajectory so that the impact is angled and the velocity is likely to be different to the car's forward impact velocity. The relationship between the vehicle velocity and the impact angle and velocity of the head depends on the stature and stance of the pedestrian and on the shape of the car. With a young child the front of the car impacts the child quite high up. If the head is above the bonnet leading edge height the contact will be on the upper body and this high contact will limit the extent to which the body of the child wraps around the car, so that the head impacts at a velocity that could be less than the impact speed of the car. If the child's head is at about the height of the bonnet leading edge then it is likely to be hit directly by the front of the car with an impact velocity close to that of the car. With adults, a whipping-action is possible, potentially giving head impact velocities in excess of the initial car velocity.

The appropriate headform impact speeds and angles to use in sub-system testing have been debated for some time. They should be representative of the impact of a pedestrian's head with the impact area on the vehicle. However, determining these values is difficult.

When discussing the head impact velocity, it is often described by the term 'k' which is the head velocity as a ratio of the vehicle velocity. The relationship is shown in Equation 3.1.

$$v_{HF} = kv \qquad \text{Equation 6.1}$$

where:

v_{HF} = the head impact velocity

k = a constant

v = the vehicle velocity

EEVC WG10 considered many sources of the head impact velocity data including results of PMHS tests, accident reconstructions using pedestrian dummies and mathematical simulations for the adult and child (Glaeser, 1991). For the adult, the consensus of the data they considered indicated a k value of more than 1. This implies that the head hit the car at a higher velocity than that at which the car was travelling. However, taking into account both feasibility and their mandate, which restricted testing to the bonnet only, WG10 selected a 'k' value of 1 for both child and adult (a test speed of 40 km/h). When reviewing the head test methods WG17 considered more recent mathematical simulation results of impacts between 5th percentile adult female, and 50th and 95th percentile adult male pedestrian dummies and three vehicle shapes, small, medium and off-road (Green and Young, 1998). These results showed that at a vehicle impact velocity of 40 km/h the head impact velocity of the 5th percentile was 32 km/h for the small vehicle and 39 km/h for the medium vehicle (k values of 0.79 to 0.97). For the 50th percentile male with a vehicle velocity of 40 km/h the head velocity was 55 km/h for the same two vehicle shapes and for the 95th percentile it was about 60 km/h (k value of about 1.5).

In the child (International Organization for Standardization, 2003a, Annex C) and adult (International Organization for Standardization, 2003b, Annex B) draft ISO headform test procedures the value of 'k' is quoted as being between 0.72 and 0.78 for a child and between 0.7 and 1.4 for an adult. These data apparently come from MADYMO modelling and PMHS testing. The latest adult test procedure from ISO (International Organization for Standardization, 2006) recommends an average 'k' value of 0.75. As justification they provide a range of computer simulation results from two comparatively old studies (1988 and 1993). The combined data give a range of values between 0.4 and 1.1. However, the authors of the 1993 study (Ishikawa *et al*., 1993a) commented that elbow contact reduced head impact velocities (i.e. gave a lower k value) in a number of cases. In the 40 km/h impacts, the impacted hand of the PMHS was tied across the front of the body, whereas in the computer simulation the arms were free, inducing a different head impact with the bonnet. Obviously, in real world accidents a pedestrian's arms will be free.

To help understand the human dynamic and injury-related responses in a car-pedestrian accident, Matsui *et al.* conducted impact tests using the Polar full-scale physical 50th percentile male dummy (Matsui *et al.,* 2002 and Matsui *et al.,* 2005). In these two studies, three different types of vehicle were used for the investigation by Matsui *et al.*; a compact car, a medium size sedan and a SUV. Each vehicle was tested in two positions at the centre of the bumper and in line with the frontal bracket. Matsui *et al.* found that in all of their experiments, the head impact speed was lower than the initial car speed. The mean impact speed for the compact car was 8.9 m/s, for the sedan it was 9.8 m/s and for the SUV it was 8.0 m/s, compared with the initial car speed of 11.1 m/s. This gives 'k' values of 0.8, 0.88 and 0.72 for the compact car, medium size sedan and SUV, respectively.

Two child models (age 6 and 15) were used in an extensive parametric study using mathematical simulation by Liu and Yang (2003). Liu and Yang simulated pedestrian collisions with a vehicle model based on a mid-size passenger car. The vehicle model consisted of four basic elements which represented the bumper, bonnet edge, bonnet top and the windscreen. By altering the geometry of these parts, Liu and Yang studied the effects of vehicle shape and stiffness on the dynamic responses of child pedestrians. A range of collisions, with varying vehicle geometries and an impact speed of 40 km/h, were simulated by Liu and Yang. The results of these simulations showed that the linear impact velocity of the head of the six-year-old child was around 41 km/h (close to the impact speed), whereas the impact velocity for the head of the 15-year-old was around 51 km/h (1.3 to 1.5 times that of the impact speed). Liu and Yang also noted that a higher bonnet-edge height could reduce head injury risk for younger children but may aggravate the impact loads to the heads of older children.

The IHRA working group have also used mathematical simulation results to determine child and adult head impact conditions. The aim of this work is to provide test specifications that include a more complex impact condition relationship between head velocity, vehicle shape and stature or wrap around distance on the car than that adopted by WG10 and WG17. The provisional IHRA head test velocities have come from three different pedestrian impact models, all simulating the same range of vehicle shapes and vehicle impact velocities. These different models produced a wide variation in results even when the same vehicle speed and shape were compared. In order to provide provisional values for the three main vehicle shape categories of sedan plus, SUV and one box (flat fronted vehicles), the simulation results were combined and the mean and the ± one standard deviation values were calculated. The IHRA provisional head impact test conditions can be seen below, in Tables 6.2 and 6.3, for a vehicle impact speed of 40 km/h.

Table 6.2: IHRA Child head impact conditions – mean and ± 1 standard deviation – 40 km/h car impact speed

Shape corridor	Impact velocity (km/h)			Impact angle (°)		
	Bonnet	Windscreen	BLE/Grille	Bonnet	Windscreen	BLE/Grille
Sedan +	30.0 ±4.0	nc	nc	66.0 ±6.3	nc	nc
SUV	27.2 ±1.6	nc	32.0 ±3.6	59.2 ±2.6	nc	22.5 ±4.2
One box	27.6 ±0.8	nc	33.2 ±3.2	49.8 ±1.8	nc	17.4 ±6.1

Table 6.3: IHRA Adult head impact conditions – mean and ± 1 standard deviation – 40 km/h car impact speed

Shape corridor	Impact velocity (km/h)			Impact angle (°)		
	Bonnet	Windscreen	BLE/Grille	Bonnet	Windscreen	BLE/Grille
Sedan +	30.4 ±7.2	35.2 ±6.8	nc	66.0 ±14.0	38.4 ±10.9	nc
SUV	30.8 ±8.8	nc	nc	76.7 ±22.2	nc	nc
One box	nc	29.6 ±3.2	nc	nc	47.3 ±9.6	nc

The IHRA working group (IHRA Pedestrian Safety Working Group, 2005) stated that computer simulations for a child indicated that the head impact speed equals 80 percent of the car impact speed. On the other hand, a physical test using an adult PMHS indicated that the ratio for the head impact speed against car impact speed varies widely between 80 and 150 percent. The values for the head impact speed related to the vehicle impact speed in simulations of a head collision with the bonnet or the windscreen show significantly different results according to the simulation model and vehicle shape used; the average ratio varies significantly from 0.7 to 1.1 according to vehicle shape. Also, there are differences between contacts on the bonnet and contacts on the windscreen, due to the big differences in terms of impact conditions. Based on the PMHS tests and simulation result variations as well as concerns about the biofidelity of the human models used in the computer simulation, the IHRA PS WG could not come to a solid conclusion to use average ratio of head-to-vehicle ratio for all vehicle shapes. However, the IHRA PS group believe that the information generated by this work is the best available information at the present time (IHRA Pedestrian Safety Working Group, 2005). It should be noted that the child velocity in the IHRA paper was found using a model of a six year old. Based on the conflicting data it can be seen that no one ratio of car velocity to head impact velocity is well supported.

A subset of IHRA simulation data was provided to the Japanese MLIT, selected on the basis of rejecting runs where specific problems could be identified such as over penetration of the rigid ellipsoid of the model which results in inappropriate contact forces (wrong magnitude and direction). From the selected subset of simulation data, the mean value for test velocity was taken. As a result, an average ratio value of 0.8 was selected by the Japanese MLIT and when applied to a car velocity of 40 km/h gives the 32 km/h found in their headform to bonnet top regulation.

It might be thought reasonable to use the mean values for the test velocity. However, a mean head velocity is, at best, likely to provide full protection in only 50 percent of the accidents that occur at the selected vehicle speed, and will be insufficient for the remaining higher head speed accidents. In the case of the selected IHRA head velocity data, which were used to determine the Japanese test velocity, there were a few very low velocity values that skewed (reduced) the data. This resulted in a mean head velocity value of 32 km/h for a vehicle velocity of 40 km/h. As a result the velocity of 32 km/h selected for the Japanese test represents less than 50 percent of accidents. The aim of the Directive is to provide effective protection that will produce significant savings in casualties in accidents at 40 km/h. This would not be achieved by using a mean velocity of 32 km/h.

The IHRA work is not yet complete and the current impact conditions are provisional. The wide variation in the results can be seen in the large ± one standard deviation values (Mizuno and Ishikawa, 2001), as shown in Tables 6.2 and 6.3. It is considered that one of the important deficiencies in the three computer models used was the simplified stiff shoulder, which, if it makes contact before the head, could erroneously affect the recorded head impact velocity. Following the study used to generate the above IHRA provisional impact conditions, the IHRA working group selected one of the three models used, the JARI model, as a basis for further developments. Once the model is sufficiently well developed the IHRA aim is to simulate the same matrix of vehicle shapes in order to refine the impact conditions for their headform test method[1]. Neale compared the performance of the IHRA (JARI) model with two other pedestrian models, one a TNO model and the other a modified version of the JARI model which included a revised shoulder (Neale *et al.,* 2003). He compared the performance of the three simulation models when the shoulder was impacted in a similar test to that performed to the shoulders of PMHS subjects and concluded that they all had very poor shoulder biofidelity. Comparing the original JARI pedestrian model with the TNO pedestrian model in simulated vehicle-pedestrian impacts into the same vehicle front, Neale found differences in predicted head impact velocity as high as 14 km/h. More recently Neale developed a shoulder with greater biofidelity for the IHRA computer pedestrian model (Neale *et al.*, 2005). Having evaluated the biofidelity of the improved shoulder, he made further improvements to the model and compared the performance of the original IHRA model with the improved model, in impacts with vehicles of different shapes and sizes. He found that just changing to a shoulder with greater biofidelity increased the head impact speed between 1.2 to 5.1 km/h. Neale also made other changes to improve the vehicle model to give it 'safe' stiffness characteristics. For the simulated vehicle to have 'safe' characteristics, Neale assigned the bumper, bonnet and bonnet leading edge of the model to have a maximum contact load of 4 kN past 0.02 m of contact penetration. The original vehicle model had continuously increasing load with increasing penetration (i.e. 4 kN at 0.02 m up to 20 kN at 0.1 m). The combined effect of the improved shoulder and other improvements gave a change, (increase) in head velocity of up to 10.8 km/h over the original IHRA simulations results.

In light of the findings by Neale *et al.* regarding shoulder biofidelity, it seems appropriate to review the results of Matsui *et al*. using the Polar dummy also (Matsui *et al.*, 2002 and Matsui *et al.*, 2005). The global kinematics of the dummy have been validated against head trajectories from PMHS tests (Akiyama *et al.*, 2001). However, there remains some uncertainty as to whether the link from shoulder and torso through the neck to the head has sufficient biofidelity on which to base head impact velocity and angle requirements. The Polar dummy was based on the THOR frontal impact dummy. The baseline, component-level, performance of the THOR in oblique and side impacts is reported by Rangarajan *et al.* (2000). Rangarajan *et al.* found that in shoulder impact tests, "the shoulder structure is quite stiff and needs improvement in its design." Whilst the THOR shoulder, shown in Figure 6.3, is designed to allow limited motion in the fore-aft direction (forward shrugging), very little lateral compression is expected in the side or pedestrian impact configurations. This will result in a performance that is stiffer than that of the more compliant human shoulder.

[1] It should be noted that the future of the IHRA Pedestrian Safety Working Group is uncertain since the IHRA Steering Committee has been disbanded

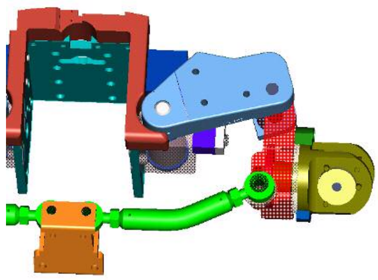


Figure 6.3. THOR shoulder assembly

As suggested by the work of Rangarajan *et al.*, it was noted by Akiyama *et al.* that the resistance of the Polar dummy shoulder was relatively stiff compared with a human. To resolve this stiffness issue, the effective moment of the arm of the main shoulder block was increased during the phase II revisions to the dummy, to allow for greater rotation. This seemed to improve the head kinematics slightly, but will not have addressed the problem completely. With a stiffer shoulder than a human it is expected that the impact of the head with the bonnet top will be less severe than with a softer shoulder. In particular this would be expected to reduce the head impact velocity as is suggested by the mathematical modelling undertaken by Neale *et al.* (2005).

6.5.1.1 Head impact velocity summary

It can be seen that there is a wide variation in head impact velocities found in different studies. There are a number of reasons for the wide range of the final head impact velocities; these include pre-impact positions, stature, vehicle shape and, perhaps most importantly, the more random effects of contacts of arm, shoulder, chest, etc. In dummy and mathematical simulation tests, unrealistically low head velocities are likely to be seen when arm (hand and elbow) and shoulder contacts occur, as these parts are normally far stiffer in dummies than in humans. In PMHS tests the joints are likely to be less stiff and the internal organs less well constrained than a live human, due to lack of muscle tension, which will give different results to real accident cases. However, it is difficult to predict the effects of these differences.

It is clear that both vehicle shape and pedestrian stature will need to be taken into account in a new improved head test method aimed at testing more types of vehicle and the whole area of the vehicle likely to cause serious pedestrian injuries. It is also thought important that vehicles or mathematical models of vehicles used to derive head impact velocity should be pedestrian friendly because, for example, a strong bumper would make a more violent impact than a pedestrian friendly one and the severity of the bumper impact is likely to influence subsequent kinematics. Taking into account the likely scope of an improved test method it is thought that the available data are insufficient to specify head impact velocity. This is due to, amongst other things, limitations in simulation tools used and, particularly for PMHS tests, limited vehicle shape information as well as the vehicles used not being pedestrian friendly. One area where current data are particularly weak is the limited range of statures covered when compared with the real world situation with statures starting from young children through to tall adults.

It is thought likely that, due to the sensitivity of head velocity to stature and vehicle shape, amongst other accident variables, that more than one velocity or ‘k’ value will be needed. These ‘k’ values could be, for example, for a sub-set of pedestrian statures and could be vehicle model specific or could be for a group of vehicles of similar size and shape. It is likely that if other accident variables are taken into account (such as pedestrian position, stance and motion) that for any one vehicle shape and pedestrian stature, that a range of head impact velocities will be found. Initially it might be thought to be reasonable to use the mean velocity values for the test method. However, if the range of head velocities found represents the variations that occurs in real life, then using a mean head velocity is likely to provide full protection in only about 50 percent of the accidents that occur at the selected vehicle speed, and will be insufficient for the remaining higher head speed accidents. Ultimately, the decision on what proportion of accident casualties to try to save is a political matter and should be judged on the basis of a proven cost benefit.

6.5.2 Headform impact angle

The ISO child and adult head test procedures specify an impact angle of 53 degrees for the child and 65 degrees for the adult with respect to the horizontal. However, the simulation data on which the ISO angles are based show a wide variation for impact speed and other variables. These values are given in the form of a series of points in a graph in the ISO procedures. By scaling from a graph in a draft of the child procedure it has been found that the ISO simulations at 40 km/h vary between 68 to 42 degrees. As justification for the adult impact angle, they provide a range of computer simulation results from two comparatively old studies (1988 and 1993). The combined data give a very large range for impact angle (scaling from the graph) of between 48 to 108 degrees. This large range gives little confidence in the data.

The resulting head impact angles from the Polar dummy tests conducted by Matsui *et al.* (2005) fall within the range suggested by the ISO modelling. Respectively for the compact car, the medium size sedan and SUV, the head impact angles are 80, 85 and 94°. As mentioned with respect to the impact velocity and as with numerical simulation testing, the head impact conditions in these dummy tests are dependent on the biofidelity of the dummy components. Whilst there are uncertainties over the biofidelity of the Polar shoulder and taking account of the potential effects of a stiff shoulder, as determined by the modelling of Neale *et al.*, it is possible that these angles may not offer a good representation of those that would be observed in a car and human pedestrian collision.

The provisional IHRA head impact angles are also given in Tables 6.2 and 6.3. For comparison with the Directive phase two requirements, the bonnet of the sedan+ shape category is thought to be most appropriate and this gives 66 degrees (59.7 degrees to 72.3 degrees) for the child and 66 degrees (52 degrees to 80 degrees) for the adult, with the range given in brackets being the mean plus or minus one standard deviation values. However, as already noted, the IHRA work is not yet completed. The current impact conditions are provisional and are based on simulation models that have, amongst other limitations, poor shoulder biofidelity (Neale *et al.,* 2003 and Neale *et al.*, 2005). The MLIT draft head test procedure is based on a subset of the IHRA data. The angles used vary by car type, but for the sedan are 65 degrees for both the child and adult headform impactors.

The EEVC headform test angles, used in phase two of the EC Directive, of 50 degrees for the child and 65 degrees for the adult can be compared with the above angles. It can be seen that the child headform angle lies inside the ISO range for 40 km/h but outside the IHRA ± 1 standard deviation range. The EEVC adult headform angle is the same as the ISO angle for 40 km/h and is only one degree away from the provisional IHRA value. These EEVC values were selected from a combination of full-scale car to PMHS tests and computer simulations. The PMHS tests considered by WG10 (Glaeser, 1991) were all for adults and included initial standing positions of facing sideways, backwards and forwards. The results from these PMHS tests had a modal value of 60 degrees for the head impact angle with the majority of them falling within the range of 50 to 80 degrees. The results from the simulations considered by WG10 gave fairly consistent results for the 50th percentile adult for all car shapes considered, with an average of about 67 degrees (77° relative to the bonnet surface) (Janssen and Nieboer, 1990). So it can be seen, for the adult, that WG10 selected a nominal angle between the results found by simulation and PMHS tests when selecting 65 degrees. For the child, WG10 considered simulation results for a 5th percentile adult female and a 6-year-old child (Janssen and Nieboer, 1990). A 5th percentile adult female is often taken to be equivalent in stature to a 50th percentile 12-year-old child. The simulation results for the 5th percentile female gave similar average values to those found for the 50th percentile adult male. The simulation results for the 6-year-old child showed that the head impact angle was more sensitive to car shape, particularly to the height of the bonnet leading edge; however, an average value of 45 degrees (55° relative to the bonnet) was found. So it can be seen that WG10 used a combination of 6-year-old child and 5th

percentile female simulation results to select the child head impact angle of 50 degrees, with a bias towards the 6-year-old child.

6.5.2.1 Head impact angle summary

The range of results in the ISO, IHRA and EEVC impact angle data described above is most probably due to a combination of different initial conditions and deficiencies in the methods and tools used. Nevertheless they are probably representative of real life variations due to differences in stature, initial standing position (stance), vehicle shape and vehicle to pedestrian interactions. However, the difference in absolute values from the simulations may be due to differences / deficiencies in the biofidelity of the models.

Because of the wide range of results in the above impact angle data it is necessary to consider the sensitivity of the head protection level achieved to this parameter, in order to decide if a fixed or variable test angle is needed in the test method.

The highest level of protection would be required when the impact is normal to the bonnet surface when all the headform's energy has to be absorbed by the structure, and less protection would be required in more oblique impacts. If it is assumed that a wide variation in head angle occurs randomly in real life, then the proportion of the accident population protected would increase as the test angle approached normal to the bonnet surface. It can be concluded that, given sufficient data on head impact angle, that it should be possible to select fixed angles for the child and adult test methods that would be effective in requiring protection for a selected proportion of accidents.

6.5.3 Effective mass

The 'effective mass' is the estimated head mass seen by the car bonnet when striking a whole pedestrian and includes an allowance for the force acting through the neck during the head impact. The ISO WG2 head test method discussed in Section 6.1.2, like the EEVC method, uses two headform impactors, one to simulate the head of a child pedestrian and one for the head for the adult pedestrian. The ISO headform specifications differ from those of the current EEVC WG17 headforms. For the ISO child headform the group concluded that effective mass was the same as the 'static mass' (cut-off mass) of a typical 6 year old child, at 3.5 kg, and they specified a diameter of 165 mm which also matches the diameter of a typical 6 year old child's head, measured about the forehead (this is about the same diameter as the average adult head, but the child face is shorter). However, EEVC WG17 had concluded that the 'effective mass' of the child headform should be 1 kg less than the static mass of a typical six-year-old child, i.e. 2.5 kg (Lawrence (1989) found the equivalent impactor mass to be between 0.93 and 2.83 kg from tests with a six-year-old child dummy). To achieve this lower mass the 130 mm diameter of the EEVC headform is smaller than that of the six-year-old child it represents. For the ISO adult headform the diameter is the same as that of the EEVC adult headform at 165 mm, which matches a typical adult head diameter, but the mass is slightly lower than that specified by the EEVC. Again, ISO concluded that the adult 'effective mass' was the same as the 'static mass' of the average adult and selected 4.5 kg. However, the EEVC had concluded that the 'effective mass' should be more than the static mass of the average adult and selected a mass of 4.8 kg, which includes an 'effective mass' allowance, chosen by WG10 and confirmed by WG17, of 0.3 kg. Other authors have suggested that the effective mass should be even greater; 5.3 kg (Ishikawa *et al.*, 1993b) or between 4.7 and 6.5 kg, depending on vehicle geometry (Lawrence and Harris, 1988).

As with impact speed and angle, the effective head mass can be found using two principle methods; by reconstruction of real or PMHS impacts or by the use of a real or mathematical pedestrian dummy. The EEVC pedestrian working group determined 'effective mass' using mathematical simulations for both the child and adult and, in addition for the adult, they reconstructed PMHS tests. ISO used just mathematical simulations for both headforms to determine 'effective mass'. Any method that uses dummies to determine 'effective mass' is reliant on the biofidelity of the dummy, in particular the neck, shoulders and chest. Unfortunately, these features were unlikely to be sufficiently accurate in the models available to EEVC and ISO. It is questionable whether any current model is of sufficient biofidelity to resolve this issue. Similarly, testing with PMHSs does not account for the muscular contribution to the kinematics. Therefore, the existing means of evaluating the effective masses that sub-system headform tests should use cannot be considered as reliable. However, even with these limitations, examination of pedestrian kinematics tends to support a lower effective mass for the head of small children and a higher mass for adults. It could be argued that EEVC WG10, by reconstructing PMHS head impacts with a 4.8 kg headform and obtaining reasonable agreement in head acceleration and HPC values, showed that the EEVC adult headform is more realistic; however, it is unlikely that the results would be particularly sensitive to small changes in mass.

The discussion on effective mass seems to support the masses selected by EEVC of 2.5 kg and 4.8 kg to represent respectively a six-year-old child and an adult pedestrian. However, if the EEVC decision on headform mass is considered in conjunction with their test method, where the whole ‘child area’ is tested with an impactor representing the effective mass of a six-year-old child, then the appropriateness of the 2.5 kg mass is less clear. This is because the child test area, which lies between the 1000 mm and 1500 mm wrap around lines and the bonnet side reference lines, would in real life be struck by the heads of pedestrians of a range of ages and statures, from approximately four years old up to about twelve years old and will also include some small adults. The static head mass of small adult females (5th percentile) is approximately the same as children of about twelve years old. Robbins estimates the 5th percentile female head mass to be 3.7 kg (Robbins, 1985). The difference between static and effective mass for this group is thought to be small, so 3.7 kg is thought to be an appropriate value for the effective head mass for those pedestrians of statures likely to hit towards the rear of the child zone. Therefore, in real life, the effective head mass is thought to start at about 2.5 kg at the front of the child zone and increase to about 3.7 kg at the rear of the child zone. Based on this, it might be more appropriate for a headform of greater than 2.5 kg to be used in representing the average effective head mass from the range of ages and statures striking the whole child area. Therefore the decision to use a 3.5 kg headform in both the IHRA and ISO child head test procedures appears to be the appropriate for use with the EEVC child test zone.

6.5.3.1 Head effective mass summary

It can be seen from the above discussions that determining an appropriate effective head mass is difficult. As with impact speed and angle, the effective head mass can be found using two principle methods; by reconstruction of real or PMHS impacts or by the use of a real or mathematical pedestrian dummy. However, for effective mass neither method appears to produce a definitive answer due to various limitations in the methods. Obviously, ideally, a head mass should be selected for each wrap around zone that would best protect the majority of pedestrians struck. Because the head can often appear to impact almost independently to the body then one option would be to use the static mass of the head. Considering the extremes of heavy and light effective mass cases, along with what is thought to be the more common head independent of body cases, is thought to support the static mass proposal as follows.

In the ‘normal’ case the bumper and bonnet leading edge impacts would be below the pedestrian’s overall centre of gravity, causing then to pitch at comparatively high speed onto the car. The head would strike the car typically without significant shoulder or arm involvement, so there would be little force in the neck and the head’s effective mass would be close to its static mass. The shoulder is likely to miss the car or collapse easily as it is held in place by a combination of muscles with only the collar bone as a possible rigid support (but only if it is loaded axially). Similarly, if the forearm or upper arm makes contact, it will only provide a significant force in the rare cases where the loading is along the axis of the humerus. Therefore the head protection stiffness should be tuned for the static head mass.

A low effective mass case will occur when there is a significant force in the neck pulling the head away from the car as might happen for example when the bonnet leading edge contacts the upper body of a small child. Similarly for an adult a low effective mass might occur when the shoulder makes a significant contact before the head. In this case the head will strike the bonnet at a comparatively low velocity as it will be held back by the force acting through the neck and will need little protection. Therefore protection tuned for the heavier 'normal' head will be adequate.

A high effective mass case will occur when there is a significant force in the neck pushing the head towards the car as might happen for example when an adult is hit at high speed such that they dive headfirst into the car. In this case the head impact velocity is likely to be high. The effective mass of the head will depend on the compliance of the neck (shortening). A stiff and rigid neck would transmit much of the mass of the body into the head giving it a very high effective head mass. A more compliant neck would give a head mass closer to the static mass, but the neck might be injured after the head impact is essentially over. In real life the neck compliance is likely to be such that the effective head mass is somewhat more than the static mass (during the injurious head impact phase), but far less than the mass seen in some dummy tests where the neck and spine can have virtually no capacity to foreshorten. If a realistic head first effective mass were to be found the car would most probably have to have comparatively stiff pedestrian protection to arrest the head safely. This protection would be inappropriate for the 'normal' cases where the head strikes the car at comparatively high speed with little force in the neck.

Ideally a sensitivity study should be carried out to obtain a better understanding of this complex issue. However, such a study would benefit from a better representation than is currently available of the neck of a live human and possibly also the spine. In the absence of such a study it is recommended that the static head mass is used. If wrap around zones are used to determine test areas and impact conditions for different sub-groups of statures then each zone should use the static head mass that best represents that sub-group of statures. The number of different headform masses needed will depend on the number of stature zones chosen. For example the EEVC test method has one zone for 'child' statures and one zone for 'adults' statures, an improved test method might have more stature zones.

6.5.4 Impact condition discussion

In real life each pedestrian accident is unique in some way so that there are an almost infinite number of real accident situations. When the range of statures and other accident variables are taken into account it can be seen that the area of the car that can potentially contact the head is large. It can therefore be concluded that that the only feasible test method for the head is one that is based on a sub-system test approach (real or mathematical).

It is clear that for a next generation of improved sub-system head test methods it will be important to determine improved impact conditions, in terms of the velocity, angle and possibly effective head mass, to be used. This will be particularly important if the scope is expanded to cover the windscreen and frame and more types of vehicle. The potential expanded range of vehicle shapes and larger test area combined with the range of pedestrian statures and scenarios observed in real accidents means that it is likely that more than two sets of test conditions are needed, as used in the current EC Directive.

As has been described above, there are many sources of information relating to the impact conditions that could be used for headform impactor testing. The data were suitable for producing a first step legislation such as those in Europe and Japan. However, none of the data discussed here are thought to be suitable to produce the next generation of improved head test procedures. This is particularly true when considered alongside an expanded scope which includes more vehicles of different styling and sizes than current regulations and extending the boundary of the test method beyond the rear edge of the bonnet to include the windscreen and frame. Also the make-up of the vehicle fleet in Europe and many other countries has been evolving with more differing styles and sizes of vehicle than in the past. It seems that conventional car-shaped vehicles now make up a smaller proportion of the vehicle fleet, due to the popularity of people carriers and SUVs.

When attempting to determine the impact conditions for sub-system headform testing, existing numerical simulation and physical dummy test results have been shown to provide variable, or unreliable, results. The variability of each test or test series depends on a number of features, both in terms of the set-up for the test (the conditions of the impact) and the limitations of the vehicle and pedestrian dummies used. For instance, it is known that a different stance and stature of pedestrian will produce different impact kinematics. In addition, the interaction of the pedestrian and vehicle representation will be controlled by features such as vehicle geometry and stiffness and the compliance (e.g. rotational and compressive stiffness) of various parts of the pedestrian. In particular, a lack of biofidelity with the mathematical or physical pedestrian dummies, used to date, has been demonstrated. The sensitivity of test tools (human body models and physical dummies) to factors such as pedestrian stance and vehicle geometry will vary with different levels of biofidelity.

PMHS tests overcome some but not all of the deficiencies in mathematical or physical dummies, but to date very little data have been provided on the cars or car representations used to strike the PMHSs in terms of their shape and pedestrian friendliness. A further significant limitation of PMHS data is that they are only available for adults, but in real life children are involved in a large number of pedestrian accidents. The results of a new programme of more appropriate PMHS tests could be transferred into a regulatory test in terms of impact conditions for a sub-system test; however, if the scope includes a wide range of vehicle styles, sizes and a large test area then this would require an unrealistically large test matrix and would need to include a full range of statures including children.

Taking into account the limitations of existing methods for determining head impact conditions it can be concluded that an improved method is needed in order to develop an improved head test method with increased scope. Computer simulation methods appear to be the best tool for this task, but the biofidelity of the pedestrian model must be appropriate and the car models used should be representative and pedestrian friendly. Development of advanced human models is already underway and these appear to offer good potential for determining head impact conditions. Detailed numerical models of the adult human, such as THUMS, are being developed and represent a potential starting point for the next generation of pedestrian models.

One problem for developing appropriate mathematical pedestrian models to represent children is the sparseness of biomechanical information concerning the material properties of children, and the tolerance of children to injury. This makes producing advanced dummies, mathematical models and sub-system test tools representative of a child more difficult than with adult test devices. Due to the lack of child data, scaling of adult numerical simulation models to reflect the physical properties (other than anthropometry) of children will be based largely on estimates of mechanical properties with little supporting data. Additionally there are no test data by which the resulting model can be validated. One assumption often made is that a child mathematical model, made by scaling down an adult, can be regarded as acceptable if the adult version had been validated against the kinematics of a ‘matching’ PMHS to car test (in practice the car model is often only matching in terms of shape and not stiffness). The adult mathematical model is then often considered to be validated if it matches the global kinematics of the PMHS test. However, at around head impact, the head kinematics of the model is often very different to that of the PMHS. Nevertheless, even if the adult model matches both the global and local head kinematics, validation as an adult gives very little confidence that a child model scaled from it will be suitable, unless additional care is taken. This is because for the adult the upper body is not hit directly and realistic biomechanics of the upper body (flexing of the upper body and spine) is not critical, whereas for the child the upper body is often hit directly by the bonnet leading edge and its biofidelity is critical. The lack of information concerning child biomechanics is not limited to the pedestrian testing area and is not new. However, it will remain as an issue and limitation until new data are generated. In the absence of suitable child data it is recommended that only detailed adult models, with an accurate representation of the human upper body, including the spine, shoulder girdle, neck and neck musculature, and so forth, be scaled to represent children.

Accident reconstruction potentially offers a means by which test methods and tools can be validated. This technique has been used to evaluate the appropriateness of the legform and upper legform test methods. However, with headform tests the results of a successful reconstruction are less useful because there is still likely to be uncertainty over the exact vehicle impact speed and whether a test at a different impact velocity and angle, with a different mass of headform, would have produced the same result in terms of dent size and shape.

Assuming that an advanced dummy or human model is accepted as being representative of a living human, of a particular stature or statures, then it remains to decide how best to use that tool. As mentioned with the consideration of impact angles it is possible to fit vehicles to a set of predetermined impact conditions as has been the case with conventional test methods. Otherwise, to account for small geometric and strength changes from vehicle model to model, it may be considered more appropriate to define impact conditions for every new vehicle. These vehicle-specific impact conditions would need to be based on a suite of tests conducted with the advanced and accepted test tool. If a numerical model was used, the input parameters for the simulations would rely on the provision of either a detailed model of the vehicle (from the vehicle manufacturer) or outputs from legform impactor tests and a simplified vehicle model. This second option assumes that the legform impactor(s) has sufficient biofidelity and instrumentation to provide meaningful and useful outputs for this purpose.

Adopting the use of such a technique into a regulatory framework would not be trivial from a logistical point of view. Any advanced test tool would have to be made available for research, vehicle development and regulatory enforcement purposes. For this reason, any releases would have to be closely controlled. Responsibility for that control, by the regulatory body for instance, may be quite onerous. Additionally, as with any potential virtual testing regulation, checking that each manufacturer provides up-to-date and realistic models of the vehicle under assessment should also be of some concern. Some means of checking the accuracy of the model would probably need to be built in to the testing system.

6.5.5 Headform test area

The EEVC headform test methods were restricted to the bonnet top for a number of reasons, including feasibility issues. Accident data show that a large proportion of all serious and fatally injured casualties are due to head injuries caused by contact with the windscreen, windscreen frame, dashboard and roof. Therefore, the IHRA and other groups such as APROSYS have identified these areas as a high priority requiring appropriate test methods and protection criteria.

Kuehn *et al.* (2003) used the MADYMO human body model developed by TNO to investigate differences in pedestrian-car collisions with different vehicle geometries and occupant sizes. They found that at 40 km/h a 50th percentile human model can encounter head impact at Wrap Around Distances (WADs) in excess on 2.1 m.

The IHRA working group have gathered data from in-depth accident studies. Analysis of the data with measured head impact locations showed that the transition from child to adult starts at the WAD of 1400 mm and ends at 1700 mm. Although these data have not been published it is the reason why IHRA had selected this as an overlapping child and adult zone in their test methods (Mizuno, 2003). It can be seen that the child to adult transition WAD of 1500 mm in the EEVC method is almost in the middle of the IHRA child to adult transition zone. The EEVC method has a step change transition from child to adult test areas, which although unrealistic is likely to result in car designs that have a zone around the transition line where the protection is suitable for both child and adult head masses. This method is likely to be appropriate for most vehicles, the only situation where this method will not provide a safe zone for both child and adult is when the transition line coincides with a change in the vehicle structure, such as the joint between the rear of the bonnet and the heater air intake / windscreen base.

Since last reporting the proposed IHRA head test procedures (Mizuno, 2003) the IHRA working group have changed the start point of the child head test zone from 900 mm to 1000 mm to align with other test methods. Therefore the current IHRA zones are:

- for the child zone, start at a wrap around distance of 1000 mm and end at 1700 mm;
- for the adult zone, start at 1400 mm and end at 2400 mm (or up to the top windscreen frame for shorter vehicles). Unlike the EEVC method the IHRA adult test area extends beyond the base of the windscreen up to 2400 mm.

However, the IHRA working group also give the option of a sudden transition between child and adult head test areas.

For the anticipated expanded scope of a new improved head test method the wrap around zones selected by IHRA, based on accident data, appear to be appropriate. There is some debate as to whether the child and adult zones should overlap or have a step change. This may become less important if the scope of a new test method is expanded as it is likely to result in more sub-wrap around zones to reflect different statures and vehicle shapes.

6.5.6 Windscreen

A headform test to the central windscreen area was included in phase one of the Directive, but only for monitoring purposes. This central area is known to be relatively safe for pedestrians. As discussed in Section 6.3, accident data reported in the IHRA Pedestrian Safety Working Group report (2001) showed that the windscreen glass accounted for about 15 percent of the injury causing contacts for the 3,305 AIS 2 to 6 injuries from pedestrian accidents. However, Mizuno and Kajzer (2000) had already shown that, in their study, contact with the windscreen had been the cause for 32 percent of the minor (AIS 1 to 2) injuries from accidents involving cars with conventional shapes (not minivans). These were mainly bruises and lacerations. More severe brain injuries occurred less frequently from contacts with the windscreen unless the impact locations were near to the windscreen frame. Mizuno and Kajzer performed impactor tests using the EEVC adult headform (4.8 kg) and found that indeed the HIC value increased from less than 1000 in the centre of the windscreen towards maxima (sometimes in excess of 5000) at the boundary of the windscreen. Therefore it seems that there would be considerable benefit for pedestrians if the windscreen test were extended to the edge of the windscreen, as a requirement, rather than for monitoring purposes. However, this would also increase the cost of providing protection to pedestrians considerably. The windscreen frame area is now being considered by EEVC WG17 and it is also within the scope of the IHRA PSWG. Issues in providing protection for this area have already been discussed in Section 6.3.

If the windscreen is considered as a valid test area, then the appropriateness of the current headform as a test tool may need to be taken into account. The human head can be thought of, at a simplistic level, as the mass of the brain which is contained (and to a certain extent, constrained) within the deformable and frangible skull, over which lies skin, hair, the muscles of the face, etc. In real head impacts the mass of the brain is 'decoupled' from the skull to some extent by the fluid filled gap (subarachnoid space) between the brain and the skull. Dummy headforms have traditionally taken account of the mass of the head, but the skull part does not incorporate any specific deformation stiffness or frangible components. Nor do they have a mechanism to allow relative brain to skull movements to de-couple the brain mass. As a result the skin or flesh of the headform is the only part of a dummy head that deforms significantly. The stiffness of the head flesh (and sometimes its friction) is used in tuning of the head response to match the human response in drop tests on to a rigid surface.

In 2004, Neale *et al.* modelled a human head (using the University of Louis Pasteur (ULP), Strasborg head model (Willinger and Baumgartner, 2003)) with either deformable brain elements or a rigid skull and brain (Neale *et al.*, 2004). Neale *et al.* found that in simulated drop tests onto a horizontal rigid plate, the different properties with the rigid model could account for resultant impact forces and linear skull accelerations which exceeded those of the deformable model by 16 and 36 percent, respectively. It may be inferred from this that as windscreens are approximately rigid until the initiation of any breakage, that there are implications for comparing the pedestrian headforms with results expected from a human head. It is easy to see how a 16 percent difference in impact force may bridge the impact force required to break the glass and therefore give fundamentally different behaviours. However, there may be more subtle effects which relate to the timing of glass fracture initiation and propagation. These effects are likely to require a significant research effort to determine if this is an issue when testing glass. If windscreen crack initiation is found to be influenced by skull deformation or brain mass de-coupling then a suitable headform specification will have to be found and a headform developed to meet that specification. Without this research it is only possible to say that there is uncertainty as to whether the headform impactor is of sufficient biofidelity to evaluate the risk of injury to a human head from an impact with a windscreen.

In the same paper by Neale *et al.* (2004), a model of a headform with a brain mass that is decoupled from the skull was also evaluated. With this tool, Neale *et al.* found that the resultant impact forces and linear skull acceleration only exceeded those of the deformable head by 2 percent and 3 percent, respectively. This shows the potential for a headform to be developed with greater biofidelity in the dynamic distribution of mass. It is likely that such a tool would be better for evaluating the injury risk from windscreen impacts. However, the prototype Bimass 150 headform (Willinger *et al.*, 2001) developed at ULP for demonstrating the potential benefits of decoupling the mass of the brain is not suitable as a headform impactor in its current state. The Bimass 150 is based on a Hybrid III head with the brain mass decoupled via a flexible contact plug on which it is mounted. This would have to be adapted to give decoupling in at least one other axis of rotation before it would be suitable as a sub-system impactor. Therefore, the development of an advanced physical headform is not a short-term solution.

McGrath *et al.* (2004) investigated the effects of having a rigid or deformable skull in a head model. The simulations were of drop tests onto a flat linear elastic block. This again used the head model from the ULP but in one condition set the skull to be rigid. McGrath *et al.* found that maximum differences in peak von Mises stress amounted to approximately 7 percent of the absolute peak values predicted by the models. McGrath *et al.* commented that the 7 percent difference figure was relatively small when compared with the deviations that can be expected in regular head model predictions. Therefore, one might infer that the ability of the skull to deform has a minor effect on the behaviour of the brain and therefore injury risk. However, one of the limitations of the McGrath *et al.* study was that it was conducted at impact conditions below those expected to produce skull fracture. Skull fracture is a feature of a real skull that is likely to dramatically change the kinematic response during a head impact; the effects of which are still to be quantified.

If it is assumed that the impact of a pedestrian headform with a windscreen is effectively different from that which might be expected from a human head which is frangible / deformable, then any differences in linear head accelerations could affect both the windscreen glass failure mode and the measured head performance criterion (HPC). The human head / skull may deform significantly before reaching the failure level of the windscreen, in which case the duration of the impact would be increased and the HPC decreased. This effect is probably not a significant issue when considering the bonnet top, as the crush of the bonnet would be far greater than the deformation of a head or headform and therefore mask any differences between a human head and a pedestrian headform impactor. However, for the windscreen the lack of deformation offered by the headform may be important to the initiation of windscreen failure and the HPC measured. Therefore, before the current headform is transferred to the windscreen for regulatory use, it is strongly suggested that the appropriateness of using the HPC with a headform, in such conditions, is demonstrated. If it is found that the existing headform designs are not appropriate for use on windscreens, then a more realistic headform will need to be developed for windscreen testing.

It is understood that OICA has reported at a GTR pedestrian protection informal group meeting that there can be large variations in the result when windscreens are tested with a conventional impactor (OICA, 2005). Apparently windscreen panes from the same batch demonstrated two different failure mechanisms in identical tests. One mechanism allowed about 10 mm of bending (in about 1 ms) before the glass fractured whereas the other mechanism allowed up to about 30 to 40 mm deflection before a sudden fracture at around 3 ms. This difference gave very large variations in the amount of energy absorbed by the glass (three times greater for the longer bending and then sudden fracture mechanism) and the HIC value recorded during the test. If tests that are broadly equivalent (i.e. the tests are to the same vehicle at the same impact point) can produce different results, then the performance of the glass itself must be questioned. Furthermore, the variability of glass fitted to vehicles currently in the fleet is likely to be greater if vibration exposure, roadside replacement methods and stone impacts are taken into consideration. This will therefore have implications for the assumed protection of windscreens in the current vehicle fleet.

In a research program of 2002, J-NCAP, in headform tests with un-damped accelerometers, recorded abnormal acceleration signals with high HIC values both in windscreen impacts and also, occasionally, in impacts to the bonnet top. It was estimated that this was due to the resonance vibration of the un-damped accelerometer, which would occur if the impact excited a frequency near to the resonance frequency of the accelerometer. Upon the completion of the J-NCAP pedestrian assessment, JARI studied the cause of the generation of abnormal acceleration and possible solutions (JARI, 2004b). JARI found that the output signal from the un-damped accelerometer showed resonance vibration which, at times, reached 3000 g, exceeding the input range of the amplifier and the channel amplitude class (CAC) which was set at 500 g. When a signal exceeding the set range of the amplifier is input, the amplifier output signal will be distorted. Depending on the amplifier used, the signal may tend towards a positive voltage level, a negative voltage or with some systems, towards the zero level. From their investigation JARI concluded that the self-excited oscillation (resonance) of an un-damped accelerometer can occur not only in windscreen impact tests, but also, on rare occasions, in bonnet impact tests. Therefore, in headform tests, damped accelerometers should be used. Un-damped accelerometers should not be used. If it is unavoidable, then the design of the measurement system for use with un-damped accelerometers should be such that the unfiltered original waveform can be obtained as raw data at a high sampling rate. Then in the case of a problem, it should be possible to check for the generation of excessive acceleration caused by self-excited oscillation (resonance). In certain circumstances it may also be possible to filter the resonance from the underlying signal if the sampling frequency and channel amplitude class is high enough.

Finally, there is the issue as to what the vehicle manufacturers can do to influence the performance of the windscreen. The material properties of the glass will be, to a certain extent, limited by the fabrication process. Therefore, the vehicle manufacturer can only alter effective properties by changing the overall windscreen design, for example, the curvature and angle of the screen. This may lead to feasibility issues or restrictions in vehicle design.

6.5.7 Area around windscreen

For the EEVC WG17, Hardy reported on a study of the benefits of increasing pedestrian protection to cover the windscreen frame (Hardy, 2005). Hardy considered the proportion of impacts reported within the IHRA and APROSYS accident databases where the pedestrian was struck within a speed range where a benefit would be possible. Then he considered the proportion of those pedestrian casualties with an injury to a body region that could have been prevented through the vehicle offering greater protection. Hardy accounted for a proportion of those casualties that would have been strong enough to have benefited from the additional protection. From these considerations, Hardy estimated that the percentages of those casualties still injured by the current test options that could be ‘saved’ by additional protection to the windscreen frame. Compared with the 2005 EC Proposal for phase two of the EU Directive, and assuming a similar level of protection would be offered for the windscreen frame as for the bonnet, Hardy found that the additional windscreen frame protection could save 4.6 percent and 4.3 percent of the serious and fatal casualties, respectively. These estimates were then combined with estimates for the numbers of fatalities and seriously injured casualties occurring within the EU-25 area each year, to estimate the potential numbers of pedestrian casualties that could be ‘saved’ for each test combination being considered. Hardy found that the potential increase in safety of the windscreen frame could save 530 pedestrian fatalities and 10,902 seriously injured casualties each year. These estimates were made assuming the WG17 test methods, including a 40 km/h test speed and HIC ≥ 1000 criteria, were applied to the windscreen frame. Depending on the test speed chosen, which in turn is dependent to some degree on new protection technologies such as A-pillar airbags, there could be a significant benefit to extending the pedestrian head impact protection requirements to include the windscreen frame. Particularly as the estimates made by Hardy may be somewhat pessimistic for Europe, because the accident data he used were somewhat old and the trend towards shorter bonnets in Europe is likely to transfer more head impacts from the bonnet to the windscreen area.

Some inferences about the feasibility of testing the windscreen and surrounding area can be made from a review of the Japanese New Car Assessment Programme results (provided by the National Agency for Automotive Safety & Victims' Aid, NASVA). JNCAP have tested the windscreen and windscreen frame as part of their pedestrian head protection assessment since 2004. The JNCAP tests are conducted at 35 km/h with a 3.5 child or 4.5 kg headform; details of the impact angles used are provided on the NASVA website. The results are published in the form of coloured segments on the bonnet/windscreen areas. These colours relate to different ranges of HIC value, as shown in Figure 6.4.

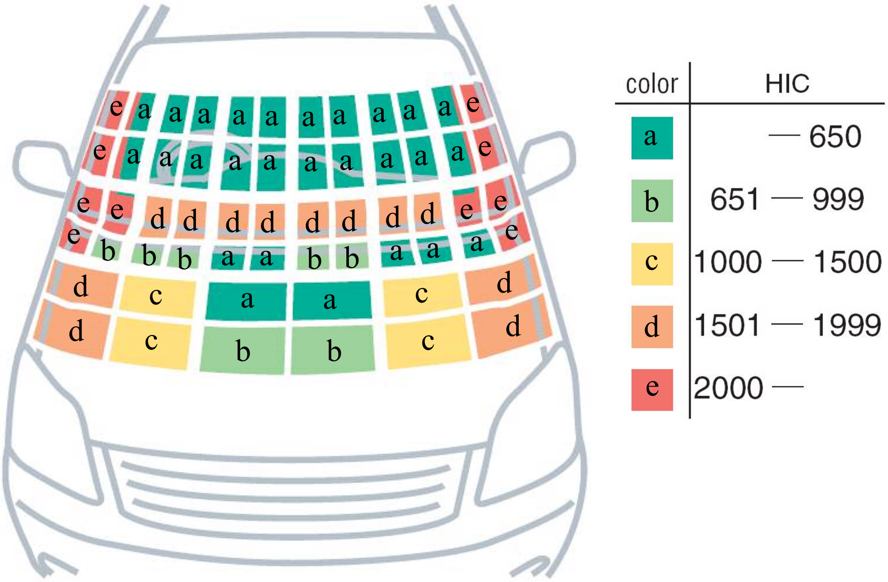


Figure 6.4. JNCAP level scheme for reporting HIC results from headform impact tests (from NASVA website)

From a review of the past test results, it was observed that many of the different classes of vehicle were capable of producing Level 3 (HIC 1000 to 1500) across the base of the windscreen, and in some areas the performance was even better. However, it was also seen that certain vehicle models of each class offered much less protection across the base of windscreen, in some cases with HIC values exceeding 2000.

The area of the frame and windscreen close to the A-Pillar showed the worst performance, with every vehicle resulting in Level 1, or HIC greater than 2000.

For nearly all of the smaller, mini-sized cars, the upper wrap around distance limit of 2100 mm equated to the roof of the vehicle. For impacts to the upper edge of the windscreen, apart from the area adjacent to the A-Pillar, HIC values in the range of 651 to 999 were achieved.

The amount of the actual windscreen glazing that was tested was dependent upon where the upper limit of wrap around distance fell. For the larger passenger cars, this tended only to incorporate the lower edges. For all areas of the windscreen tested, inwards of the supporting frame, the resulting HIC values were shown to fall within the lowest category of HIC <650.

These results show that the centre of the windscreen glazing, as was assumed, is a relatively safe area, as is the roof, away from the A-pillars. It should also be feasible for the base of the windscreen region to be improved to meet the HIC < 1000 requirement, at 35 km/h with some modification. However, the A-pillars themselves and the glazing or roof adjacent to the pillars would require significant modification or deployable pedestrian protection solutions in order to meet the existing regulatory head protection requirements. These test results are based on the assumption that the headform impactor is a suitable test device for evaluating pedestrian protection of the windscreen and windscreen area. However, as discussed above, this assumption needs further consideration.

The possibility of using airbags to protect the A-pillar has been considered (Maki *et al.*, 2003), and these solutions could also be extended to the upper windscreen frame. The results showed that the HIC value from a headform impactor test was less than 1,000 when the A-pillar airbag system was used. This compares favourably with a value of over 6,000 without the airbag system. The A-pillar airbags evaluated by Maki *et al.* were designed to deploy within 40 ms of the bumper colliding with the legs of a pedestrian. Therefore, for conventional impacts a bumper contact switch would be required. However, one of the key benefits of providing A-pillar protection, as described by Hardy (2005) is that casualties involved in a side-swipe or glancing impact could also be saved. For these types of impact the first point of contact will not be with the bumper and therefore some other method of pre-impact pedestrian sensing would be required to activate the A-pillar airbags in time and to avoid unacceptable inappropriate activation. Currently A-pillar airbag systems are not thought to be sufficiently well developed for use now. However, rapid progress is likely to be made in resolving the remaining issues which include packaging, coverage, and the development of triggering systems which are reliable and can discriminate between the type of object with which the collision has occurred. Therefore, it is thought that it is not appropriate to have, at this time, a regulatory test for the A-pillar area. However an agreed test method would be of help in developing A-pillar airbag systems and could be introduced as a regulatory requirement once the airbag and trigger systems are considered ready.

If non-deployable solutions were used to increase the protection (decrease rigidity) in the windscreen frame area, then feasibility issues are expected to arise. For instance, physical requirements for keeping the windscreen steady at high speed and protecting the cabin space in rollover or impacts with large animals (e.g. moose-strike) would be severely compromised.

6.5.8 Certification

To certify the pedestrian headforms according to the technical prescriptions, for use in the EC Directive (Commission of the European Communities, 2004a), the headform must comply with the requirements of an impactor test. The impactor used for these tests is linearly guided, of 1.0 kg mass and has an impact face of 70 mm diameter. The requirements for the different headforms are shown in Table 6.4. The stabilised temperature of the impactors during certification shall be 20° C ±2° C.

Table 6.4: Summary of certification test response requirements for headform impactors (Commission of the European Communities, 2004a)

Impactor and mass	Certification velocity (m/s)	Lower Boundary (g)	Upper Boundary (g)
Child 2,5 kg	7	405	495
Child/small adult 3,5 kg	7	290	350
Adult 4,8 kg	10	337,5	412,5

Conversely, the ISO and Draft GTR headform test procedures specify drop tests to certify the headforms. In these procedures the headform is dropped from a height of 376 mm onto a horizontal steel plate, over 50 mm thick which has a clean dry surface and a surface finish of between 0.2 and 2.0 µm. For the adult headform the peak acceleration response must be 250 ±25 g and for the child headform it must be between 245 and 300 g.

The drop test procedure is more closely linked to biomechanical tests than the impactor procedure and also has the benefit of matching the requirements for the heads of full-body dummies. However, the impact condition, to a hard, rigid surface, causing a short duration impact is not closely matched to the conditions experienced in bonnet top testing. For this reason the impactor test may be better as a certification procedure. Considering the use of the headform impactors to test the windscreen, then the reasoning about the relation of certification impact conditions to vehicle test conditions could potentially be reversed. Therefore, it seems reasonable that for harmonisation, the Draft GTR procedure could be adopted.

Strangely, whilst the Draft GTR has used the same temperature range as the EC Directive (20° C ±2° C), ISO have specified the required temperature as 20 ±5° C. Depending on the material used this range could have a significant effect on the behaviour of the impactor skin and therefore should be reduced in order to increase repeatability and reproducibility of ISO headform tests.

Initially, one manufacturer supplied all the headform skins used for headform testing. Now at least three manufacturers are supplying or offering to supply skins. As the number of skin manufacturers goes up, it is increasingly likely that different materials (or at least different blends of plastic) will be used to fabricate headform skins. The assembled headform is required to meet the certification requirements and this will control the compressive performance of the headform skin. However, in the angled vehicle tests, the shear properties of and friction from the skin are also likely to be important to the measured acceleration output. Shear and friction behaviour is not assessed or controlled currently. Without information on the shear behaviour, is it difficult to estimate whether the potential differences between skin materials is a significant component in test to test variability. It is therefore suggested that this is investigated in a statistical manner.

6.6 Head injury criteria

Serious or life-threatening head injuries are typically due to damage to the brain. These can result from a number of mechanisms including local crushing of the brain caused by blunt or localised skull fracture, or more diffuse brain injuries caused by linear or rotational head acceleration with or without skull fracture.

Many PMHS studies on head impact have been carried out to investigate the mechanical response properties of the head. In general, the impact responses were described in terms of head acceleration and impact force from drop tests onto a flat rigid surface. There are two main issues with measuring head acceleration in these and other impact tests. Firstly, it is not possible to mount an accelerometer at the centre of gravity of the head, and secondly, the head is not a rigid body. Based on experiments from drop tests, impactor tests using PMHS and animals and sled tests with volunteers, the Wayne State Tolerance Curve (WSTC) was developed in the 1950s and '60s. The WSTC is generally considered to be the most important data source with respect to the acceleration of the head (Schmitt *et al.*, 2004). This is despite of the major limitations of: the paucity of data, the position of the accelerometer (mounted at the back of the head), not measuring rotational acceleration and the techniques used to scale the animal data.

HIC, the Head Injury Criterion, was developed to correlate a measure of the average acceleration with the WSTC. The form of HIC used widely now was proposed by the National Highway Traffic Safety Administration (NHTSA) as part of FMVSS 208. The HPC (Head Performance Criterion) specified for use in the pedestrian head impact tests is the HIC evaluated over a 15 ms time interval. As with the WSTC, HIC and the HPC are limited in that they do not take account of rotational acceleration and a further drawback is the lack of a functional relationship with a particular test device (thereby assuming perfect biofidelity, which is not the case).

Most accidents involving impacts to the head are likely to involve a combination of linear and rotational acceleration. In some cases the rotational acceleration component is thought to contribute substantially to brain injury but the relationship between rotational acceleration and brain injury is difficult to quantify. The Generalized Acceleration Model for Brain Injury Threshold (GAMBIT) criterion was proposed (Newman, 1986) on the assumption that a combined load case of translational and rotational accelerations can cause head injury. However, this criterion still lacks validation. Chinn *et al.* (1999) replicated head impacts sustained during real motorcycle accidents while measuring the dynamics of the head. From these tests, Chinn *et al.* developed an injury risk curve plotting head injury AIS against peak resultant rotational acceleration. This showed that AIS 1 head injuries can occur at about 5,000 rad/s^2 and fatal injury, AIS 5 or 6, can potentially occur at 10,000 rad/s^2. It was noted by Chinn *et al.* that from the 13 cases where the motorcyclist sustained a head injury, the rotational acceleration was approximately, 9,000 rad/s^2. This work demonstrates interesting research towards injury criteria that account for rotational accelerations, but further work would be needed to develop robust injury risk functions. In addition, any tool used to evaluate head injury risk will require a tool-specific injury risk function, adding the need for yet further effort.

Another means of accounting for rotational as well as linear acceleration components in injury criteria is to use a numerical simulation of the head impact. The Wayne State University Head Injury Model (WSUHIM) and the NHTSA Simulated Injury Monitor (SIMon) are two computer models that are being developed to investigate head injury (Franklyn *et al.*, 2003). These could be incorporated into a full human body model to investigate injury risk in pedestrian-car collisions, as demonstrated by Dokko *et al.* (2003). Alternatively, the linear acceleration response from a physical test could serve as inputs for the head model; then, from a run of the head model in isolation, outputs relating to injury risk could be taken as the results. However, gaining useful head injury data from either method is reliant on the input to the head being correct. Before this approach could be considered realistically, the issues over the biofidelity of the whole body model and the accuracy of physical test impact conditions would have to be resolved.

Assuming that a suitable measure for assessing injury risk from rotational acceleration components can be developed then it will become important to consider how injury risk could be assessed physically and what protection could be designed into a vehicle. To generate appropriate angular motion components for a sub-system headform impact, it would be necessary to add some simulation of the shoulder and neck interaction. Potentially, this could be through modification of the headform itself to include a 'shoulder' and 'neck'. However, this impactor would need to be validated for use in such an impact configuration. This validation would be even more complicated than that of the conventional headform impactors as the relation between shoulder impact condition to the head impact condition would need to be shown to be appropriate for the necessary range of test conditions. In the case of the conventional headform impactor, the test conditions vary with the geometry of the vehicle being tested. As well as the geometrical aspects the conditions for an impactor incorporating some shoulder element would also be likely to depend on the compliance of the bonnet, underlying structures that may be contacted by the shoulder, friction of the bonnet surface, etc. The justification for the shoulder and head impact conditions would have to come from an extensive suite of numerical simulation runs, making the procedure even more dependent on the behaviour of a human model than the current headform test procedures.

Alternatively rotational acceleration head injury risk could be evaluated as part of whole body dummy impact tests, if a suitable anthropometric test device was available. As with any injury risk assessment device, a dummy-specific injury risk function would have to be developed before this could be adopted into regulatory testing. However, this may represent a longer-term solution.

Once a means of assessing head rotation injury risk is available, then the conceptual response of vehicle designers to reduce injury potential is worth considering. A limit on head rotation acceleration would require the bonnet top to exert a lower rate of change in rotational velocity which could be generated by increasing the duration of the impact. The most effective means of doing this would be through allowing greater deflection of the bonnet top, i.e. more crush depth. This would be the same requirement as that developed from consideration of linear head accelerations. Therefore, it may be that a review of the linear head acceleration criteria would be a simpler solution, resulting in limited head rotation by association.

Based on these considerations, it is concluded that including a rotational brain injury measure in a pedestrian test method suitable for regulatory use and providing protection measures in cars would be a major challenge. In the short-term, the alternative of a head injury criterion based on rotational acceleration is not considered a viable option for a regulatory pedestrian test and would be particularly difficult to use within the sub-system test methods.

Given that for pedestrian sub-system testing a protection criteria based on rotational injury risk is not thought to be feasible, then continuing to use the well accepted HIC is considered to be the best option. One option to improve head protection would be to reduce the protection criteria from the current HIC 1000 used in the Directive. As can be seen from Figure 6.5 HIC 1000 equates to an injury risk of 15 percent. Car manufacturers are known to apply an additional margin of safety on top of regulatory requirements and it is understood that a typical manufacturer's target for head protection is HIC 800, reducing the typical injury risk to about 11 percent. The feasibility of reducing this further is discussed in Section 6.7.

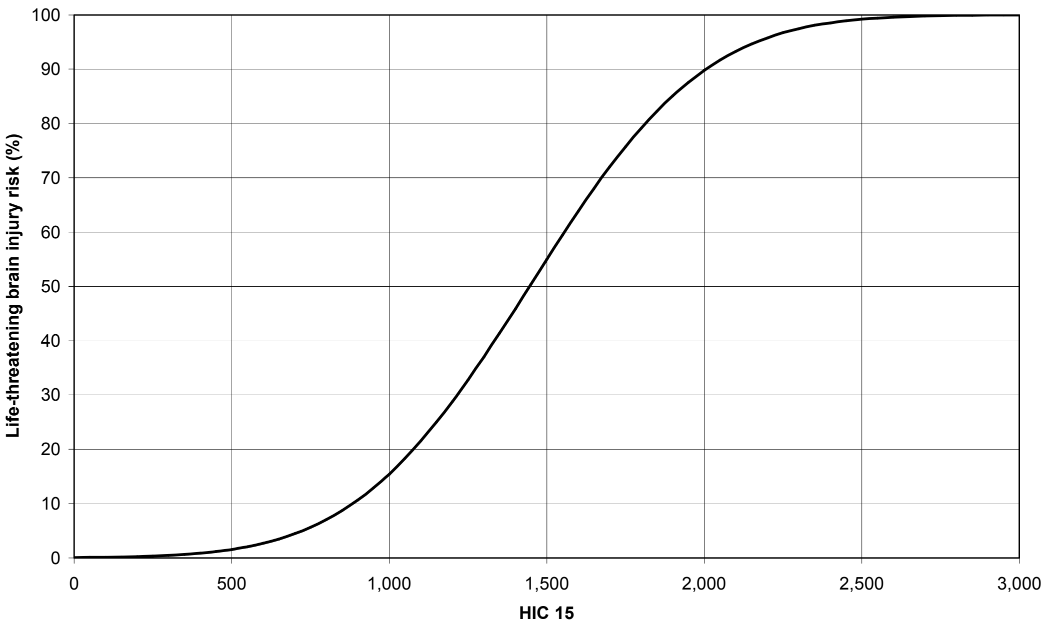


Figure 6.5. HIC injury risk (Derived from Mertz 1993, re-plotted by TRL)

6.7 Feasibility

A number of options for an improved head test method have been suggested for increasing the 'savings'. Expanding the scope to other types of vehicle should in principle not be a feasibility issue, as in essence it will require the transfer of measures already shown to work on cars to similar parts on bigger cars, vans, etc. However, increasing the tested area, protection speed and protection criteria are thought to be most important when considering feasibility for protecting the head.

As already discussed, the main area of concern when expanding the area to include the windscreen frame is the A-pillars. Here it has already been recommended that test methods be developed, but that they are used only in regulations when it has been shown that airbag protection systems are feasible.

Increasing the test speed and improving the head protection criteria will both have implications for feasibility, principally in terms of crush depth, although both will also have some effect on the dynamic stiffness of the structure. It is possible using simple calculations to estimate practical crush depth requirements for various options of speed and protection criteria assuming a manufacturers safety margin of 20 percent, an efficiency of absorbing energy of 80 percent and that only 90 percent of the available crush depth will be usable due to residual crushed material. If test speeds of 35, 40 and 50 km/h are considered along with HIC 1000 and HIC 800 then six estimated crush depths can be calculated for these combinations as shown in Table 6.5.

Table 6.5: Estimated total crush depths required to meet speed and protection options

Speed (km/h)	35		40		50	
HIC (Manufacturer's target in brackets)	1000 (800)	800 (640)	1000 (800)	800 (640)	1000 (800)	800 (640)
Total crush depth (mm)	74	85	105	122	192	223

There is some debate about the level of protection it is feasible to provide in a conventional vehicle structure. Lawrence *et al.* (2002) tested the Honda Civic 2001 version which was the first production car with significant level of pedestrian protection. Below in Figure 6.6 Lawrence's results can be seen from tests at 40 km/h with the EEVC 2.5 kg child headform impactor.

Figure 6.6. Results of testing the 2001 Honda Civic at 40 km/h with a 2.5 kg child headform (Lawrence *et al.*, 2002)

Taking into account that this car was a first production solution and that better results could be expected with a 3.5 kg headform it seems reasonable to conclude that it would be feasible with conventional designs to provide protection effective at 40 km/h to meet a criterion of HIC 1000. Though it may not be feasible with conventional designs to achieve significant protection in excess of this due to the increase in crush depth needed as indicated in Table 6.5, but new protection technologies such as deployable systems (airbags, pop-up bonnets, etc) may well be able to provide the additional crush depth needed for protecting at 50 km/h. Nevertheless, there are likely to be difficult areas in most designs where different features (joints, curves, attachment points, etc.) combine to make the structure too stiff. For these areas it is thought that there will be a continuing need for some relaxation of the protection requirements as included in phase one of the EC Directive.

6.8 Summary / discussion

Accident data gathered by the IHRA Pedestrian Safety Working Group (IHRA Pedestrian Safety Working Group, 2001) show that the head is the second most frequently injured body region after the combined region of 'legs', at the AIS 2 to 6 injury level, and accounts for 31.4 percent of the injuries.

The IHRA report goes on to state that, 'The head is the most common site of fatal injuries to a pedestrian struck by a passenger car, either alone or in combination with one or more fatal injuries to other body regions.' Based on this it can be concluded that protection for the head should be given the highest priority for reducing serious and fatal pedestrian accident injuries as very few injuries to the legs are likely to be life threatening.

To be of benefit, improved test methods must save more pedestrians than current legislation and to achieve this they must also be suitable for use in regulations.

Options to save more pedestrians by providing vehicle based protection (suitable crush depth and stiffness, etc) are to:

- extend the scope
- protect at higher accident speed
- improve the test methods
- improve the test tools
- improve protection criteria

Options for extending the scope to cover more types of vehicles are discussed in Section 7. Increasing the scope to cover vehicles not covered by the pedestrian Directive (2003/102/EC), using either the test method specified in the Directive or new improved test methods will obviously result in additional savings. A further option to increase the scope is to require protection on more of the injury causing areas of vehicles. Currently protection for the head starts at the front of the bonnet and ends at the rear in the European and Japanese regulations. However, IHRA accident data show that 62 percent of head injuries are caused by contact with the windscreen glass and windscreen frame. So it is clear that providing protection in these areas could be very effective in reducing serious and fatal head injuries. These areas were excluded from the European Directive because no feasible protection measures for the area as a whole were ready for use at the time of its introduction. However, it is already almost certainly feasible to provide some protection in all but the A-pillar area of the windscreen. Prototype A-pillar airbag systems have been shown to be effective, but they are not thought to be sufficiently well developed for use now. However, rapid progress is likely to be made in resolving the remaining issues, therefore it is recommended that test methods for these areas be developed to both aid development of the systems and be ready for regulatory use when the time is appropriate.

The central area of laminated windscreen glass away from the support frame and underlying structures is normally considered safe at speeds up to about 40 km/h, but a test to confirm this would be of benefit. Such a test would also be of benefit for testing underlying components such as the top of the dashboard. Before a protection requirement could be placed on the glass itself it would be necessary to show that the properties of the laminated glass are repeatable and that there is a feasible method of adjusting its failure properties to provide the necessary protection.

If the windscreen is considered as a valid test area, then the appropriateness of the current headform as a test tool may need to be taken into account. The current headform design does not account for the deformable and frangible nature of human skull or the decoupling of the mass of the brain (to some extent) by the fluid filled gap between the brain and the skull. This effect is probably not a significant issue when considering the bonnet top; the compliance of the bonnet is far greater than that of a human head or a pedestrian headform and is therefore expected to mask any differences between the impacting object. However, for the windscreen, which is initially rigid, the lack of deformation offered by the headform may be important to the initiation of windscreen failure and the HPC measured. Therefore, before the current headform is transferred to the windscreen for regulatory use, it is strongly suggested that the appropriateness of using the HPC with a headform, in such conditions, is demonstrated and if necessary that a more realistic headform be developed.

It should be noted that the scope for pedestrian test methods has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the head impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.

It can be seen from Figure 7.1 in Section 7.2 that N2 and N3 vehicles cause a disproportionately high number of pedestrian fatalities compared with the number of serious injuries. For these vehicles although the absolute number of casualties that could be saved might appear comparatively small, a cost benefit ratio might show protection on these vehicles to be worthwhile. Therefore, it is recommended that a more detailed analysis of accident statistics be carried out with weighting applied for the number of vehicles in each category in order to determine a well-focussed scope. It has been assumed that the scope for future test methods would at least include the windscreen and frame and would be applied to all M1 vehicles and possibly to all N1 vehicles.

Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. From the IHRA accident data it can be seen that increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be prevented. Although going beyond 40 km/h would probably only be feasible using new technologies such as pop-up bonnets.

There are three fundamental approaches that can be used for pedestrian protection test methods:

- physical dummies
- sub-systems tests
- mathematical modelling (of pedestrian or impactor and car)

These three methods can be used separately or in combination.

In real life, each pedestrian accident is unique in some way so that there are an almost infinite number of real accident situations. For the bumper and bonnet leading edge it might be feasible to use physical or mathematical pedestrian dummies in a test method across the front of the vehicle. When the range of statures and other accident variables are taken into account, it can be concluded that the area of the car that potentially can be contacted by the head is so large that that the only feasible test method is one that is based on a sub-system test approach (real or mathematical).

Whilst whole-body physical dummy testing is not a reasonable alternative to the existing test procedures, it can be used to address potential issues with deployable (pop-up bonnet or airbag) pedestrian protection solutions. Currently, such systems are triggered by bumper contact so the procedure for evaluating them is to test the bumper with a dummy or legform to evaluate the sensor system, then to test the bonnet-top with a headform test. On its own this omits any effects from the interaction between the body of the pedestrian and the bonnet during deployment. Therefore manufacturers are currently combining this with full body testing, either physical or mathematical. However, the deficiencies of current dummies, particularly the overly stiff shoulder make interpreting these results difficult. For this reason, testing with improved, more biofidelic, pedestrian dummies (physical or mathematical) of different statures would offer improved information.

It is thought very likely that at some time in the future, virtual testing techniques will have developed to such a standard that they could be used in regulations. However, even then there will be problems over confidentiality of manufacturer's car models, controlling improvements and versions of the pedestrian models and auditing the approval process. Taking both this and the concerns of WG17 regarding virtual approval into account it has been concluded that the next generation of test methods will use physical headform tests but that the impact conditions used will be based to some extent on computer simulation.

The conditions of the impact between the head of a pedestrian and the bonnet top of a vehicle from a pedestrian-vehicle collision depend on several factors such as: stance and stature of the pedestrian, geometry, stiffness and velocity of the vehicle. The interaction of the pedestrian with the vehicle (e.g. twisting of the body, elbow contact, shoulder contact, whipping of the neck) will also affect the head to vehicle contact. To simulate a pedestrian-vehicle collision, different tools can be used; these are

PMHS tests, physical dummy testing, sub-system tests and numerical simulation. However, these tools will not have perfect biofidelity. Indeed, the behaviour of a living human in a pedestrian accident can only be assumed. Therefore, it becomes important to consider the behaviour that would be expected from a living human subject with respect to what is observed from tests using the alternatives.

To evaluate pedestrian head protection levels for regulatory enforcement, it is generally accepted that sub-system testing represents the most robust solution, particularly in terms of repeatability, reproducibility and cost. However, for the sub-system tests to be representative of the real world situation the impact conditions need to be determined by other means. The IHRA group have chosen to increase the head test area to include the windscreen and windscreen frame. They have therefore conducted a lot of work to determine appropriate impact conditions for their test method. This activity has been based on numerical simulation. However, recent reviews of the human body models that have been used in the simulations have raised concerns over their biofidelity. In particular, the interaction of a stiff shoulder with the bonnet of the vehicle protects the head (reducing the impact velocity) in a manner which would not be expected with a human. These concerns are also true for the pedestrian dummy, Polar, which also has poor lateral shoulder biofidelity. Conversely, one cannot take the results of PMHS tests to be representative of a living human as they lack muscle tone, and as such are less stiff than a living human would be. It is uncertain how this would affect the global kinematics during an impact. It is clear from this review that further work is needed in the area of the dummy pedestrians used in numerical simulation and physical testing.

Advanced human body models could reduce the concerns over the biofidelity of pedestrian models. Numerical simulation could be used with these improved models to generate the impact conditions for improved head test methods (velocity, direction and possibly effective mass). The human models could be used along with appropriate vehicle models to generate impact conditions for a matrix of different pedestrian statures and vehicle shapes. Alternatively, a matrix of pedestrian statures could be run with a mathematical model for each individual vehicle model to be tested to determine tailored impact conditions. This would allow tailoring of the tests to suit each individual vehicle model in the fleet of the various global regions (e.g. Europe) and would automatically adapt to changes in styling and fashion. Before this position is reached, a decision would have to be taken by the relevant expert groups that a particular simulation tool was suitable for this function. Then there would be the question of who would run the simulations before the testing. If this was left to each test house, there may be a level of complexity which required an independent numerical simulation specialist to be present. Alternatively, if the experts at vehicle manufacturers were relied upon the simulated data would probably need to be audited in some way, in order to confirm that consistent techniques and results were being used and generated from manufacturer to manufacturer. Even if these matters were resolved there would still be the problems that different versions of the pedestrian model, different modelling codes and even different hardware would all influence the results. To avoid these issues, it may be better for a suite of simulations to be run covering the necessary vehicle styles and shapes from which look-up tables could be generated for the sub-system tests. This process will also have difficulties associated with it, such as provision of the human body model for research, development and regulatory enforcement purposes as well as provision of vehicle models.

Based on accident data IHRA pedestrian safety group have a child zone that starts at a wrap around distance of 1000 mm and ends at 1700 mm and the adult zone, starts at 1400 mm and ends at 2400 mm (or up to the top windscreen frame for shorter vehicles). Overlapping of these zones will result in an area that is safe for both child and adult head impacts; however, in practice a sudden transition between child and adult will normally achieve a similar effect.

For the anticipated expanded scope of a new improved head test method the wrap around zones selected by IHRA, based on accident data, appear to be appropriate. There is some debate as to whether the child and adult zones should overlap or have a step change, this may be become less important if the scope of a new test method is expanded as it is likely to result in more sub-wrap around zones to reflect different statures and vehicle shapes.

Most accidents involving impacts to the head are likely to involve a combination of linear and rotational acceleration. In some cases the rotational acceleration component is thought to contribute substantially to brain injury, but the relationship between rotational acceleration and brain injury is difficult to quantify and to date there are no well supported injury risk functions.

Assuming that a suitable measure for assessing injury risk from rotational acceleration components can be developed then it will become important to consider how injury risk could be assessed physically and what protection could be designed into a vehicle. To generate appropriate angular motion components for a sub-system headform impact, it would be necessary to add some simulation of the shoulder and neck interaction. Potentially, this could be through modification of the headform itself to include a 'shoulder' and 'neck'. However, this impactor and test method would need to be validated for use in such an impact configuration.

Alternatively rotational acceleration head injury risk could evaluated as part of whole body dummy impact tests, if a suitable anthropometric test device was available. As with any injury risk assessment device, a dummy-specific injury risk function would have to be developed before this could be adopted into regulatory testing. Therefore, this may represent a longer-term solution.

Once a means of assessing head rotation injury risk is available, then the conceptual response of vehicle designers to reduce injury potential is worth considering. A limit on head rotation acceleration would require the bonnet top to exert a lower rate of change in rotational velocity which could be generated by increasing the duration of the impact. The most effective means of doing this would be through allowing greater deflection of the bonnet top, i.e. more crush depth. This would be the same requirement as that developed from consideration of linear head accelerations. Therefore, it may be that a review of the linear head acceleration criteria would be a simpler solution, resulting in limited head rotation by association.

Based on these considerations, it is concluded that including a rotational brain injury measure in a pedestrian test method suitable for regulatory use and providing protection measures in cars would be a major challenge. In the short-term, the alternative of a head injury criterion based on rotational acceleration is not considered a viable option for a regulatory pedestrian test and would be particularly difficult to use within the sub-system test methods.

Given that for pedestrian sub-system testing a protection criteria based on rotational injury risk is not thought to be feasible, then continuing to use the well accepted HIC is considered to be the best option. One option to improve head protection would be to reduce the protection criteria from the current HIC 1000 used in the Directive. Car manufacturers are known to apply an additional margin of safety on top of regulatory requirements and it is understood that a typical manufacturer's target for head protection is HIC 800, reducing the typical injury risk to about 11 percent.

New protection technologies such as deployable systems (airbags, pop-up bonnets, etc.) may well be able to provide the additional crush depth needed for protecting at 50 km/h. Nevertheless, there are likely to be difficult areas in most designs where different features (joints, curves, attachment points, etc) combine to make the structure too stiff. For these areas it is thought that there will be a continuing need for some relaxation of the protection requirements as included in phase one of the EC Directive.

6.9 Conclusions

1. Accident data show that protection for the head should be given the highest priority for reducing serious and fatal pedestrian accident injuries.
2. To be of benefit, improved test methods must save more pedestrians than current legislation and to achieve this they must also be suitable for use in regulations.
3. Options to save more pedestrians by providing vehicle based protection (suitable crush depth and stiffness, etc) are to: extend the scope, protect at higher accident speed, improve the test methods, improve the test tools and improve protection criteria.

4. Increasing the scope to cover vehicles not covered by the pedestrian Directive (2003/102/EC), using either the test method specified in the Directive or new improved test methods will obviously result in additional savings.
    a. A further option to increase the scope is to require protection on more of the injury causing areas of vehicles, including the windscreen. Accident data show that providing protection in these areas could be very effective in reducing serious and fatal head injuries.
    b. These areas were excluded from the European Directive because no feasible protection measures for the area as a whole were ready for use at the time of its introduction. In future, protection here may become feasible.
5. Although the central area of laminated windscreen glass away from the support frame and underlying structures is normally considered safe, a test to confirm this would be of benefit and can also be used to test underlying components such as the top of the dashboard, which are likely to cause serious head injuries if too rigid.
    a. Before a protection requirement could be placed on the glass itself it would be necessary to show that the properties of the laminated glass are repeatable and that there is a feasible method of adjusting its failure properties to provide the necessary protection.
    b. Because the windscreen is initially rigid, until cracking is initiated, then it may be more sensitive to headform properties than deformable components like the bonnet top. As the headform does not take account of the deformable and frangible nature of human skull or the decoupling of the mass of the brain then it may not cause realistic crack initiation in the windscreen. Therefore head injury criterion results from windscreen impact tests may not be appropriate.
6. It should be noted that the scope for pedestrian test methods has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the head impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.
7. N2 and N3 vehicles cause a disproportionately high number of pedestrian fatalities compared with the number of serious injuries. Therefore, consideration should be given to including these vehicles along with all M1 vehicles and possibly all N1 vehicles in the scope for future test methods.
8. Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. Accident data show that increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be prevented. However, going beyond 40 km/h would probably only be feasible using new technologies such as pop-up bonnets.
9. In real life, each pedestrian accident is unique in some way so that there are an almost infinite number of real accident situations. When the range of statures and other accident variables are taken into account, it can be concluded that the area of the car that potentially can be contacted by the head is so large that that the only feasible test method is one that is based on a sub-system test approach (real or mathematical).
10. Currently, deployable (pop-up bonnet or airbag) pedestrian protection solutions are triggered by bumper contact. Whole-body physical dummy testing will be useful in testing the trigger and the interaction between the body of the pedestrian and the bonnet during deployment. However, the deficiencies of current dummies, particularly the overly stiff shoulder make interpreting these results difficult. Testing with improved, more biofidelic, pedestrian dummies (physical or mathematical) of different statures would offer improved information.
11. It is thought very likely that at some time in the future, virtual testing techniques will have developed to such a standard that they could be used in regulations. However, even then there

will be problems over confidentiality of manufacturer's car models, controlling improvements and versions of the pedestrian models and auditing the approval process. Therefore, it is recommended that the next generation of test methods will use physical headform tests but that the impact conditions used will be based to some extent on computer simulation.

12. To simulate a pedestrian-vehicle collision, different tools can be used; these are PMHS tests, physical dummy testing, sub-system tests and numerical simulation. However, these tools will not have perfect biofidelity. Therefore, it becomes important to consider the behaviour that would be expected from a living human subject with respect to what is observed from tests using the alternatives.

13. To evaluate pedestrian head protection levels for regulatory enforcement, it is generally accepted that sub-system testing represents the most robust solution, particularly in terms of repeatability, reproducibility and cost. However, for the sub-system tests to be representative of the real world situation the impact conditions need to be determined.

    a. The IHRA group have chosen to increase the head test area to include the windscreen and windscreen frame. They have therefore conducted a lot of work to determine appropriate impact conditions for their test method. This activity has been based on numerical simulation.

    b. Recent reviews of the human body models that have been used in the simulations have raised concerns over their biofidelity. In particular, the interaction of a stiff shoulder with the bonnet of the vehicle protects the head (reducing the impact velocity) in a manner which would not be expected with a human.

    c. These concerns are also true for the pedestrian dummy, Polar, which also has poor lateral shoulder biofidelity.

    d. Conversely, one cannot take the results of PMHS tests to be representative of a living human as they lack muscle tone, and as such are less stiff than a living human would be. It is uncertain how this would affect the global kinematics during an impact.

    e. It is clear from this review that further work is needed in the area of the dummy pedestrians used in numerical simulation and physical testing.

14. Advanced human body models could reduce the concerns over the biofidelity of pedestrian models. Numerical simulation could be used with these improved models to generate the impact conditions for improved head test methods (velocity, direction and possibly effective mass).

    a. These human models could be used along with appropriate vehicle models to generate impact conditions for the headform.

    b. Before this position is reached, a decision would have to be taken by the relevant expert groups that a particular simulation tool was suitable for this function.

    c. Alternatively, a matrix of pedestrian statures could be run with a mathematical model for each individual vehicle model to be tested to determine tailored impact conditions.

        - However, in practice this might prove very difficult.

    d. To avoid these issues, it may be better for a suite of simulations to be run covering the necessary vehicle styles and shapes from which look-up tables could be generated for the sub-system tests. This process will also have difficulties associated with it, such as provision of the human body model for research, development and regulatory enforcement purposes as well as provision of vehicle models.

15. Accident data show that child head impacts start at a wrap around distance of about 1000 mm and end at 1700 mm and for adults head impact starts at about 1400 mm and ends at 2400 mm. For a test method overlapping of the child and adult zones will result in an area that is safe for both child and adult head impacts.

16. There is some debate as to whether in a test method the child and adult zones should overlap or have a step change. This may be become less important if the scope of a new test method is expanded as it is likely to result in more sub-wrap around zones to reflect different statures and vehicle shapes.

17. Most accidents involving impacts to the head are likely to involve a combination of linear and rotational acceleration. However, in practice, it is not thought feasible to include this in a test method and, in real life, it may not be important as the solutions for a linear acceleration criterion will also be effective in reducing rotational acceleration.

18. Given that for pedestrian sub-system testing a protection criteria based on rotational injury risk is not thought to be feasible, then continuing to use the well accepted HIC is considered to be the best option. One option to improve head protection would be to reduce the protection criteria from the current HIC 1000 used in the EC Directive. However this option is not thought necessary given that car manufacturers are known to apply an additional margin of safety on top of regulatory requirements.

19. In the authors' opinion it is feasible, with conventional designs, to provide protection effective at 40 km/h to meet a protection criterion of HIC 1000. It may not be feasible with conventional designs to achieve significant protection in excess of this due to the increase in crush depth needed.

    a. However, new protection technologies such as deployable systems (airbags, pop-up bonnets, etc.) may well be able to provide the additional crush depth needed for protecting at 50 km/h.

    b. Nevertheless, there are likely to be difficult areas in most designs where different features combine to make the structure too stiff. For these areas it is thought that there will be a continuing need for some relaxation of the protection requirements as included in the EC Directive.

7 Scope

7.1 Introduction

Accidents to vulnerable road users (VRU - pedestrians and pedal cyclists) occur with a wide range of accident conditions. When the pedestrian test procedures were developed, decisions were taken about the specific accident situations that were to be simulated by the specified test procedures. It was also decided to use sub-system tests rather than a dummy-based test method. Two critical advantages of sub-system tests are that they are more repeatable and that, for each pedestrian body part concerned, one or two impactors can be used to test the whole area of the vehicle likely to be involved with that body part in real-life accidents involving a range of statures. However, sub-system tests require a number of simplifications and assumptions to be made. These tend to result in test methods that are only appropriate for certain styles and sizes of vehicles. For a specific class of vehicle, provided that changes in size, shape and construction do not go outside the range suitable for the sub-systems methods then the simplifications and assumptions will be appropriate. It will also be acceptable if the test methods are somewhat less appropriate for a small category of vehicles within the fleet covered by the scope, provided that they still provide some benefit. However, changes to the scope, construction methods, styling fashions and changes to the fleet make-up can all influence the suitability of the test methods. The EEVC pedestrian test methods appear to be reasonably robust in this matter. However, the issue of high bumpers, for example, has become far more important in Europe due to the increasing proportion of large off-road type vehicles in the vehicle fleet. Increasing the scope of a pedestrian protection regulation, to include larger vehicles, will affect the appropriateness of the test methods, tools, mark-up rules, and so forth.

The closer a real-world accident matches the simulated accident the better the test procedures will be at predicting the real-world injury. However, it must always be accepted that only a few accidents can be simulated and that the test procedures are therefore being used to imperfectly represent a much wider range of accidents. Vehicles designed to pass legislative test procedures will probably be optimised to pass these tests and therefore the protection provided to VRU should be optimised for these accidents, assuming appropriate acceptance criteria. Lower levels of protection are generally likely to be provided in accidents not matching the simulated accident so well, though being hit at a lower speed is of course normally advantageous.

One of the main variables in VRU accidents is the type of vehicle involved. VRU are hit by and / or hit every type of vehicle on the road. When the current legislative test procedures were planned a decision was taken about the vehicle type that they were intended for, i.e. cars. Inevitably the test procedures were developed with a focus on typical cars of the period. There are certain features of the test procedures that are intended to allow them to work over a wider range of cars, but other features, such as the design of the impactors (representing the 50th male stature), are broadly fixed for all vehicles. Also, the style of a typical car has changed since the test procedures were first designed, as has the mix of different car types. The test procedures are less appropriate for some car types than others. When other types of vehicle are considered the test procedures tend to become even less appropriate.

When the scope of test procedures is decided or reviewed, therefore, a decision has to be taken on the scope of the test procedures, based partly on how useful the test procedures would be in preventing injury and deaths of VRU. Other factors will be taken into account, both technical and political. As well as the potential benefits of an increased scope the increased costs have to be considered.

The EC's current test procedures (Directive 2003/102/EC) were developed by European Enhanced Vehicle-safety Committee (EEVC) Working Groups 10 and 17 (WG10 & WG17). These were therefore developed around the characteristics of the European vehicle fleet. However, there have more recently been worldwide discussions, under the United Nations Economic Commission for Europe (UNECE) that have led to a draft of a global technical regulation (GTR) on protecting VRU. The intention is that the EC legislation and the UN GTR would be harmonised. Therefore, while this report is for the EC, it is necessary to consider both the European and world-wide contexts when considering issues of scope. It is understood that different jurisdictions could apply the GTR test procedures to a different scope of vehicles; however this would partially negate one of the primary benefits of a GTR, of having common standards for the benefit of trade and industry.

This section of this report will consider issues of an increased vehicle scope in more detail. While some parts might be generally relevant to any vehicle type, special emphasis will be made to those vehicle types and weight limits that are being considered in the current discussions on scope. Another aspect of 'scope', the possible extension of the test area to the windscreen and windscreen frame, was considered in Section 6. This current section, however, only considers the extension of the vehicle scope to the current test area.

The current European legislation for VRU (Directive 2003/102/EC) applies to M1 vehicles and to N1 vehicles that are derived from M1 vehicles, in both cases to vehicles of a maximum mass not exceeding 2.5 tonnes. Category M vehicles are passenger carrying vehicles (with four or more wheels), whereas category N are goods vehicles. M1 vehicles are those seating up to eight passengers and a driver, with no upper weight limit. N1 vehicles are goods vehicle with a maximum mass not exceeding 3.5 tonnes. M1 vehicles are therefore essentially cars, including large cars such as SUVs. However, exceptionally, this category can include much larger vehicles such as a coach with most of the seats removed, or vehicles such as a camper van built on a goods vehicle chassis. The N1 vehicles are for the most part small vans, and the ones covered by the current legislation are those that are a van variant of a car model. (N1 vehicles are mostly vans in Europe but elsewhere, where pick-up trucks are popular, the description 'light trucks and vans' (LTVs) is often used. References here to 'vans' are not intended to exclude pick-up trucks.)

It is worth noting at this point that the term 'maximum mass' is not a well defined term or a measurable quantity. The 'maximum mass' is defined by the vehicle manufacturer and is the maximum weight of the vehicle that may be used on the road, including the maximum load the vehicle may safely carry. The vehicle would have to be engineered to be safe at the declared maximum mass, and the manufacturer would have regard to other issues such as insurance costs, driving licence requirements and other marketing considerations. Gross vehicle weight (GVW) is another expression of similar meaning to 'maximum mass'.

The current draft of the GTR (Informal Working Group on Pedestrian Safety, 2006) has a similar scope (referred to there as 'application'). However, the UNECE uses different vehicle categories. The scope is vehicles [gross vehicle mass 0.5 to 2.5 tonnes] of category 1-1 and category 2 having the same general structure and shape forward of the A-pillars as a pre-existing category 1-1 vehicle (weight limit applies to both categories). The 'square brackets' reflect the fact that the weight range is still being discussed within the UNECE. Category 1 vehicles are power driven vehicles with four or more wheels designed and constructed primarily for the carriage of people. Category 1-1 vehicles can have seats for up to eight passengers and a driver, with no upper weight limit; they cannot have standing passengers. Category 2 vehicles are power driven vehicles with four or more wheels designed and constructed primarily for the carriage of goods. It can be seen that in almost all cases category 1-1 is equivalent to M1, and similarly category 2 with N. The phrase concerning the 'same general structure and shape' is presumably going to be interpreted in practice much the same as 'derived from'. The only significant difference in scope between the EC Directive and the draft GTR is therefore the lower mass limit of 0.5 tonnes GVW. Even then, the practical effect in Europe will be insignificant, as there will be virtually no European M1 vehicles that would have such a low mass.

The current discussions on vehicle scope are essentially about two issues:

- Should the scope be extended to heavier vehicles?
- Should all vans be included or only those derived from cars?

There are currently three proposals 'on the table' for extending the vehicle scope specified in the draft GTR (documents are available from the UNECE website, Informal Group on Pedestrian Safety):

- The EC has proposed (Expert from the European Commission, 2006) that the upper weight limit be removed for category 1-1 vehicles, and that the lower limit be an *unladen* mass of 0.5 tonnes. Also, category 1-2 vehicles (those carrying more than eight passengers and a driver) would be included if they had the same shape and structure as a category 1-1 vehicle. Both these and the category 2 vehicles would be for vehicles not exceeding 2.5 tonnes *unladen* mass.

- The USA has proposed (Expert from the United States of America, 2006) that all category 1-1, 1-2 and 2 vehicles should be covered by the GTR test procedures. However, the intention is that jurisdictions would then limit the scope of their requirements as each decided, so most or all jurisdictions would apply a legislative vehicle scope that was less extensive than this.
- Japan has proposed (Expert from Japan, 2006) that the scope be extended to all vehicles up to 3.5 tonnes in categories 1-1, 1-2 and 2 that have the same shape and structure as a category 1-1 vehicle weighing up to 2.5 tonnes (with the 0.5 tonne minimum limit in both cases).

The scope options for the GTR are not necessarily the options that would be considered for legislation in the European Union and elsewhere. Within the EU the following options might be considered, though this may not be a complete list:

- M1 vehicles up to a higher weight limit, such as 3.5 tonnes GVW
- M1 vehicles up to a unladen weight limit, such as 2.5 tonnes
- M1 vehicles with no weight limit
- N1 vehicles derived from or of similar size and shape to M1 vehicles
- N1 vehicles of similar general shapes to cars
- All N1 vehicles

The test procedures used in the EU are based on those developed by EEVC WG10 and then WG17. Their mandate was to develop test methods for the fronts of cars; hence the main focus on vehicles during the development of the test procedures was on typical cars. At the start of the process, SUV type vehicles were much less common than they are currently. At a relatively late stage WG17 recognised that the lower legform test would not work as intended on vehicles with high bumpers, such as SUVs. A number of options were considered, but they decided to add an alternative high bumper test that used the upper legform impactor. In their final report (European Enhanced Vehicle-safety Committee, 2002a), the issue of the scope of vehicles that could be tested by the procedures (with the added high bumper test) was not addressed. The EEVC test procedures themselves (in the form of a draft Directive) give the scope as M1 vehicles and N1 derived from M1 vehicles, with no weight limits (N1 is limited by definition to 3.5 tonnes but M1 is unlimited).

A draft Directive of March 2001 specified the scope as M1 and N1 derived from M1 vehicles, both with a 2.5 tonnes limit on total permissible mass. This was then carried through to the EC Directive (2003/102/EC). The authors are not aware of the basis on which this limit was selected.

Another international working group is the International Harmonized Research Activities (IHRA) Pedestrian Safety Working Group (PSWG). They also did not seem to have taken a clear decision on scope. The 2005 draft of their lower legform test procedure does specify category 1-1 vehicles of up to 2.5 tonnes GVM (presumably Gross Vehicle Mass) but their draft headform test procedures of the same date do not specify a vehicle scope. The IHRA Steering Committee no longer meets and therefore it is uncertain how this working group will function in the future.

In the following sections the accident data will be considered. Then vehicles that could be affected by an increase in the scope of the pedestrian test requirements will be categorised and the effect that their size and shape has in pedestrian accidents will be summarised. The way that the current test methods would work on these vehicles will then be considered and where necessary changes to the test procedures will be suggested. The literature review that was carried out only found papers that were relevant to the accident and injury data section so the literature review is within that section.

However, some other work by the IHRA PSWG and others is also relevant and this will be considered in the following sections.

7.2 Accident, vehicle and injury data

Pedestrian accident data for Great Britain are shown in Figure 7.1, broken down by vehicle type. The injury severity categories ‘fatal’ and ‘serious’ are those used in the British Stats19 data and relate to injuries resulting in death within 30 days and non-fatal Abbreviated Injury Scale, AIS2+ injuries, respectively. It can be seen that goods vehicles of both weight categories are over-represented in fatal accidents, compared to the proportions in serious accidents. SUVs cannot easily be identified in the accident data and are included here under cars.

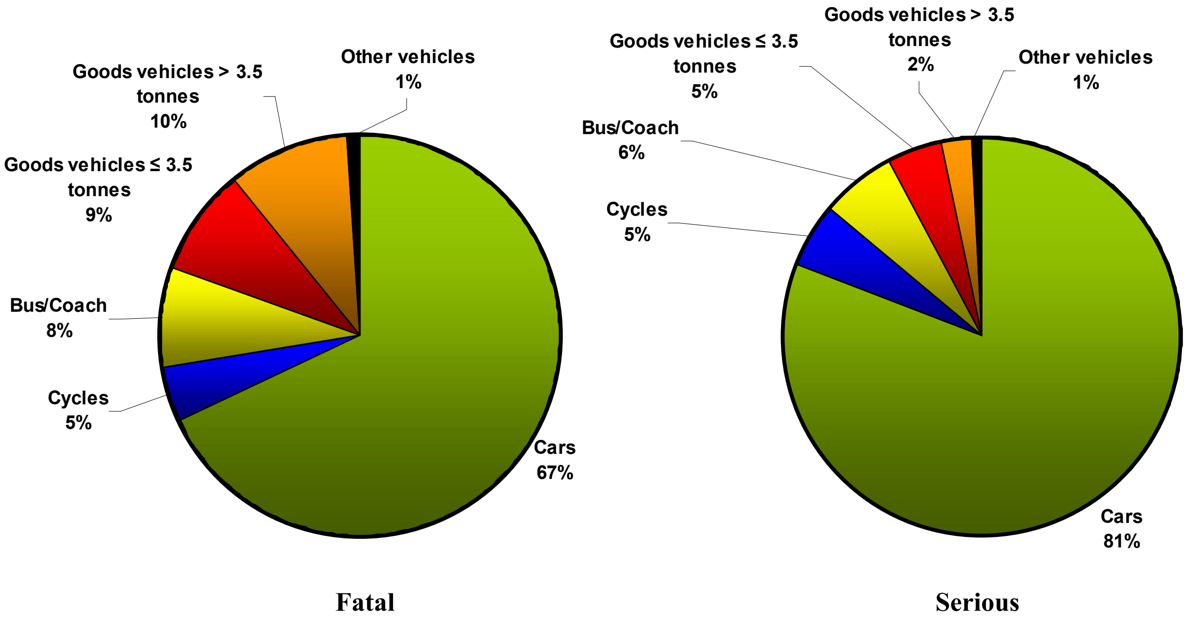


Figure 7.1. Vehicles involved in pedestrian accidents (Great Britain, 2005 data)

When considering the value of expanding the scope of the current European Directive it would be useful to obtain an estimation of the extra casualties that could potentially be saved. For the vehicles concerned this would require a detailed breakdown of accident data to identify the proportions of casualties hit by the front of the vehicle and the injury severity speed distribution. Unfortunately not all the necessary data could be found in the literature reviewed. Heavy goods vehicles are likely to have a different injury severity to speed distribution than cars, with more serious and fatal injuries occurring at lower speeds. Nevertheless, a very approximate pro rata estimate can be made for the potential savings using the proportions of cars to other vehicles in Figure 7.1. The European Directive currently applies to M1 and N1 based on M1 vehicles up to 2.5 tonnes. Very crudely it can be estimated that expanding the scope to cover all or most of the M and N vehicles over 2.5 tonnes would apply to 15 percent of the serious accidents and 30 percent of the fatal accidents in Figure 7.1 (includes cars over 2.5 tonnes). Therefore the savings of an expanded scope might be of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive’s savings.

Data on vehicles currently licensed in Great Britain in 2005 show 2.9 million light goods vehicles and 0.4 million goods vehicles (i.e. >3.5 tonnes GVW) in a fleet of 32.9 million. The proportions of light goods and goods vehicles on the road are therefore 9 percent and 1.3 percent respectively. By vehicle fleet, light goods vehicles are proportionately represented in fatal accidents and are under-represented in serious accidents. However, goods vehicles over 3.5 tonnes GVW are very over-represented in the fatality statistics and are over-represented to a lesser extent in the serious accidents. The differences in accident and vehicle proportions are a reflection both of the exposure to road types (speeds) and the risk of injury posed by the vehicles.

Data on first registrations are also relevant as the costs of meeting any pedestrian protection requirements would largely fall on new vehicles rather than vehicles on the road. Of 3.02 million new registrations, 0.34 million (11 percent) were light goods vehicles and 50,000 (1.7 percent) were goods vehicles over 3.5 tonnes (2005 data).

Data provided by ACEA show that 4x4 vehicles had a 7.0 percent market share in the EU15 in 2005. However, 4x4 vehicles can include conventional cars with four-wheel drive, as well as SUVs. Data obtained for a previous project (Lawrence *et al*., 2006) show that the market share of cars weighing more than 2.5 tonnes GVW, including SUVs, is roughly 2.5 percent in Europe.

7.2.1 Literature review

An extensive literature search was unable to reveal any detailed studies within the EU specifically looking at SUVs, pick-ups and vans causing injury to pedestrians. Therefore in order to allow a comparison of possible variations in injury pattern and severity with these vehicle types, published data relating to collisions in the USA were used. An American representative at UNECE (Expert from the United States of America, 1998) noted a similar issue with the lack of EU data and relied on studies from the USA concerning vehicle sales to define the increasing trend in SUVs and vans. However, they did comment that the EU was beginning to show a similar trend in the increasing number of these vehicles and offered data from a few EU countries which generally showed that the increase in new registrations of combi/small trucks were higher than for passenger cars. They also noted that these figures related to the mid 1990’s and did not account for the newer, more popular, vehicle models coming to the market, such as the Land Rover Freelander, BMW X5, Mercedes M-Class, etc.

In the USA, a number of studies have been completed to assess the relative injury-causing capacity of Sports Utility Vehicles (SUVs), pick-ups and vans compared to passenger cars. Some of these studies group together SUVs, pick-ups and vans into a category called Light Trucks and Vans (LTVs). However, other studies use a similar acronym to define Light Truck Vehicles, which do not include vans. The definition of LTVs here includes vans unless otherwise stated.

Henary *et al*. (2003) described the shift in the passenger vehicle fleet in the USA towards SUVs, pick-ups and vans, stating that they accounted for one-third of all light vehicle registrations and almost one-half of all new vehicle registrations. Lefler and Gabler (2004) later showed that in 1999 LTVs accounted for approximately 48 percent of all light vehicle sales.

7.2.1.1 Injury comparisons between passenger cars and LTVs

A study by Ballesteros *et al*. (2004) found that in the USA pedestrians struck by LTVs were more likely to die as a result of the injuries they sustained, particularly for the SUV which had a fatality rate almost twice that of passenger cars. However, there was no distinction made between injuries to adults and injuries to children to help identify particular vulnerabilities. The authors also noted that SUV’s and pick-ups tended to have their crashes on higher speed limit roads than with passenger cars, although no explanation was given for this observation.

A similar trend was also noted in the report of Hoogvelt *et al*. (2004), who studied the impact of SUV’s on traffic safety and the environment in The Netherlands. The SUV accident sample size was small (32 cases), and while there did appear to be a greater risk of a fatality for a pedestrian in collision with an SUV, this difference was not statistically significant.

Lefler and Gabler (2004) produced figures showing the number of US pedestrian fatalities by vehicle type per 1000 accidents. These data showed that while approximately 4.5 percent of pedestrians struck by a passenger car resulted in a fatality, this fatality rate increased to 8 percent for compact

SUVs and 12 percent for the larger SUVs. The percentage of pedestrians killed when struck by large vans was 13 percent.

Paulozzi (2005) looked at all pedestrian fatalities and found that approximately 50 percent involved impacts with a passenger car, while a further 40 percent were related to impacts with LTVs, highlighting the increasing proportion of LTVs in the USA. Similarly, Roudsari *et al*. (2004) reported on overall pedestrian injury severities, segregated by both age and vehicle type. In this study, injuries of the severity levels AIS 4+, for impacts with passenger cars, were sustained by 9 percent of children and 21 percent of adults. (The Abbreviated Injury Scale (AIS) rates injuries from 1 (minor) to 6 (maximum) with AIS 4+ being considered as life-threatening injuries.) (Roudsari *et al*. used the different definition of LTV that did not include vans, and found that 6 percent of children and 33 percent of adults sustained an AIS 4+ injury. Impacts involving vans resulted in 17 percent of children and 22 percent of adults sustaining AIS 4+ injuries.

The US National Center for Statistics and Analysis reported (Starnes and Longthorne, 2003) on child and adult pedestrian fatality rates per million vehicle years, based on the type of vehicle striking them. SUV's, pick-up and vans all had relative risks greater than for impact with passenger cars, and this was particularly apparent for children under the age of 8 years old. The relative fatality risk for those under 8 years old (0-3 years old and 4-7 years old) was between 1.30 and 1.87 compared to passenger cars, while pedestrians aged 16 years and older had relative risks less than 1.25.

7.2.1.2 Injury distribution

The various USA studies also assessed the injuries sustained by body region. Ballesteros *et al*. (2004) analysed the non-superficial injures sustained by the pedestrians and discovered that the injury pattern was different between vehicle types. Exactly what the authors classed as non-superficial was not detailed. Overall, it appeared that the percentage of all types of head injury were consistent across the three vehicle classes (cars, SUVs/pick-ups combined and vans). However, within the head injury category there seemed to be an increase in the percentage of traumatic brain injury for the other vehicle types over passenger cars. Thoracic and abdominal injuries increased significantly for impact with LTVs. Spinal injuries increased significantly for the SUV and pick-up category and to a lesser extent for vans.

Injuries to the lower extremities were broken down into data for above the knee, at the knee and below the knee. 17 percent of pedestrians in the sample sustained an injury above the knee level when struck by a passenger car. This figure rose to 23 percent and 20.5 percent for SUVs/pick-ups and vans respectively. Injuries at the knee level reduced very slightly for SUVs, although this variance was not statistically significant. The percentage of pedestrians sustaining injuries below the knee were significantly less for both the SUVs/pick-ups and vans. It was concluded that in general, similar lower extremity injury patterns were caused by SUVs/pick-ups and vans.

Interestingly, when assessing traumatic brain, thoracic and abdominal injury, the authors found little difference in the number of injuries at impact speeds of 30 mph (48 km/h) and above between the different vehicle types. However, below 30 mph (48 km/h) more of these injury types were sustained with SUVs than with passenger cars.

Henary *et al*. (2003) had an initial sample size of 552 pedestrians; however, only 388 cases were used that fell within one of the two age bands, children (126) aged 2 to 14 and adults (262) aged 19 to 50 years old. Subjects aged 15-18 were excluded to rule out the possibility of overlapping physical characteristics between child and adult populations and older subjects were excluded because of concerns regarding 'body frailty and degree heterogeneity'. The SUVs, pick-ups and vans were combined into a single group (LTVs) for assessment due to the low sample size. The highest risk of severe injury and death was for impacts between adults and the LTVs. The lowest risk group were children struck by passenger cars. The risk for both adults and children were greater with the LTVs than with passenger cars. When the impact speeds were less than 30 km/h, injuries (severe and fatal) were significantly higher for the head, torso, upper and lower extremity. At impact speeds over 30 km/h there did not appear to be much variation by vehicle type.

The speed related injury pattern by vehicle type was also noted by Lefler and Gabler (2004). They looked at AIS 3+ injuries to the head, chest and lower extremities, comparing passenger cars to LTVs and speed ranges of 0 to 20 km/h, 21 to 40 km/h and 41 to 60 km/h. This study showed that head and chest injuries were always more prevalent, irrespective of speed, for impacts involving LTVs. Lower extremity injuries occurred as a higher percentage with passenger cars at speeds of 41 km/h and above, while in the range of 21 to 40 km/h LTVs were shown to have a greater percentage. However, it should be noted that lower extremity injuries were not broken down in any more detail, such as in the study of Ballesteros.

A NHTSA report (Mallory and Stammen, 2006) provided an analysis of the Pedestrian Crash Data Study (PCDS) database. About a third of the vehicles involved were LTVs (‘light trucks and vans’, i.e. minivans, pickups, SUVs & vans). Most of their analysis, and all the values reported here, were for ‘relevant’ injuries only, that is, injuries due to parts of the vehicles that could potentially be covered by regulatory pedestrian test procedures. The report includes a tabulation of vehicle contacts against the injured part of the pedestrians’ lower extremities. The front bumper was given as the source of 74 percent of AIS 2+ ankle and foot injuries of known source, 80 percent of lower leg injuries, 85 percent of knee injuries and 64 percent of thigh injuries. However, for the hip and pelvis injuries, 52 percent were from the hood (bonnet) edge / trim and 24 percent from the hood surface but only 1 percent from the front bumper. For AIS 2+ injuries, there were a significantly greater proportion of hip/pelvis injuries (14 percent passenger cars, 39 percent LTVs) and thigh injuries (6 percent cars, 16 percent LTVs) for pedestrian collisions involving LTVs. As a consequence, the percentages of lower leg injuries and knee injuries reduced in the LTV class, to 19 and 13 percent respectively, compared with 47 and 22 percent respectively for passenger cars. For AIS 3+ injuries, there were an even greater proportion of hip/pelvis injuries (21 percent cars, 49 percent LTVs) and thigh injuries (10 percent cars, 28 percent LTVs) for pedestrian collisions with LTVs. As a consequence, the percentages of lower leg injuries and knee injuries reduced, to 15 and 8 percent respectively, compared with 49 and 19 percent respectively for passenger cars. The report included projections that showed the number of injuries above the knee increasing due to an increasing proportion of LTVs in the USA fleet.

Roudsari *et al*. (2004) assessed passenger cars, vans and LTVs (in this instance referring to light trucks only) and looked at injuries to different body regions. Results included data on the site of the principal injury. For children, the site of principal injury was shown to be the lower extremity, abdomen and thorax more frequently for LTVs than for cars, while the percentage was greater for vans than passenger cars for lower extremity, upper extremity, and spinal injuries. In fact, it was only the head region that was the site of principal injury more frequently for passenger cars than for either LTVs or vans. Similar analysis for pedestrians older than 14 years also showed that there was a greater percentage of principle injuries to the head region from passenger cars than from the other two vehicle types. The results were less clear than with children as LTVs and vans were not always in greater proportions than passenger cars for the other injury regions. For thorax injuries the order of percentage occurrence was LTV then car, with vans being the lowest. Similarly, abdominal injuries were LTV, car, van; spinal injuries van, car, LTV; lower extremity injuries van, car, LTV; and, upper extremity LTV, car then van. These injury distributions appear to be in contrast to the other studies, but this may be a result of the definition of the severity of injury which was considered across the various studies.

7.3 Passenger and goods vehicle types

In much of the vehicle legislation, vehicle mass is used to determine which vehicles are subject to specific tests. Mass is obviously a convenient parameter to use for this purpose. However, the question can be asked as to what difference does vehicle mass alone make to the pedestrian or pedal cyclist that is hit by a given vehicle, if other factors such a stiffness that may be correlated with mass are held constant? There is a benefit in being hit by a lighter vehicle, but it is only a small benefit. This is because as the pedestrian is accelerated up to roughly vehicle speed momentum is transferred from the vehicle to the pedestrian; this loss of momentum means that the vehicle’s velocity is reduced.

If it is assumed that a 60 kg pedestrian reaches a common velocity with the vehicle then when hit by a 1000 kg vehicle at 40 km/h the pedestrian would be accelerated to 37.7 km/h or 94.3 percent of the impact speed. As the vehicle gets heavier the common velocity increases slightly, to 38.5 km/h (96.2 percent) for a 1500 kg vehicle, 39.1 km/h (97.7 percent) for a 2500 kg vehicle and 39.3 km/h (98.3 percent) for a 3500 kg vehicle.

As mass has such a limited direct effect it is only of relevance to the impacted pedestrian in so far as it is correlated with other factors such as vehicle front-end size and shape. It would perhaps be preferable to use size and shape to determine the test requirements rather than gross vehicle weight (GVW). However, it must be understood that there will be other considerations when setting the scope of the pedestrian test procedures. For instance, there are benefits in having common 'break points' with other (non-pedestrian) requirements. Also, considerations of accident frequency and the cost effectiveness of requiring protection from other vehicle types must be taken account of. Even if mass is likely to be used in the legislation, in the following discussion, size and shape will be used to categorise vehicles, to examine their likely performance when in collision with VRUs and to consider how well the current test procedures would work if used to test them.

A number of typical vehicle profiles are shown in Figure 7.2, scaled to be approximately the correct size in relation to a 50th percentile adult male pedestrian and a six year old child pedestrian. As the 50^{th} percentile knee height is important to the discussion, as this is the height of the lower legform knee, and as the image used is a little misleading with regard to the knee position, the knee height is indicated in the diagrams by the arrow. Vehicle data are taken from manufacturers' UK websites; vehicles sold in other countries may differ in weight. Vehicle profiles were obtained from www.smcars.net or from the manufacturers' websites.

The first three vehicles are typical family cars that are within the scope of the current EC Directive (2003/102/EC). These are included for comparison purposes. However, it is interesting to note that the heaviest variant of the Mondeo is quite close to the 2500 kg limit, with a GVW of 89 percent of that limit. No example of the executive class is shown here but some members of that class would be outside the scope of the current Directive, either for all variants or just for the heavier variants of the model. Some of these or similar family-size passenger car models will have van variants that generally would also be within the scope of the Directive, as N1 derived from M1 vehicles. As the front ends, back at least to the windscreen, would be almost identical, the diagrams showing cars cover these vehicles also.

It can be seen that the front end of the MPV (multi-purpose vehicle) shown is at a similar height and is a similar shape to the family cars shown. Possibly the typical European MPV design would have a steeper bonnet and be taller overall, but it can be seen that the Astra family car also has these characteristics. All variants of the Grand Voyager are outside the scope of the current Directive but this class will also have many models that are wholly inside the scope or are inside for some of the lighter variants.

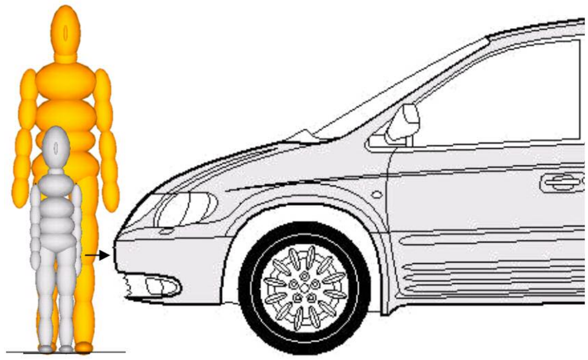
The next category shown in Figure 7.2 is the SUV (sports utility vehicle) or off-roader category. (Most or all are 4x4 (four-wheel drive) vehicles but some 4x4 vehicles are otherwise-typical passenger cars rather than off-roaders.) It can be seen that these are generally tall vehicles and that in particular the bumpers are much higher. Some SUVs are within the scope of the current test procedures but others exceed the weight limit. For example, the CR-V is less than 2.5 tonnes GVW and is therefore within the scope of the current European legislation, whereas the Landcruiser and L200 are both outside the scope.

Two van models are shown next in Figure 7.2. Neither is covered by the current test procedures as they are not 'derived from M1' vehicles; also, some of the heavier variants are N2 rather than N1 vehicles. Some of the lighter Transits are less than 2.5 tonnes GVW but the remainder and all Sprinter variants are over 2.5 tonnes GVW. Both of these models, along with most vehicles of this type, have a steeply angled bonnet and a windscreen at almost the same angle. Bumper and bonnet leading edge heights are generally in between those of normal cars and of SUVs.

Ford Focus

Small family car

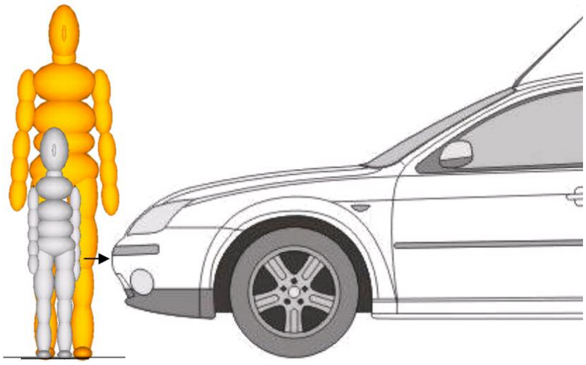
Kerb Weight:	1229 to 1467 kg
Gross Vehicle Weight:	1690 to 1905 kg



Vauxhall (Opel) Astra

Small family car

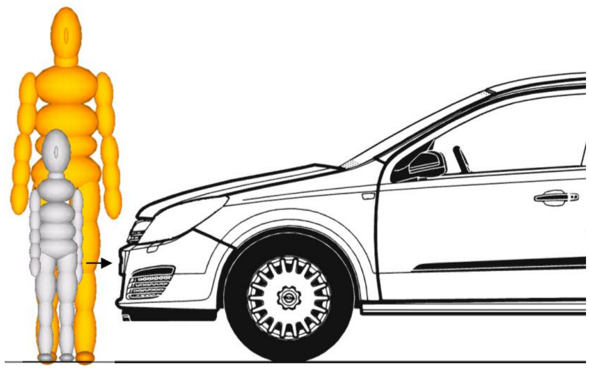
Kerb Weight:	1155 to 1463 kg
Gross Vehicle Weight:	1705 to 2005 kg



Ford Mondeo

Large family car

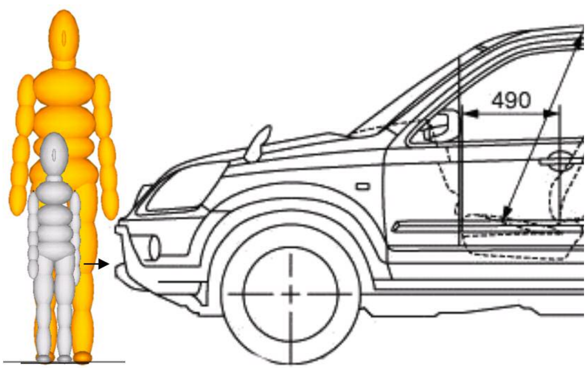
Kerb Weight:	1364 to 1615 kg
Gross Vehicle Weight:	1895 to 2235 kg



Chrysler Grand Voyager

MPV

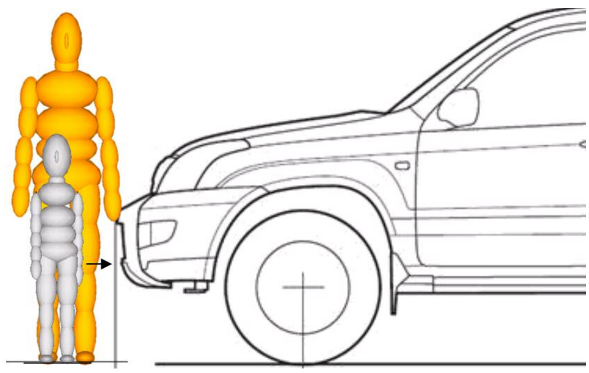
Kerb Weight:	2140 to 2225 kg
Gross Vehicle Weight:	2595 to 2680 kg



Honda CR-V

Small SUV

Kerb Weight:	1517 to 1668 kg
Gross Vehicle Weight:	2050 to 2160 kg



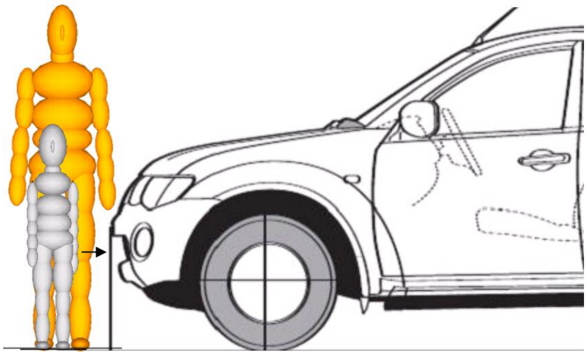
Toyota Landcruiser

Large SUV

Kerb Weight:	2080 to 2190 kg
Gross Vehicle Weight:	2850 kg

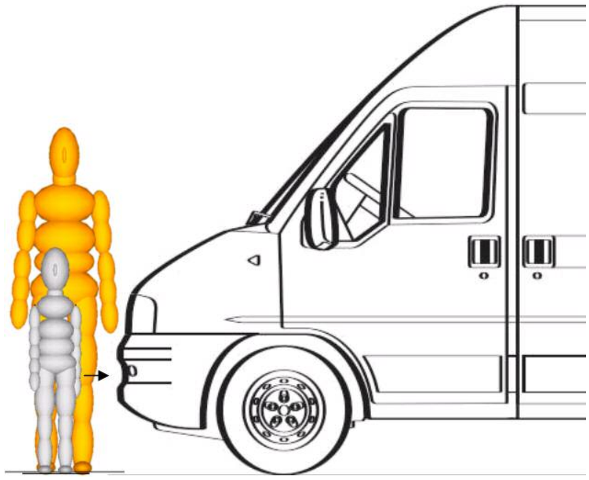
Figure 7.2. Typical passenger and goods vehicles in relation to 50th percentile adult male and six year old child pedestrians

Arrow shows 50th percentile adult knee centre



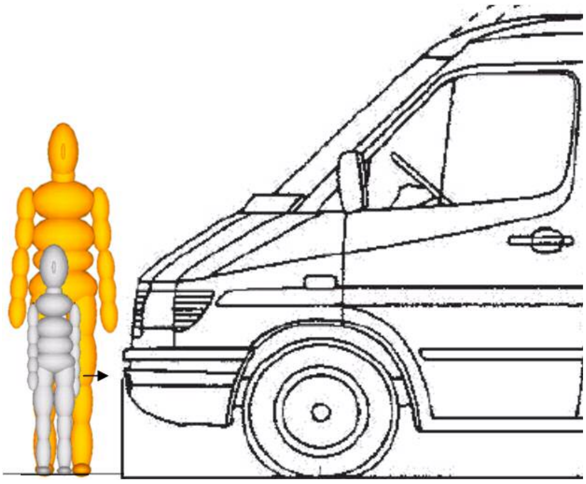
Mitsubishi L200

Large SUV
Kerb Weight: 1410 to 1675 kg
Gross Vehicle Weight: 2570 to 2830 kg



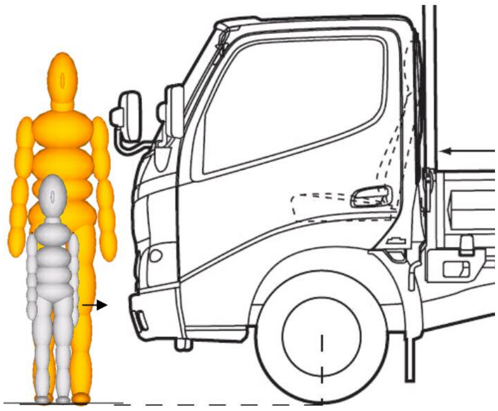
Ford Transit

Van
Kerb Weight: 1612 to 2255 kg
Gross Vehicle Weight: 1970 to 4250 kg



Mercedes Sprinter

Van
Kerb Weight: 1795 to 2285 kg
Gross Vehicle Weight: 2590 to 4600 kg



Toyota Dyna

Truck
Kerb Weight: 1465 to 2255 kg
Gross Vehicle Weight: 3000 to 3500 kg

Figure 7.2 continued. Typical passenger and goods vehicles in relation to 50th percentile adult male and six year old child pedestrians
Arrow shows 50^{th} percentile adult knee centre

The final example is a small truck. All variants of this model are within the N1 limit of 3.5 tonnes. The front of the vehicle is almost vertical up to the base of the windscreen, and the windscreen itself is much more upright than the other vehicle types. The bumper is at a similar height to those of the vans. The structure of this vehicle is very different, with a chassis structure. The engine would be below the cab and is presumably accessed by tilting the cab. The driver's seating position is directly above the front wheels. Though this example is not an HGV (Heavy Goods Vehicle) the shape of the cab is similar to that of most HGVs.

These vehicles fall into four basic size and shape categories: normal cars, SUVs, goods vehicles with angled fronts and good vehicles with near vertical fronts. Whether a goods vehicle is a van or truck may not be relevant as, as well as the vehicles shown, there are likely to be vans with near vertical fronts and trucks with angled fronts. Also, some MPV passenger vehicles may have a similar shape to the angled-front vans; the shape is more important than the purpose of the vehicle. The IHRA PSWG has considered vehicle shapes and has developed shape corridors for three types of vehicle, based on vehicles from Europe, Japan and the USA. See for instance their most recent ESV conference paper (Mizuno, 2005) and Figure 7.3 below. Their shapes directly correspond to the first three categories above, with the fourth probably being outside the range of vehicles considered by the working group. The IHRA descriptions for these three groups are ‘Sedan’ (including light vehicles and sports), SUV and ‘1Box’.

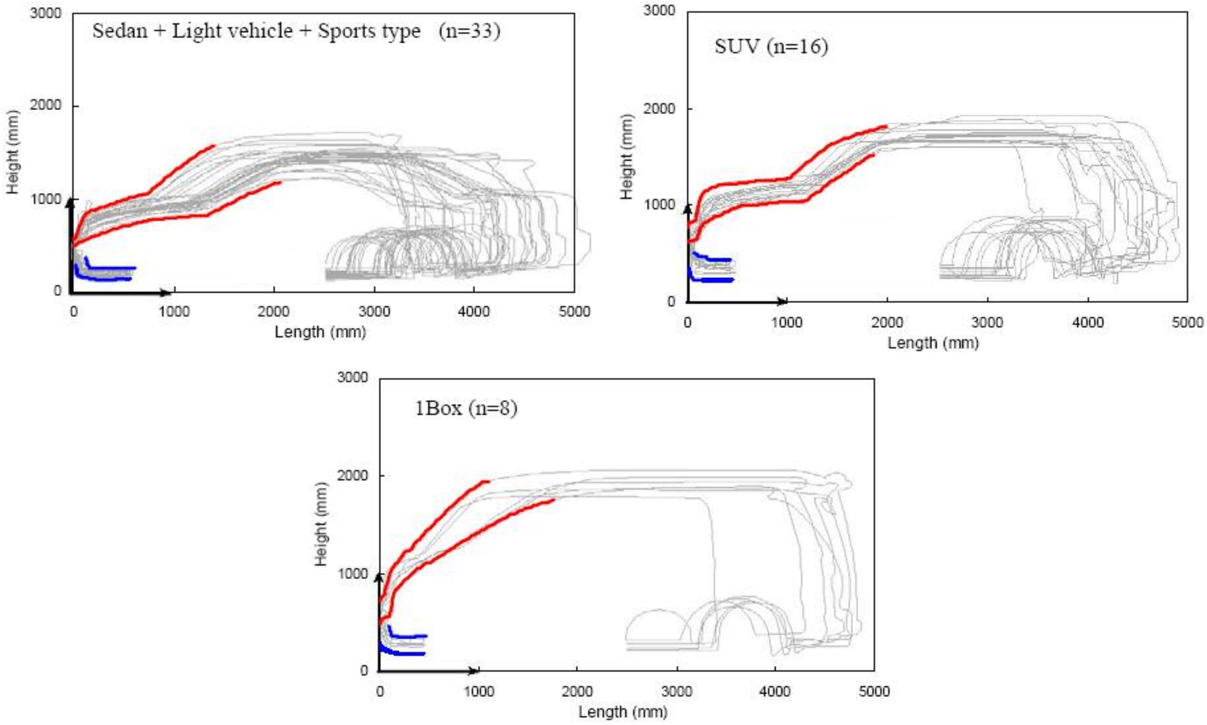


Figure 7.3. IHRA PSWG car front shape corridors (Mizuno, 2005)

7.4 Effect of vehicle size and shape on pedestrian impact

The IHRA PSWG has carried out a series of computer simulations of pedestrian impacts using simulated vehicles, based on their three car front shape corridors. These simulations were carried out for the purpose of determining the headform test parameters, and have been previously discussed in Section 6.5.1. The literature review didn’t reveal any other papers containing accident reconstructions or simulations involving larger vehicles, so the comments below relating to large vehicle impacts are partly based on the IHRA PSWG simulations and partly on a ‘commonsense’ extrapolation from ‘normal’ pedestrian accidents. It was outside the brief of this project to carry out such reconstructions or simulations. Some results and details of the IHRA simulations have been published (Mizuno, 2003); however the current authors also had access to a working group paper (Anon, 2002) that illustrated the kinematics for a selection of the simulations.

The typical car to pedestrian impact is considered first, for comparison with the larger vehicle categories. See the first four vehicles in Figure 7.2. The initial, bumper impact hits the 50th percentile adult male on the top part of the lower leg. Some vehicle bumpers will hit entirely onto the lower leg, below the knee centre, others will extend to just above the knee centre. Either way, the pedestrian’s legs are swept sideways (assuming the typical side-on impact), causing the pedestrian as a whole to rotate. However, this impact to the legs, if not well managed by the front of the car, has the potential to cause injuries such as tibia fractures and knee ligament injuries. The second impact phase is when the rotating pedestrian contacts the bonnet leading edge area, typically with their upper thigh. This area was once a significant cause of injuries but current car designs, with their rounded, aerodynamic designs, cause few injuries at this contact. (This was discussed in more detail in Section5). The pedestrian continues to rotate and these contacts will have brought the pedestrian's velocity up close to the car velocity. The thorax will hit the bonnet top area. Thorax injuries are not seen as a significant problem so the focus of the bonnet top test procedures is on preventing or mitigating head injuries. The head will hit either the bonnet top or the windscreen, with a predominately downwards velocity vector. A 50th percentile adult male would probably hit the windscreen or A-pillars on the majority of typical cars, especially those with short bonnets. The heads of smaller adults would however hit the bonnet top on most cars.

The six year old represents the smaller and younger pedestrians that are hit by cars. Pedestrians of all ages appear in the accident statistics but the frequency increases from very low in the first two years to a peak at about 11 or 12 years old (in Great Britain). The bumper of a typical car will impact a six year old in the upper thigh or possibly the pelvis. The pedestrian will rotate onto the car, with the bonnet leading edge impacting from the pelvis to the chest, depending on vehicle height, and the head impacting the middle or towards the front of the bonnet, again depending on the vehicle size. With the relatively higher contact points on the body, less rotation and hence lower head impact speeds than with the adult might be expected, but the IHRA simulations show very similar head impact speeds (see Table 7.1).

Table 7.1: Adult and child pedestrian head impact velocities and angles for 40 km/h vehicle impacts (average +/- 1 SD) (Mizuno, 2003)

Pedestrian	Shape corridor	Impact velocity (km/h)			Impact angle (degrees)		
		Bonnet	Windscreen	BLE/Grille	Bonnet	Windscreen	BLE/Grille
Adult	Sedan +	30.4 +/- 7.2	35.2 +/- 6.8	nc	66.0 +/- 14.0	38.4 +/- 10.9	nc
	SUV	30.8 +/- 8.8	nc	nc	76.7 +/- 22.2	nc	nc
	One box	nc	29.6 +/- 3.2	nc	nc	47.3 +/- 9.6	nc
Child	Sedan +	30.0 +/- 4.0	nc	nc	66.0 +/- 6.3	nc	nc
	SUV	27.2 +/- 1.6	nc	32.0 +/- 3.6	59.2 +/- 2.6	nc	22.5 +/- 4.2
	One box	27.6 +/- 0.8	nc	33.2 +/- 3.2	49.8 +/- 1.8	nc	17.4 +/- 6.1

nc: no contact

The SUV bumpers will typically impact an adult male pedestrian between about knee height and upper thigh height. Knee, femur and pelvis injuries may occur if the bumper has not been designed to mitigate these. The pedestrian will again rotate, though probably less rapidly than with typical cars as the initial impact is nearer their centre of gravity. The bonnet leading edge will impact between the pelvis and lower chest area, depending on vehicle height. The abdomen in particular is likely to be vulnerable to impacts as it is relatively unprotected and contains vital organs. However, the examples of SUV in Figure 7.2 have relatively rounded bonnet leading edges that would minimise any penetration into the abdominal area. The accident data available are inadequate to judge how safe current European SUVs are at the bonnet leading edge. Accident studies show very few injuries from this area with current conventional cars, but there are few SUV accidents within the samples. The NHTSA study (Mallory and Stammen, 2006) mentioned in Section 7.2.1.2 shows a higher rate of bonnet leading edge injuries in accidents from a database where about a third of the vehicles involved were LTVs, but many of these are likely to be outside the range of sizes seen in Europe. As with a conventional car, the head will impact the upper surface and because of the size of these vehicles this will occur much more frequently onto the bonnet top rather than the windscreen. Head impact velocities could be expected to be lower than with conventional cars because of the lower rotation rate and higher pivot point; this effect should be more pronounced with the taller SUVs that are unlikely to be within the current 2.5 tonnes weight limit. However, the IHRA simulations obtained marginally higher average head impact velocities with the SUV, though the difference was small compared with the standard deviation of the results.

When SUVs hit the six year old, the bumper will hit from the pelvis to the mid-chest, depending on vehicle height. The bonnet leading edge of the shorter SUVs will be at shoulder or neck height, and the head will hit the front of the bonnet. Both the bumper and bonnet leading edge impacts will therefore have the potential to cause injury to vulnerable areas of the body that would probably not be injured if the pedestrian was hit by a smaller vehicle. The larger SUVs will have a bonnet leading edge reference line above the child's head, so the head will hit the grill or the near vertical part of the bonnet ahead of the defined reference line. In both cases the six year old child is wrapped around the front of the vehicle, and the body will not rotate onto the bonnet top. Head impacts onto the bonnet top can be expected to be at a lower velocity than with conventional cars as with the torso more vertical the neck has to bend further to allow the head impact; the IHRA simulations show a roughly ten percent reduction in average impact velocity. However, head impacts onto the grille or front of the bonnet will be at a higher and much more horizontal velocity as lower contacts will have less opportunity to accelerate the head before it impacts; again this can be seen in the average impact velocities obtained by IHRA. Some older children will, like the six year old, see little rotation of their bodies but their heads will be further above the bonnet leading edge. In these cases there will be no head contact or a low velocity contact.

The angled front or '1Box' vehicles will first impact the adult pedestrian with the bumper between the knee and about the middle of the thigh. This range of bumper heights will mean that some bumpers behave more like those of conventional cars and others more like those of SUVs. In most cases the IHRA simulations show the pedestrian wrapped around the vehicle front, rather than rotating from contact to contact. Where the front changes from vertical to angled-back will in many cases coincide with the bonnet leading edge reference line but, because of the way this is determined using a straight edge at 50°, it may be that the reference line will not be where it might be expected to be. The 'actual' bonnet leading edge could impact between the upper thigh and abdomen or lower chest. However, because this part of the car doesn't have such a pronounced change of angle as in either conventional cars or SUVs, it is unlikely to be as important an impact. The adult head will impact the windscreen or A-pillars in most cases.

The six year old child will be hit initially somewhere between the thigh and the lower chest. They will wrap around the front of the vehicle with the head impacting the bonnet. The IHRA simulations give an average impact speed that is slightly less than with conventional cars.

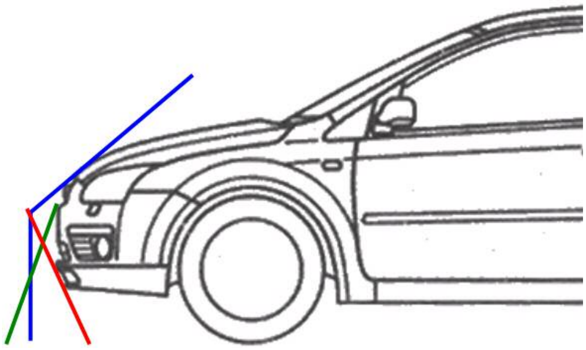
The almost flat-fronted truck in Figure 7.2 will provide almost a line contact to the adult between the bumper to knee contact and the head to windscreen, or A-pillars. There is no pronounced angle to increase local loading but the area around the base of the windscreen may provide a strong point, particularly if the windscreen gives way under impact. For the six year old the impact starts on the thigh and the head is likely to impact below the windscreen.

7.5 Testing larger vehicles with the current test procedures

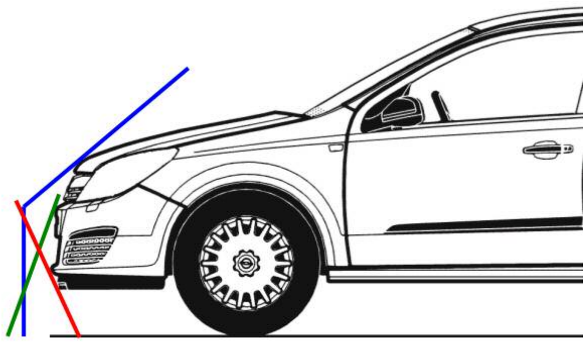
The test procedures were developed for conventional cars so they work well when used on such vehicles. However, even with such vehicles some features on the cars may occasionally cause problems. Problems in using the test tools and methods for vehicles they were not necessarily designed for could include:

- Inappropriate impact conditions and / or missing test tools
- Different protection priorities may be appropriate for larger vehicles (or some areas of them)
- Inappropriate or missing mark up and test zone rules for larger vehicles

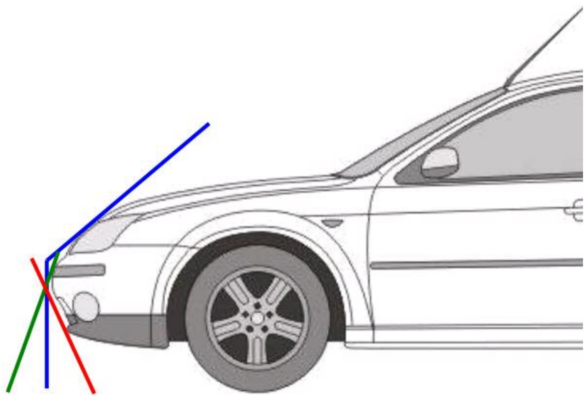
The following is a 'paper' exercise to attempt to anticipate any problems that might arise in applying the test procedures to the larger vehicles described above. Figure 7.4 shows the straight edges used to mark-up the front of test vehicles, in relation to the same vehicles that were discussed previously.



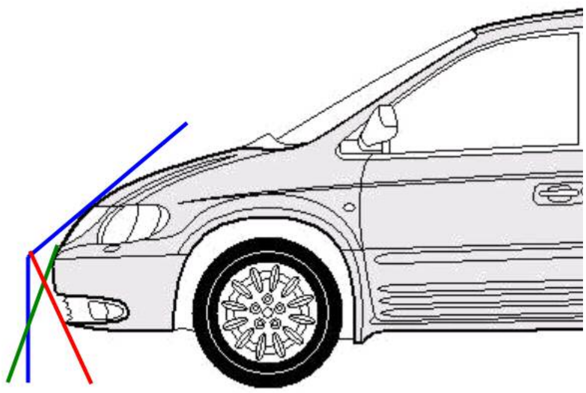
Ford Focus



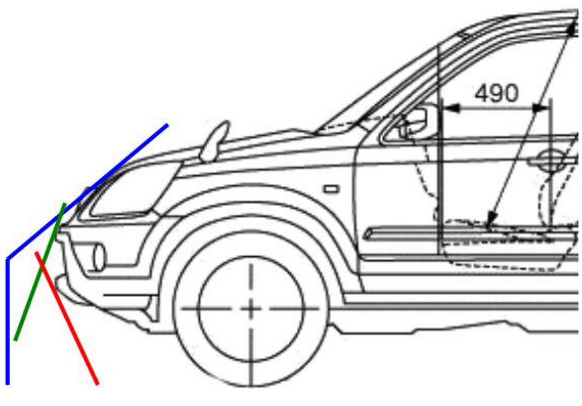
Vauxhall (Opel) Astra



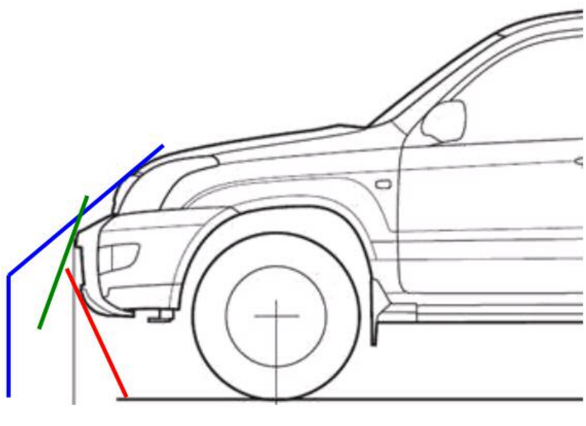
Ford Mondeo



Chrysler Grand Voyager

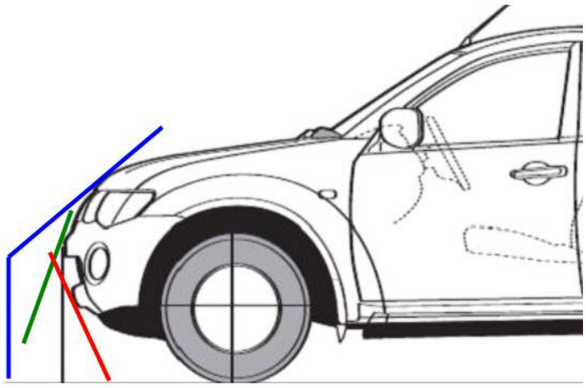


Honda CR-V

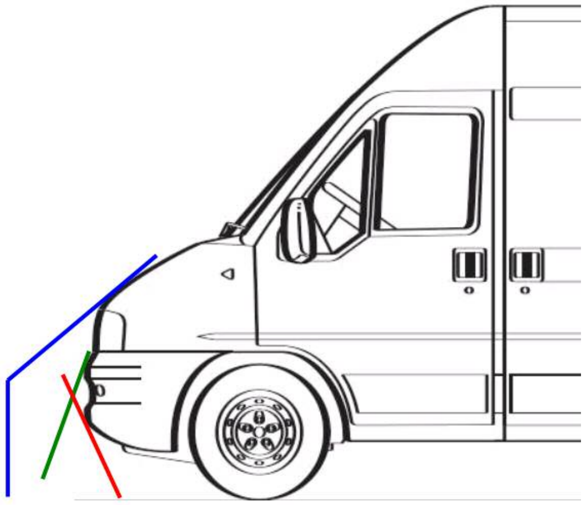


Toyota Landcruiser

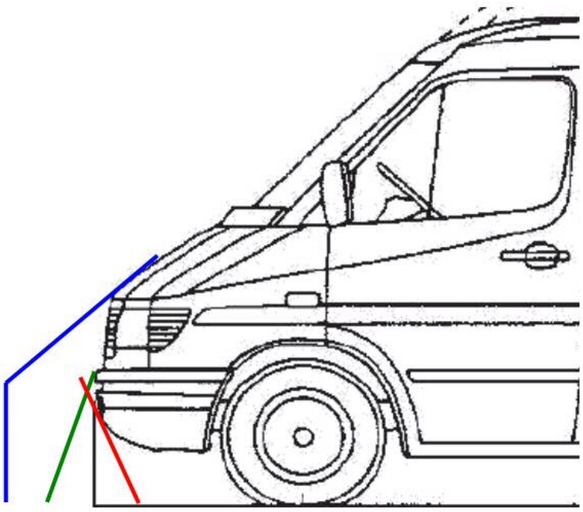
Figure 7.4. Straight edges used to mark-up the front of vehicles, shown in relation to typical passenger and goods vehicles



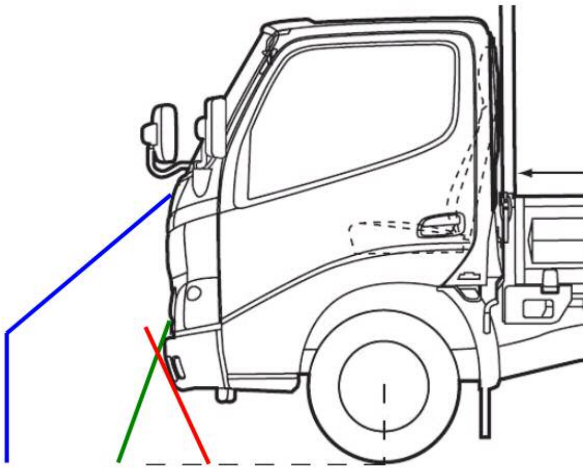
Mitsubishi L200



Ford Transit



Mercedes Sprinter



Toyota Dyna

Figure 7.4 continued. Straight edges used to mark-up the front of vehicles, shown in relation to typical passenger and goods vehicles

With the relatively recent addition of the high bumper test the test procedures have been applied to smaller SUVs with few problems. However, even with some small SUVs the straight edge used to determine the upper bumper reference line has been found to miss the top of the bumper, because the procedure defined in EEVC WG17's and the EC's test procedures (i.e. in EC Decision 2004/90/EC) required the bottom of the straight edge to be in contact with the ground. This then meant that the upper legform was not properly centred on the bumper. A change has been proposed that this straight edge can be raised up when necessary to contact the top edge of an 'identifiable' bumper ('identifiable' is not defined in the Directive). This change has already been incorporated in the draft GTR and it is understood that the EC document that replaces Decision 2004/90/EC will also include this change. Therefore, the straight edge used to mark the upper bumper reference line has been shown raised where necessary in Figure 7.4 to reflect this change.

With the largest SUVs, the marking-up procedures have another potential problem, again due to a straight edge of specified length being held at a specified height. The straight edge used to determine the bonnet leading edge reference line has a bottom end at 600 mm, which fixes the top end at 1243 mm, if the angle remains at 50° to the vertical. This is probably just adequate with current

European SUVs but there may be large American vehicles where the end of the straight edge makes contact with e.g. the vehicle grille. In this case the procedure specifies that the defined bonnet leading edge reference line will be at a wrap around distance of 1000 mm, which would be well below the actual bonnet leading edge, and instead the reference line would be on the grill or near vertical front of the bumper. The headform test area for large SUVs, in the draft GTR test, starts 82.5 mm (a headform radius, measured with a taut tape) rearward of the defined bonnet leading edge reference line. The purpose of this is to avoid testing the area of the bonnet leading edge, on feasibility grounds, as this is considered to be a difficult area to make safe. A very large vehicle might therefore be tested with the child headform very close to or on the actual bonnet leading edge, or on the vertical panel below the actual bonnet leading edge. There is no upper legform to bonnet leading edge test in the draft GTR but if this test remains in the EU test requirements there could be problems, as the impactor centreline has to align with the defined bonnet leading edge reference line. The consequence could be that first contact would be an angled impact with the end of the impactor's front member, which could cause the impactor's 'torque limiting joint' or clutch to rotate; although it should be possible to carry out a valid test despite this. However, because of the angled impact, the impactor would not behave in a way that is representative of a pedestrian impact.

The bumpers of large SUVs would be tested with the upper legform, as is often also the case with those SUVs that are within the current scope. The effect of the above mentioned limit on the front edge of the child headform test area, in the more common case where the end of the straight edge is not contacted, is that with taller vehicles more young children could be impacted in the head with parts of the bonnet that would be outside the test area (even though they were beyond the 1000 mm wrap around distance) and were therefore potentially injurious.

With the angled-front vehicles or '1Box' the only potential problem noted, other than those already mentioned for SUVs, is the problem of determining the bonnet leading edge reference line where the bonnet is angled. When the current rule was drafted a bonnet inclined at 50° to the vertical seems to have been the limit of what was considered. However, with this type of vehicle some bonnets are likely to be steeper than this. As they are not at 50° then strictly the straight edge should remain at 50° to the vertical, in which case it will make contact at its top end and the bonnet leading edge reference line will revert to a wrap around distance of 1000 mm. Even if the straight edge angle was pragmatically changed to 40° to the vertical, as allowed for bonnets inclined at 50°, there would still be a problem with bonnets steeper than 40° to the vertical. These would contact the end of the straight edge and hence the bonnet leading edge reference line would be at a 1000 mm wrap around distance. This would probably be on the bonnet in most cases but for large vans it could be on or below the actual bonnet leading edge. This would then affect the headform test area, and in many cases the headform test area would be reduced even though the affected area was a normal bonnet top. As with SUVs, if the upper legform test wasn't centred on the actual bonnet leading edge, whether above or below it, the test might cause the torque limiting joint to rotate.

Some angled-front vehicles would require the lower legform to bumper test and others the upper legform to bumper test. As with SUVs, the taller vehicles of this shape could present an untested area to child pedestrians, beyond the 1000 mm wrap around distance. The headform test area, being limited at the rear by the windscreen, would be quite small.

The (almost) flat-fronted vehicles would present further problems. The bumper test, though, should present no problem. Again, the top of the straight edge used to determine the bonnet leading edge reference line would make contact, this time for all vehicles. If the current rules were applied, the headform test area would therefore start at a wrap around distance of 1082.5 mm (1000 mm plus a headform radius), which would be at a height of just under that value. This would mean testing with the headform on the vertical surface below the windscreen. The upper legform to bonnet leading edge could again be carried out 'by the book', even though there is no recognisable bonnet leading edge. Another problem with marking-up such vehicles will occur when marking the side reference lines. Figure 7.5 shows the normal method, with the straight edge maintained in the transverse vertical plane. When applied to a flat-fronted vehicle the straight edge will slide inwards, removing significant areas from the tested area.

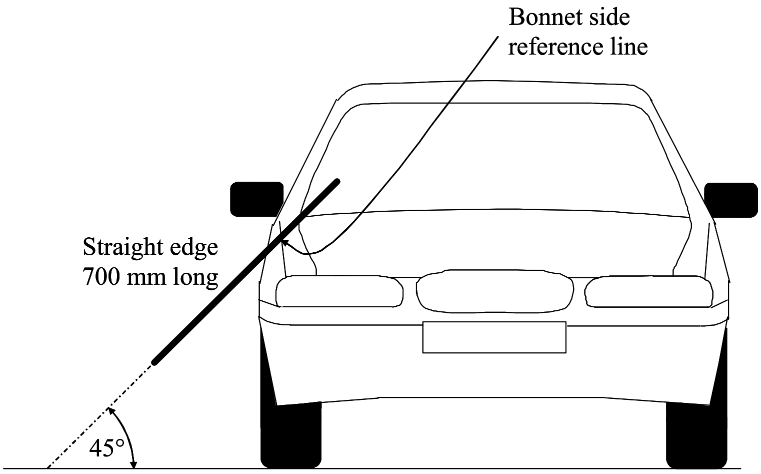


Figure 7.5. Determination of side reference lines with a conventional vehicle

Some flat-front vehicles would require the lower legform to bumper test and others the upper legform to bumper test. Vehicles of this shape would only present a thin untested area to child pedestrians beyond the 1000 mm wrap around distance, as testing could start at 1082.5 mm. The headform test area, being limited at the top by the windscreen, would be quite small on vehicles of the size shown in Figure 7.4.

7.6 Suggested further work and changes to the test procedures to encompass larger vehicles

The suggestions below are broken down into three sections. While these are not necessarily exclusive packages, there are essentially three options available, once it has been decided to extend the vehicle scope to some or all of the large vehicle categories that have been discussed. The first is to make the minimum changes that are necessary to the current test procedures. The second is to make more extensive changes but only those that can be agreed and implemented within a short time-frame. The third option would be to carry out a much larger programme to develop the test procedures for larger vehicles. This option would give the best end result, but if the extension of vehicle scope were delayed until this development was completed there would be several extra years when VRUs were not provided with any protection from these vehicles. There could also be difficulties in resourcing such a programme, as in most countries the benefits would be seen as relatively small, bearing in mind that these vehicles are a relatively small part of the vehicle fleet. Therefore, the authors advise that any extension in vehicle scope should be implemented within the test procedures as soon as possible. It would, of course, be necessary to allow adequate time for manufacturers to develop their vehicles to meet the legislative requirements. Any long-term development work should be aimed at a later and improved second phase of requirements for larger vehicles.

Values in square brackets are suggestions that could be modified after further discussions or after testing the rules on a selection of vehicles.

Some of these suggestions may not be needed if certain vehicle shapes are excluded from the vehicle scope.

The operation of the amended test procedures should be checked by marking-up and testing a sample of large vehicles. This may also assist in determining values that are shown in square brackets.

7.6.1 Minimum changes required to the current test procedures

- Either the test procedure wording should be clarified throughout as to direction, to cope with flat-fronted vehicles, or some general phrase should be inserted, such as “When applying the test procedures to vehicles with vertical or near vertical fronts, ‘rearwards’ should when necessary be read as 'upwards' (with increasing wrap around distance in both cases), and similarly with other references to direction".

This change for the upper bumper reference line is already in the draft GTR.

- The upper bumper reference line should be determined with the straight edge not being required to be in contact with the ground (except where there is no identifiable bumper).

The top end of the straight edge used to determine the bonnet leading edge reference line can contact other parts of the vehicle when the angle of the 'bonnet' is less than 50° to the vertical. The current rule of reverting to a wrap around distance of 1000 mm can mean that large areas of bonnet that would normally be tested with a headform are not tested, thereby potentially reducing the protection offered to pedestrians. However, on vehicles with an 'actual' bonnet leading edge height above 1000 mm wrap around distance the same rule will mean that areas have to be tested that would normally be excluded due to feasibility considerations. It is assumed that on angled-front vehicles this feasibility adjustment would still be necessary. However, as the vehicle front becomes flatter and any recognisable bonnet leading edge disappears, this feasibility adjustment may no longer be necessary. The following suggestion provides a cut-off by shape alone; however, it would be possible to take into account other factors such as whether there is an opening bonnet (as bonnet catches are more difficult to make safe).

- If the bonnet is inclined at an angle of less than 50° to the vertical, the straight edge should be inclined rearwards at an angle that is [10°] more vertical than the bonnet angle; however it should not be less than [20°] from the vertical.
- If the bonnet angle is less than [20°] to the vertical then no bonnet leading edge reference line is defined. The front / bottom edge of the headform test area is at a wrap around distance of 1000 mm. No upper legform to bonnet leading edge test is required.

When the 'actual' bonnet leading edge is very high, above the top end of the straight edge used to determine the bonnet leading edge reference line (at a height of 1243 mm (with the straight edge at 50°), the contact will be below the 'actual' bonnet leading edge. This may not happen with current European SUVs but it is possible that it might with some goods vehicles. Some SUVs in the USA or elsewhere may also be tall enough for this to happen. In this situation the reference line reverts to a wrap around distance of 1000 mm, which will mean that a headform test will be required in areas around or below the bonnet leading edge that would normally be excluded due to feasibility considerations. It could be argued that a new vehicle could be designed to avoid having such a high bonnet leading edge, and that any vehicles that are designed this tall will therefore have to be designed to pass the headform test in this difficult area. This option would give a greater benefit to pedestrians. Another option would be to find the actual bonnet leading edge and to allow the headform test zone to start behind it, regardless of height. This, however, could mean that as the vehicle got higher at the bonnet leading edge, taller pedestrians would not be protected, which in practice would be child pedestrians of increasing age, of ages at which the accident frequency rapidly increases. However, the suggestion below attempts to find a balance, by avoiding abrupt changes in the test zone while putting a limit on the potential head test zone that can be 'lost'. The limit value suggested should ideally (for pedestrians) be lower but lower values would affect increasing numbers of vehicles that are within the current scope, and are therefore outside the remit of this study, and which are otherwise adequately covered by the existing rule. Some vehicles of less than 2.5 tonnes GVW may be affected but it is thought that most vehicles tall enough to be affected would be heavier than 2.5 tonnes. Most of the vehicles >2.5 tonnes affected by the suggestion would not be tall enough to require the straight edge to be raised. If it was decided that only those vehicles tall enough to require the straight edge to be raised should be affected by a limit on the front of the head test zone, then the limit value would need to be at about 1325 mm wrap around distance (height of the top end of straight edge, 1243 mm, plus the headform radius, 82.5 mm). Any discussion on this value should be informed by anthropometric and accident frequency data.

- If the top end of the straight edge contacts the vehicle below a major and convex change in the angle of the front end, below the windscreen, then the straight edge should be raised to contact the vehicle on that change of angle, and that contact should be the bonnet leading edge reference line.

- The front edge of the headform test zone should not exceed a wrap around distance of [1200 mm], irrespective of the position of the bonnet leading edge reference line.

This change is required if flat-fronted vehicles are included in the scope. If a figure is required, the current ‘Corner of bumper’ figure could easily be adapted.

- Where the bonnet angle is less than [45°] to the vertical, the side reference lines should be determined with the straight edge held horizontally, at 45° to the longitudinal axis of the car, and moved inwards towards the front.

7.6.2 Additional changes that could be implemented relatively quickly

In Table 7.1, the IHRA PSWG simulation results (Mizuno, 2003) for headform impact conditions appropriate to a 40 km/h vehicle speed, were shown. However, these simulations have been the subject of much discussion and re-analysis. Cases can be made for including or excluding certain simulations or even all results from two of the three models used. There may also be a preference to minimise the number of different test conditions. It isn’t clear to the authors as to whether the results in Table 7.1 are the definitive recommendations of IHRA for headform testing. A document presented to the GTR group (Anon, 2005a) recommends a head impact speed ratio or ‘k’ value of 0.8 for all vehicle shapes. This would give headform impact speeds of 32 km/h in all cases. However, the GTR group at the 8th meeting (Anon, 2005b) decided to accept the EC’s proposal for 35 km/h. The IHRA simulations covered all vehicle types except the flat-fronted vehicles and possibly large examples (i.e. with a high bonnet leading edge) of angled-front vehicles. The latter share characteristics with both the SUV and the angled-front vehicles, so it would seem reasonable to treat them in the same way. However, the flat-fronted vehicles will have a relatively direct impact to the head so a higher impact velocity might be appropriate in order to give the same level of protection. As the shoulder will be impacted first the head impact velocity will still be less than the vehicle velocity. With a common impact velocity for every other vehicle shape there would clearly be considerable resistance to setting a higher velocity for flat-fronted vehicles, and no data are available to support any specific value. Therefore, the same headform impact velocity of 35 km/h should be used for these vehicles also.

The other principal test parameter is the impact angle. Again, the IHRA simulation results are shown in Table 7.1 and some proposals are made in Inf. Gr. PS58 (Anon, 2005a). However, the GTR group discussed headform velocity and angle together, because the angle of the headform in relation to the angle of the impacted surface affects the normal velocity and hence the crush depth required. This therefore affects the feasibility. It was considered to be unfeasible to combine the higher EC velocity proposal with the generally more normal IHRA simulation headform angles, so the EC package of the 35 km/h impact velocity in combination with the EC / WG17 impact angles was selected as the more demanding of the two options. These were therefore accepted by the GTR group for the three IHRA vehicle types and could reasonably be applied to larger vehicles of these types. However, these child and adult headform angles are both more vertical than horizontal, and do not therefore seem to be appropriate for a flat-fronted vehicle where the impact would be much nearer the horizontal. The nearest comparison in the IHRA simulations was the ‘1Box’ to child impact, for which 25° to the horizontal was the selected impact angle. It is therefore suggested that this angle be used for flat-fronted vehicles, for both the child and adult headforms. In most cases this will give a similar impact angle relative to the impact surface as with the other vehicle types, so this should not add to the feasibility difficulties. However, there could be vehicles of intermediate shape which attract a near normal impact, if they are classified as flat-fronted.

Once a different headform impact angle is introduced it would become necessary to decide which vehicles fall into the flat-fronted category, so that any future vehicle can be tested, even if no current vehicles are a similar shape. If a typical angled front vehicle has a bonnet inclined at 50° to the vertical then flat-fronted vehicles could be defined as anything with a bonnet angle of less than 25°.

This definition would need more detail. Perhaps the average angle could be taken between a point a short distance above the bumper and the base of the windscreen.

As there is some evidence that the bonnet leading edge of high vehicles can cause higher rates of injuries, the argument could be put forward that the bonnet leading edge test in the EU's phase two tests should have mandatory pass requirements for some high vehicles, beyond a given height threshold. Given the limited data available, particularly for European vehicles, this is essentially a choice between having a requirement until such vehicles are proven to be safe and not setting a requirement until they are proven to be unsafe. This is essentially a political decision.

7.6.3 Suggestions for additional research and development

If there was a need to carry out further research, whether for a first or for second phase of test requirements for larger vehicles, in order to provide the best possible test procedures and hence VRU protection for large vehicles, then the following issues could be examined.

- There is a need for more accident data on large vehicle to VRU impacts. In particular, there is a need for the detailed 'on-the-spot' type of study that obtains detailed injury data and attempts to match it to parts of the vehicle or environment. As much of the available data on large vehicle impacts come from the USA there is a need to obtain data from Europe and elsewhere.
    - One specific point that should be addressed is whether the rate of injuries caused by the bonnet leading edge of large vehicles has followed a similar trend to the rate for passenger cars, or whether it continues to be a significant injury rate, and if so at what threshold of vehicle size does it become a problem?
- The injury data obtained may reveal common injury modes with large vehicle impacts that are not normally seen in conventional car impacts. This may then need biomechanical testing to better understand these injury modes and to develop injury risk curves.
- As modelling techniques improve generally they should also be applied to modelling large vehicle impacts, as improved models may give different test parameters. The IHRA PSWG intends to refine its models further. Elsewhere the THUMS finite element (FE) model is increasingly being used for modelling pedestrian impacts.
- Depending on the new injury data, there may be a need to develop additional sub-system impact tests using new impactors, to protect against injuries not covered by the current set of sub-system tests. One possibility is a test using a thorax impactor. A series of child thorax impactors of different ages was developed by Hamilton (1988), but were not taken up in legislation. These or similar devices, possibly including an adult size, may have a place for testing large vehicles. An abdomen impactor might be another possibility.
- One of the headform parameters obtained from the modelling is the required headform mass. As this is the effective head mass in the impact it is not necessarily the static head mass; it can differ from that due to forces acting through the neck. The required headform mass could vary when different sizes and shapes of vehicle are considered.
- Different acceptance criteria might be required, particularly if an impactor is used as a surrogate for a different part of the body. Also, different feasibility adjustments might be necessary for different vehicle sizes and shapes.
- A more detailed feasibility study may be required.

7.7 Options for extending the scope

There are an almost unlimited number of possible ways of extending the scope, so these options could be regarded as indicative.

The vehicle scope, in terms of weight, is currently vehicles of a maximum mass not exceeding 2.5 tonnes. ‘Maximum mass’ here is understood to be the same as gross vehicle weight (GVW). An ‘easy option’ is therefore to increase this limit to a higher value. A 3.5 tonne limit would for instance include virtually all M1 vehicles and would have the advantage of coinciding with the N1 / N2 boundary and with the M_1 scope in the frontal protection system (FPS) Directive 2005/66/EC (European Parliament and Council, 2005). The pedestrian Directive (2003/102/EC (European Parliament and Council, 2003), under ‘Whereas’ 5) asks the Commission to consider the feasibility of an extension to this maximum weight. Another option would be all M1 vehicles. This would include some unusual M1 vehicles such as M2 or M3 base vehicles that have had most of the seats removed; many of these may be covered by the small volume exemption.

As the vehicle manufacturer can declare the GVW, with there being no standard procedure for measuring it (unless the payload is first specified), a manufacturer of a vehicle of about 2.5 tonnes is likely to find it advantageous to have a GVW of just over 2.5 tonnes. A limit based on the unladen or kerb weight is therefore better, as it is a measurable quantity. The EC has proposed an increase in scope to 2.5 tonnes unladen weight. It can be seen from the weights in Figure 7.2 that an unladen weight of 2.5 tonnes could equate to GVWs of up to about 5 tonnes for goods vehicles or up to about 4 tonnes for passenger vehicles. It should also be noted that using unladen weight for the minimum mass limit of 0.5 tonnes would reduce the range of vehicles within the scope, not increase it, but by very few vehicles in practice.

For goods vehicles, potentially the greatest change would be the extension to vehicles that were not car (M_1) derived as this would include many vehicles of different shapes to those of most cars, including flat-fronted or angled-front vehicles with no bonnet top. These are not vehicle shapes that the pedestrian tests were designed for. Options include retaining the current N1 vehicles derived from M1, or using the similar UNECE requirement of vehicles having the same general structure and shape. An alternative would be to include all N1 vehicles. A ‘middle way’ might be to include some N1 vehicle shapes but not others.

Some N1 vehicles have a vertical frontal shape to which, with the exception of the bumper test, the pedestrian test methods are less well suited, because they were intended for cars. Therefore one possible option is to include NI vehicles not derived from cars, but only those of M1 shapes. This would include angled-front vans as their shape would be similar to the MPV or ‘1Box’ style of passenger vehicle. However, it should be noted that this option may encourage migration towards flat-fronted vehicle designs to avoid having to meet pedestrian protection. Flat-fronted vehicle designs by their nature are more likely to offer poorer occupant protection and fuel efficiency than conventional designs. If this option is used, a definition will be needed for those ‘not of car shape’, so that they can be excluded, or alternatively a definition will be needed of those of car shapes so they can be included. Consideration could be given to a rule based around the horizontal distance between ‘R’ point and front axle position, as the driver sits well forward in this type of vehicle. Although such a rule would be good at identifying flat-fronted vehicles, it might also select vehicles with a car-shaped bonnet and large overhang in front of the front axle; therefore it would need to be combined with a front overhang rule. An alternative rule could be based on the horizontal distance between ‘R’ point and front bumper face but this might include some car-shaped vehicles with both a short bonnet and small front overhang.

It is interesting to note that Directive 74/297/EEC (Council of the European Communities, 1974, as amended) also excludes vehicles of this type. They are called forward control vehicles in the Directive, as the flat-fronted style of N1 is normally combined with the driver sitting more forward in the vehicle, typically with the engine between the front seats or in the rear. The definition of a forward control vehicle can be found in footnote (z) of annex 1 of Directive 70/156 (Council of the European Communities, 1970, as amended) and states: “‘Forward control’ means a configuration in which more than half of the engine length is rearward of the foremost point of the windscreen base and the steering wheel hub is in the forward quarter of the vehicle length." The option of using this definition could be considered, although a definition of what is half of the engine length might also be needed. The Japanese technical standard also uses a similar method to exclude such vehicles. Only goods vehicle "whose engine is located forward of the driver's compartment" are included and this is defined as the mid-point between the front and rear edges of the engine main body being forward of the foremost section of the lower edge of the windscreen glass.

7.8 Further discussion

The benefits of providing VRU protection by secondary safety means (i.e. excluding brake assist systems) to the standard proposed by the EC for phase two were estimated by Lawrence *et al*. (2006) to be €3,420 million, with costs of €995 million. Hence the cost to benefit ratio for the secondary safety protection can be estimated as 1 : 3.4.

With a higher proportion of sales than of accidents, particularly for serious injury accidents, the benefit per vehicle would be less for light goods vehicles (N1). However, for vehicles over 3.5 tonnes GVM the benefit per vehicle would increase, as fatal accidents are particularly high. These comments are based on GB data, see Section 7.2, and may not hold elsewhere, particularly outside Europe.

For cars with high sales per model, the costs are dominated by the increased manufacturing costs. Typically, manufacturing costs are about 90 percent of total costs, with development costs the other 10 percent. For N1 vehicles the increased manufacturing costs per vehicle should be broadly similar. However, the total development costs will also be similar, but there will be fewer vehicles over which these costs will be shared out. N1 vehicles sold are roughly a tenth of car sales. If it is assumed that there are a similar number of models, so that vehicles sold per model are a tenth of the figure for cars, then development costs per vehicle will be ten times the amount for cars. Total costs per N1 vehicle will then be about twice the amount for cars. Note that 'model' here would relate to a common vehicle front end. A number of different vehicles may share the same front end but would be different models for the purposes of type-approval. However, for the VRU requirements these could be treated in the same way as different variants of a car model are currently treated, to reduce the amount of development and testing required.

Taking the reduced benefit with the increased cost, the cost to benefit ratio for providing VRU protection on N1 vehicles will be close to 1 : 1. It isn't possible to estimate whether the costs or the benefits would be the greater without a more detailed study, and probably even then the uncertainties would be too large to be certain.

It follows that for low volume M1 and N1 vehicles the costs may often exceed the benefits. When considering volume here it should be remembered than many low-volume models will be coach-built upon a vehicle chassis or made by converting another vehicle. In these cases the VRU protection is likely to be provided by the donor vehicle and therefore the development costs could be shared more widely.

Nevertheless, there may be cases where consideration should be given to exempting some vehicle models, perhaps via a 'special vehicle' status. As a possible example, the difficulties for camper van manufacturers have been brought to the authors' attention. These are M1 vehicles, typically of between 2.5 and 3.5 tonnes GVW. They are typically made from an N1 chassis cab vehicle or by converting an N1 vehicle, with small model runs. Moreover, the annual distance driven will mean that they have a low accident rate and hence a low potential benefit. If the vehicle scope were extended to heavier M1 and to N1 vehicles (at the same time) then the donor vehicles would provide the required VRU protection. However, if heavier M1 vehicles were required to provide protection but not N1 vehicles then the costs and difficulties of complying may be prohibitive for many manufacturers of these vehicles.

It is possible that the test area on vehicles could be extended at some future time to cover part or all of the windscreen and windscreen frame; this was discussed in Section 6. If this was combined with the increase in vehicle scope discussed here there may further issues arising that haven't been considered here. An extension of the test area on some of the vehicle shapes considered here could be particularly advantageous, as the current test area would protect relatively few of the pedestrians hit. This would be true of vehicles where the A-pillars and windscreen are close to the front of the vehicle, i.e. flat-fronted and angled-front vehicles.

7.9 Conclusions

1. A very approximate estimate of the savings of an expanded scope to cover all or most of the M and N vehicles over 2.5 tonnes is of savings of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive's savings.
2. A number of options to extend the scope of the Directive to include larger vehicles have been identified. These include an extension for M1 vehicles to 3.5 tonnes GVW, to 2.5 tonnes unladen or the removal of the weight limit. For N1 vehicles, options include retaining the restriction of testing only N1 vehicles derived from M1 vehicles, extending to N1 vehicles of similar basic shapes to M1 vehicles or extending to all N1 vehicles.
3. The interactions of pedestrians with these larger vehicles and potential problems in using the test tools and methods have been discussed.
4. The current test methods could be adapted for testing larger M1 and all N1 vehicles with the minimum set of changes summarised below. However, the operation of the amended test procedures should be checked by marking-up and testing a sample of large vehicles.
    a. References to direction should be clarified where necessary.
    b. When necessary, raise the straight edge used to determine the upper bumper reference line.
    c. When necessary, make the straight edge used to determine the bonnet leading edge reference line more vertical, and in extreme cases do not determine the reference line.
    d. When necessary, raise the straight edge used to determine the bonnet leading edge reference line. A maximum limit on the wrap around distance at which the headform test area starts is also suggested.
    e. Where the bonnet is more vertical than horizontal, change the orientation of the straight edge used to determine the side reference lines.
5. The following further changes might be implemented or considered relatively quickly:
    a. Change the headform impact angle to 25° from the horizontal for flat-fronted vehicles. These vehicles could be defined as those where the bonnet angle is within 25° of the vertical.
    b. Consider whether there should be a mandatory pass requirement in the upper legform to bonnet leading edge test for vehicles with a bonnet leading edge beyond a certain height.
6. A number of suggestions have been made for a longer term research programme, if this is needed in order to provide the best possible test procedures and hence VRU protection. These include accident study, biomechanical testing, improved simulations, and possibly development of additional impactors to represent other body parts. However, extension of the vehicle scope should not be delayed until the results are available; any improvements arising from the research should be used in a second phase of test procedures.
7. An extension of vehicle scope to larger vehicles including N1 vehicles will result in an improvement in the safety of VRUs. However, based on GB data, N1 vehicles have a lower involvement in fatal and serious pedestrian accidents over their lifetime than do cars. Also, it is expected that the cost of developing a safer N1 vehicle model will typically have to be shared

over a smaller model run. A rough estimate is that the costs will be about the same as the benefits.

8. For some low-volume vehicles the costs of protecting VRU would be disproportionate to the benefits. Consideration should be given to exempting such vehicles.

8 Newer Technologies: The Potential of Brake Assist, Collision Mitigation and Collision Avoidance Systems

8.1 Introduction

Technologies such as Brake Assist Systems (BAS) and, potentially, collision mitigation and collision avoidance systems offer significant reductions in road accidents and hence injuries, with these benefits occurring in all types of accident. Currently BAS and several other new technologies are being fitted to an increasing proportion of new cars as a result of increasing customer demand and falling costs. This hasn't been an issue requiring legislation or the setting of minimum standards, other than the general principle that such systems should fail safe so that the driver should never be at greater risk with a failed system than they would be if no system had ever been fitted. However, the possibility that BAS could be fitted earlier to all cars as part of a package of pedestrian safety measures, giving an equivalent or better overall level of protection than the proposed secondary safety requirements alone, has recently been the subject of discussion between the European Commission and the car manufacturers. The feasibility study's benefit analysis (Lawrence *et al.*, 2006) indicated that this package provided greater protection for pedestrians than the originally proposed more stringent level of secondary pedestrian protection without BAS. It is therefore desirable to require a minimum standard for BAS that at least corresponds to the assumptions made in the benefit study. This principle could potentially be applied to other new technologies whether for the benefit of pedestrians or other road users. The draft Regulation to replace the current Directive (2003/102/EC) on pedestrian protection allows for collision avoidance to be used as an adjunct to the requirements, subject to it achieving a sufficient degree of reliability.

The objectives of this chapter were:

- Brake Assist Systems
    - To provide an update on the accident statistics used for benefit analysis
    - Identify specific requirements for these systems that could be used in regulation
    - Make clear recommendations regarding regulatory action or change
- Collision mitigation/avoidance systems
    - To review appropriate accident data where available to examine the potential injury benefits – based upon EU data.
    - To identify the technical requirements that could be included in legislation.
    - To perform a cost benefit analysis to balance the likely cost of introduction against the benefits in injuries and related issues such as congestion, etc.

The work required to meet most of the objectives for BAS was in fact carried out as part of the ECs feasibility study (update) for the pedestrian protection Directive (Lawrence *et al.*, 2006). This report will summarise the findings of this recent review and update them with subsequent developments. The potential of collision mitigation and avoidance systems will be considered in line with the above objectives.

8.2 Brake Assist Systems

A wide range of research has been carried out investigating driver behaviour during emergency braking. This research has consistently found that most drivers do not make effective use of the full capability of the braking system available to them. Brake Assist Systems (BAS) were developed with the intention of improving drivers' braking performance in emergency situations. The basic concept is that the system will detect when a driver intends to make an emergency stop and will act to try and increase the likelihood that full ABS braking will be achieved quickly.

BAS was included as part of the proposed package of pedestrian protection measures on the basis of accident analyses reported by Hannavald and Kauer (2004a and 2004b). This analysis used GIDAS data to predict the benefits of BAS and derived a figure that as a single measure pedestrian fatalities and serious injuries would be reduced by approximately 5 percent. However, the analyses carried out was criticised by Lawrence *et al.* (2006) because of the assumption that the deceleration reached would be increased in certain cases where the presence of speed information in the data could only have been derived from tyre marks on the road suggesting that the vehicle was already very close to the maximum deceleration that the tyre road friction would permit.

It was found that other analyses (Page *et al.,* 2005) had been carried out since the time of the original analyses and that two separate methods were used. The first method was a predictive study similar to that carried out by Hannavald and Kauer (2004a and 2004b) but using a different set of assumptions that were considered to be more robust. The second method was a retrospective statistical analysis of accidents where vehicles with and without brake assist were actually involved. This was a considerably more robust method than the other two but suffered from limitations of small sample sizes and was unable to produce statistically significant results. Lawrence *et al.* (2006) concluded that it was possible to be scientifically confident that fitment of BAS would reduce pedestrian casualties by between 0 and 12 percent but that the various uncertainties inherent within the accident analyses would mean that any estimates of the effect of BAS, based on the existing accident data at the time, that were more specific than this would carry a substantial risk of over or under-estimating the magnitude of effect. However, accepting these risks, a more specific estimate of the effect was made as part of the cost benefit analysis and suggested that BAS would result in a reduction of all pedestrian fatalities of 7.7 percent (based on the difference between the EC proposal with and without BAS). It should be noted that the sources of literature studied did not always make it clear exactly how the percentage reductions were derived so it is possible that the various percentage reductions are not directly comparable.

The research into real drivers braking behaviour and the technical operation of current BAS were reviewed in order to identify technical requirements of the system that could be embodied within regulations. It was found that a range of different systems were in existence and that these had different characteristics. Only one proposal for test procedures and performance limits was found. It was concluded that this procedure did not have an adequate scope to cover all of the systems in existence and that in certain areas there were no constraints on performance. It was recommended that further work was carried out in order to develop the test procedure further to account for all current systems and to better define performance limits.

It was also found that there had been little or no published research that had evaluated whether any one system or set of characteristics was better, in terms of improving driver braking performance, than another. A further recommendation was that suitable research should be carried out to determine whether the performance of systems varied such that in future an improved optimised standard could potentially be applied.

In the short time since the completion of the study by Lawrence *et al.* (2006), these technical issues have been moved further forward. The EC is now running a new research contract with the specific objective of developing a proposal for regulatory requirements for BAS that would take account of systems presently available and ensure proper levels of quality and performance. It is intended that the requirements will be proposed to GRRF for incorporation in UNECE R13. In addition to this, the project is to carry out research in a driving simulator to consider whether there is scope for amending the requirements to be more demanding in future to produce optimised, higher performance BAS.

8.3 Further developments of brake assist and collision mitigation braking systems (CMBS)

One of the limitations of a BAS is that it is entirely reliant on the driver of the vehicle applying the brakes and applying them in a manner that falls within the BAS definition of an emergency application. Lawrence *et al.* (2006) showed that the compromises required for BAS between helping as many drivers as possible in an emergency and not interfering with ordinary driving would mean that some drivers that braked would inevitably fail to activate at least some versions of BAS. In order to solve this problem, enhanced BAS have been developed that combine the BAS with the radar sensors used for autonomous cruise control. In these cases the radar system is used to detect whether emergency braking is required and, if it is, the BAS will apply the appropriate level of braking as soon as the driver activates the brake pedal, regardless of how hard or how quickly the pedal is pressed. However, action will *only* be taken if the driver presses the brake pedal at least to some extent.

This type of system has been developed further into a system that will activate the brakes when a sensor detects an imminent collision even if the driver does not press the brake pedal at all. The systems currently on the market (for example, Honda Legend, Mercedes 'S' class) will only act when the collision is deemed to be inevitable such that the effect is only to reduce the collision speed and not to fully avoid the accident. Alleaume *et al.* (1998) found that 30 percent of the car drivers that should have braked before an accident did not, in fact, brake at all. The same sensor signal can also be used to activate secondary safety devices, such as seat belt pre-tensioners, before the crash has taken place. This suggests that there is a substantial scope for CMBS to reduce the consequences of collisions.

At the current time, these enhanced braking systems cannot influence the level of safety in pedestrian accidents because the sensing systems currently used in the production versions cannot reliably detect pedestrians. However, investigation of these systems more generally has been carried out by TRL as part of a separate project with the EC, due for completion in March (ENTR/05/17.01 Automated Emergency Braking Systems). This project has been carried out with open involvement of industry from the start and vehicle manufacturers and tier one suppliers were asked to complete a survey requesting information on current production systems and near market systems under development. This survey revealed that CMBS systems capable of being effective in pedestrian accidents are under development and in some cases, in the final validation phases. For example, one tier one supplier described four CMBS systems that were under development. Each of these was expected to have some capability for the detection of pedestrians and one of the systems was designed specifically for pedestrian and other vulnerable road user (VRU) accidents, based on the use of far infra-red sensor technology. The pedestrian and VRU specific solution was still in the concept development phase but the other systems were more advanced.

It is, therefore, clear that in years to come, more advanced and automated braking systems do have the potential to further reduce the number of casualties in pedestrian accidents. However, no such systems are yet on the market and it may be several years before they reach market and longer still before a substantial proportion of the vehicle fleet are equipped with the system. The development of such systems is clearly to be encouraged, but considerable amounts of further research will be required before the benefit of these systems can be quantified with any degree of accuracy. Issues that may need consideration include:

- Evaluation of the proportion of pedestrian accidents that do not involve pre-impact braking
- The time available before collision during which braking, or other action, could be taken in those accidents (i.e. is there no braking because the pedestrian steps off the kerb immediately in front of the vehicle or is it due to lack of attention/action by the car driver?)
- The reliability of detection and the consequences of false positives
- The technical requirements of the system, for example, compatibility of sensing systems
- Methods to test the system and demonstrate minimum standards of performance

8.4 Collision avoidance

In its simplest form, collision avoidance can be a basic reversing aid that is fitted or optional on many cars. A significant step forward has been in forward collision avoidance in the form of autonomous cruise control to maintain the headway between following vehicles; also optional on many higher value cars. The next step, which is already being demonstrated by some manufacturers, is the use of forward collision warning to provide the driver with a suitable warning that a collision is likely and that action needs to be taken. Another improvement in safety will be possible with the application of enhanced Brake Assist technologies and collision mitigation braking systems, which combine the sensing technologies used for adaptive cruise control and collision warnings with the braking technology used by brake assist. Ultimately, fully automated collision avoidance will be possible which, in principle, could take away some or all of the control currently exercised by the driver.

Manufacturers worldwide are researching these areas and demonstrating prototypes. Examples of these systems include a system to automatically brake and steer the vehicle to avoid an impact and systems that provide haptic feedback to discourage the driver from making the wrong manoeuvre. Much of the research within the European Union has been carried out as part of the PREVENT Integrated Project which includes many sub-projects relating to specific topics. The PREVENT website provides details of these particular projects, (www.prevent-ip.org). Other projects have been carried out in national programmes such as the INVENT programme in Germany and FORESIGHT VEHICLE programme in the UK. Outside the EU, there is the American Intelligent Vehicle Initiative programme, (www.fta.dot.gov website) and the ASV programme in Japan, (http://world.honda.com/news/2005/c050902.html website). These are both major programmes looking at different active safety measures including:

- Communication technology
- Intersection safety
- Vision enhancement
- Vehicle speed adaptation
- Adaptive cruise control
- Pedestrian detection
- Forward obstacle detection
- Collision mitigation
- Lane following/change safety

Fundamental in any collision avoidance system is identifying a 'safety zone' in front of the vehicle such that if any object enters this zone then action needs to be taken in order to prevent or mitigate a collision. An example is shown below:

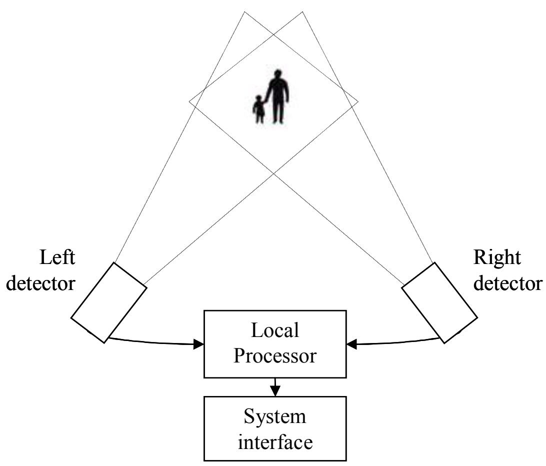


Figure 8.1. Example of 'safe zone in front of vehicle'

The 'safety zone' is intended to be the zone in front of the vehicle where the range is appropriate to take suitable mitigating or avoiding action. The position of the zone will vary depending upon the safety systems fitted to the vehicle. For example, an autonomous braking system can control the forward headway whilst a steering system can be made to swerve around an obstacle. Systems that employ steering control are able to respond later, and hence closer to the vehicle, than a braking system alone. The 'safe zone' will also vary depending upon the vehicles' speeds and road conditions. This zone will vary depending upon the vehicle's speed and the road conditions. To some extent, the performance of the vehicle may also affect this 'safe zone'; for example the braking and handling characteristics of the vehicle. The sophisticated electronic control systems can only work within the physical performance envelope provided by the brakes, steering, suspension, tyres and road surface. Ideally, it is important to be able to detect objects well before the 'safety zone' is entered in order to provide the optimum benefits from pre-crash sensing. Key to this aspect of the problem is the sensing technology used to detect objects in the forward path of the vehicle. The types of sensors suitable for this application include:

- Radar
- Infra-red
- Video cameras
- Laser
- Ultra sonic
- mmWave detectors

Examples of these are shown below:

Figure 8.2. Typical radar device used by Bosch

Figure 8.3. 'ALASCA' Laser scanner produced by IBEO

Figure 8.4. Passive mmWave detector from Millivision

Radar technology is well-understood and many systems are now used in vehicles. The main area for development has been in producing reliable low cost systems for the automotive industry. There is scope to develop multi-function radars where the beam characteristics can be modified to provide good long and short range performance. Radar systems cannot differentiate between types of object but do provide good range and position information. Infra-red technology is also well understood and has been extensively developed for military and covert operations. Simple systems are relatively cheap but more complex devices providing high quality images are still relatively expensive. Video camera technology offers a cheap solution but needs complex processing to differentiate between different images in the field of view. In comparison, infra-red is capable of differentiating 'hot' objects such as humans but has a limited image as infra-red systems cannot penetrate clothing. Laser systems can provide accurate object detection but again cannot differentiate between types of object. Ultra-sonic systems have mainly been used for short range systems, e.g. parking aids. They are limited in performance and range and are significantly affected by rain and moisture although they are very cheap. An interesting technology that has been developed from radio astronomy is the detection of passive mmWaves. In broad terms mmWaves extend from about 30GHz to far infra-red, often referred to as TeraHz. This type of electromagnetic wave has the advantage of detecting 'hot' objects and being able to penetrate clothing and therefore, has the potential to provide a better solution for pedestrian detection. To date systems have been developed for security and medical purposes, for example airport scanners and skin cancer detection. Currently these devices are expensive but could be mass produced using micromachining techniques that would significantly reduce their cost. At present, Autoliv, (Kalhammer *et al.*, 2006) and Sagem with others (COMPOSE Integrated Project within PREVENT) are examples of two manufacturers investigating this technology as well as TRL within the EC funded TRACKSS Integrated Project.

8.5 Review of accident data

According to Road Casualties Great Britain (Department for Transport, 2006), during 2004 there were 41,383 road users killed in the European Union (EU25, excluding countries where no data are available), of which 19 percent involved pedestrians. Whilst this percentage is lower than the worldwide average of about 25 percent, it is high compared with the figure for the USA (11 percent) although significantly lower than the 31 percent found in Japan (Department for Transport, 2006). Table 8.1 shows numbers of fatal accidents in most of the European Union (EU25) countries.

A great deal of research into accidents has been carried out within the European Union and, in particular, in the UK where the Department for Transport has been collecting and analysing accident data for decades. TRL has carried out many detailed analyses of road traffic accidents as part of UK government funded projects. Of particular note are the Active Adaptive Secondary Safety project (AASS) for the Department for Transport and the Advanced Protection of Vulnerable Road Users project (APVRU) for the Foresight Vehicle Programme. These projects demonstrated how pedestrian injuries could be reduced (AASS) and a system for detecting pedestrians using a combination of radar systems and an infrared camera (APVRU). The research (McCarthy and Simmons, 2005) showed that the use of frontal airbags mounted externally on the vehicle in the areas of the front bumper and on the bonnet could reduce:

- Head injury coefficient (HIC) by 93%
- Chest acceleration by 76%
- Pelvis acceleration by 24%
- Knee lateral angle by 40%
- Lateral knee force by 4%

Table 8.1: Numbers of fatal road accidents in EU-25 and selected other countries (mostly 2004 data) (Department for Transport, 2006)

Country	Total fatal accidents	Pedestrian fatal accidents	Pedestrian percentage
UK	3368	694	21.0
Austria	878	132	15.0
Belgium	1162	101	8.7
Denmark	369	43	11.7
Finland	375	49	13.1
France	5530	581	10.5
Germany	5842	838	14.3
Greece	1605	857	53.4
Irish Republic	337	64	19.0
Italy	5625	710	12.6
Luxembourg	50	12	24.0
Netherlands	804	65	8.1
Portugal	1294	233	18.0
Spain	4741	683	14.4
Sweden	480	67	14.0
Cyprus	-	-	-
Czech Republic	1382	281	21.7
Estonia	-	-	-
Hungary	1296	326	25.2
Latvia	-	-	-
Lithuania	-	-	-
Malta	-	-	-
Poland	5712	1986	34.8
Slovakia	-	-	-
Slovenia	274	35	12.8
Japan	8492	2609	30.7
USA	42636	4641	10.9
Canada	2725	367	13.5

Figure 8.5 below shows the types of vehicle involved in pedestrian accidents where there was a fatal or serious injury to the pedestrian.

It is not surprising that the majority of injuries, whether fatal or serious, occurred when the pedestrian was impacted by a passenger car, and it is known that most would have involved impact with the front of the car. Another analysis examined the distribution by age of the pedestrian casualty and is shown in Figure 8.6.

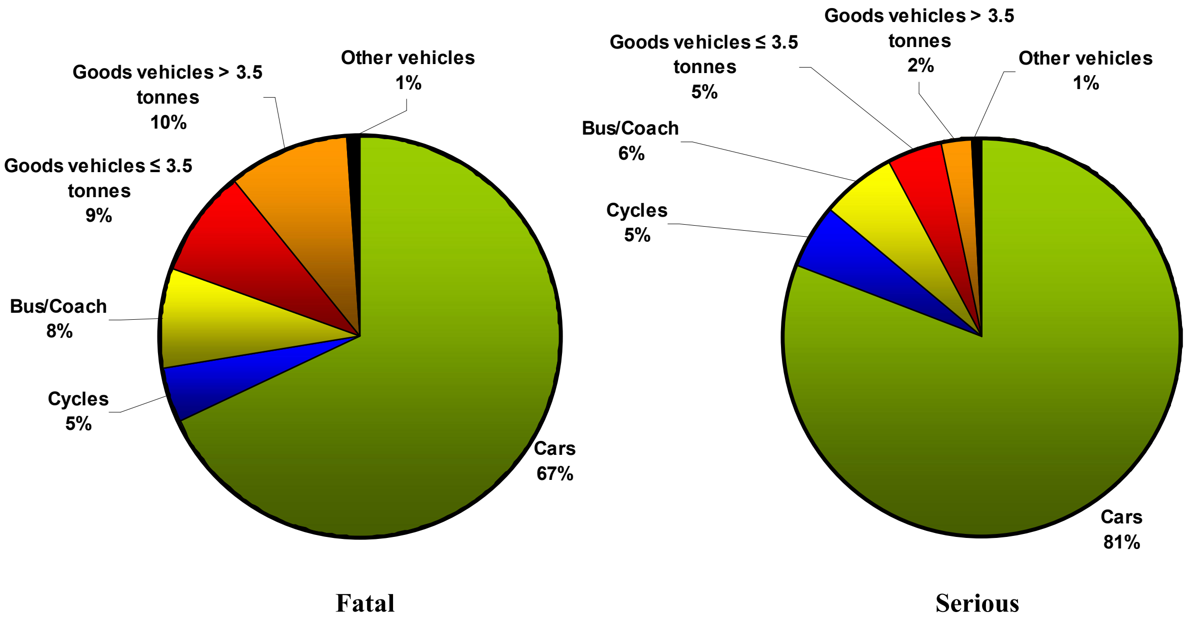


Figure 8.5. Vehicles involved in fatal and serious pedestrian accidents (GB data, 2005 data)

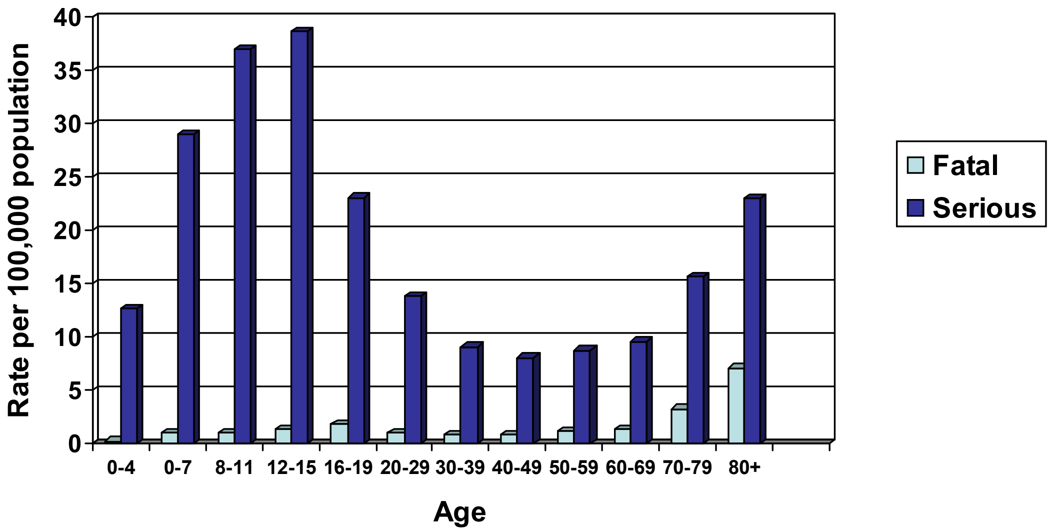


Figure 8.6. Fatal and serious pedestrian injury rates, split by age

It is evident that in the UK, those under 19 years old are at most risk of serious injury whilst there is also an increase in the risk for the older population over 69 years old. In the case of fatal injuries, there is a substantially higher rate per unit of population when the collision involves people over 69 years old. Similar results have been found in the APALACI sub-project within the PREVENT IP based upon German accident data http://www.prevent-ip.org/).

A more detailed analysis revealed the areas of the body most frequently involved in impacts and the particular impact points on the vehicle. These are summarized below:

<u>Injury locations</u>	
Legs	36%
Head	29%
Abdomen/pelvis	13%
Chest	11%
<u>Impact Points on vehicle</u>	
Bumper	25%
Windscreen or frame	28%
Bonnet	35%

Many pedestrian accidents (70 percent) involve secondary impact with the pavement.

In the UK 2005, the major factors in pedestrian fatal accidents were:

Pedestrian failed to look	53%
Careless, reckless or in a hurry	24%
Pedestrian masked from view for some reason	16%
Misjudged vehicle approaching	15%
Drunk	10%

It should be noted that many accidents involve more than one contributory factor such that the sum of all factors can greatly exceed 100 percent.

Work by TRL (McCarthy and Simmons, 2005) has also shown that about 71 percent of fatalities occurred at vehicle speed less than 64 km/h whilst, in Germany, Otte (1999) found that approximately 70 percent of pedestrian impacts with the front of a car occurred at vehicle speeds up to 40 km/h. He also found that 60 percent of pedestrians involved in impacts with the front of the car suffered head injuries. The paper shows that substantial proportions of pedestrians are suffering serious head injuries in relatively low speed collisions such that protective measures should be technically possible.

8.6 Regulation and testing

Because collision avoidance is a relatively new technology in the automotive sector, there are few specific regulations or test methods. However, one example is ISO 15623 relating to forward vehicle collision warning systems (International Organization for Standardization, 2002b). This sets out when warnings should be issued to the driver depending upon relative speeds, distances and so on. Another example is ISO 15622 (International Organization for Standardization, 2002a) relating to adaptive cruise control. It defines the operating parameters for these systems. However, there are a number of generic Regulations and test methods that are relevant to collision avoidance. These include:

- EC Directive 2004/104/EC for automotive electromagnetic compatibility
- EC Directive 1999/5/EC relating to radio transmitters and receivers and now including radar
- EC Directive 2006/28/EC that includes radar within automotive EMC requirements
- EC Directive 1999/519/EC that relates to human exposure levels to electromagnetic waves

- IEC 61508 on the safety requirements for programmable electronic systems in general
- IEC EN 60068 relating to environmental performance
- ISO WD 26262 an interpretation of IEC 61508 for the automotive industry that will be available towards the end of 2007
- ISO TR 10605 relating to electrostatic discharges

As new systems are developed and used for safety critical functions such as collision detection and specifically, in this study, pedestrian protection, there is a need to re-examine many of the regulations and, in particular, test levels that are appropriate to the required levels of safety. Many of the concepts of safety critical systems are defined in IEC 61508 (International Electrotechnical Commission, 2005) which develops the ideas of integrity levels, hazard and risk. We recommend that, in general, test levels for systems involved in safety critical applications be reviewed and increased in line with the required integrity level for the system. For example, the Automotive EMC Directive, 2004/104/EC (Commission of the European Communities, 2004b), uses the same test levels that were included in the previous amendment, 95/54/EC, which was introduced in 1996. Since 1996, the safety nature and complexity of electronic systems has grown considerably and the suitability of the levels need to be reassessed to ensure that the developments in technology have been taken into account.

There are several important issues that relate to collision avoidance systems including:

- Potential interaction between detection systems fitted to different vehicles
- For some types of sensor, the fitment to the vehicle so as to provide optimum performance and avoid reflections and resonance effects
- Potential interaction and compatibility with mobile transmitters
- Required reliability levels that are higher than previous equipment in less safety critical applications
- Specific test requirements for the physical performance of the sensing systems
- Specific test requirements for the physical performance of the actuating systems
- Hardware lifecycle issues as defined in IEC 61508, to be replaced by ISO 26262
- Software lifecycle issues as defined in IEC 61508, to be replaced by ISO 26262
- Human factors relating to the driver response, removal and return of control etc being developed within the EC RESPONSE Integrated Project (part of PREVENT).
- Periodic testing to confirm that the system is still working throughout the lifespan of the vehicle.

Reliability is an important issue with the safety critical systems required for collision avoidance systems. Not only must sensing systems provide accurate detection over a prolonged working life but controllers and actuators, although existing technology, need to provide higher levels of reliability than previously required. In addition to the documents and projects described above, there are two useful papers on this key issue. The first describes the AUTOSAR project and examines the issues of functional safety (Furst, 2006) and the second examines the issues for validation and testing of safety related embedded systems (Schoitsch and Althammer, 2006).

Many of the test methods used in the above documents are based upon international standards produced by the ISO and IEC, but they are too numerous to list here and are referenced in the specific documents listed above.

In addition to the above, there are the European requirements for Type Approval, which form the basis for the regulation of all vehicles sold in the EU. In addition to the EC Directives that are implemented by the Type approval system, a wide range of Regulations produced by the UNECE in Geneva can also be used to gain approval.

8.7 Cost benefit analysis

The nature of these advance collision avoidance and mitigation technologies is that many of the systems are still at the development stage and only the earliest systems have yet reached production. This means that there is only limited technical information on their characteristics available and no significant accident experience with them in the field. This means that detailed cost benefit analyses are not really possible at this stage and for reasons described in more detail below, this analysis should be treated as an indication of the *potential* costs and benefits of these systems only.

8.7.1 Systems evaluated

For this cost benefit analysis, three collision avoidance systems have been identified and evaluated:

- Collision warning only
- Collision warning with haptic feedback
- Automated collision avoidance with braking and steering

The collision warning only system is simply a system that will provide the driver with a suitable warning that a collision is likely and that the driver needs to take appropriate action. There is a risk with this type of system that the driver may not take the best or, indeed, any action to avoid the collision so that the potential benefits are lower than for the two other systems considered.

The collision warning with haptic feedback system takes the above warning system one stage further by introducing a level of haptic (i.e. touch sensitive) feedback into the vehicle controls to encourage the driver to take the correct action. For example, this could take the form of increased steering load if the driver chose to steer the vehicle in the wrong direction, but allowing normal steering 'feel' for the correct action. The potential benefits from this system are likely to be higher than for a simple warning system as the driver is being given some degree of help in choosing the correct action to take. Under this heading, we have included systems which provide braking assistance which would lead to some level of collision mitigation (and have not differentiated them). At the present time, the level of information required for a detailed analysis of the individual systems is not available but, in order to provide an initial study, we have simply offered an outline analysis to indicate the potential costs and benefits.

The automated collision avoidance system with braking and steering represents the optimal solution where control is taken away from the driver and the on-board 'computer' decides upon the best line of action and both brakes and steers the vehicle in order to avoid the collision. Theoretically, this type of system could lead to significant reductions in accidents and resulting injuries. However, in practice, it is likely that there would be some accidents that would be very difficult to avoid completely but might be mitigated to some degree. There may also be substantial risks associated with the introduction of this type of system if it is not sufficiently robust to completely avoid false activation of the system. It is likely that this type of system would provide the highest potential benefit although its introduction is likely to be several years in the future.

8.7.2 Benefits (methodology)

This study attempts to provide an initial estimate of the benefits by using the best available knowledge at this time, based on published literature alone. However, the level of detail available in published papers at this time is modest and some major assumptions have been made as described below. In particular, the estimates of effectiveness in terms of accident reduction are assumed rather than based on rigorous analysis of accidents. When more detailed data become available for both costs and accident reduction values, it should be possible to determine a more accurate set of values. However, the analysis offered here can be considered a starting point to provide some initial guidelines but this should be treated as an indication only of the order of magnitude of the potential benefits.

In trying to assess the likely benefits from the various technologies, two sets of outcomes are possible for each accident considered:

1. Preventing the accident occurring altogether.
2. Reducing the level of injury sustained in the accident.

At this time, it is not possible to accurately estimate the potential injury reduction as suitable data are not available. Hence, for this study, we have simply estimated the benefit provided by the prevention of a proportion of the accidents, as discussed below.

From the accident analysis review described above, it has been shown that significant further pedestrian protection benefits could potentially be achieved. However, it is difficult to translate the detailed injury mechanisms discussed previously into the fatal, serious and slight categories of injury because this depends upon the particular accident scenario. Not only is it difficult to determine the number of fatalities, it is also difficult to determine the number of fatalities that could be reduced to serious injuries. Similarly, it is difficult to determine the number of serious injuries that could be reduced and those that could be reduced to slight.

A detailed analysis of TRL's pedestrian fatal accidents database, amongst other data sources, to enable a more robust prediction of the potential benefits of collision avoidance systems would be highly desirable but was beyond the scope of this project. This would provide a more reliable estimate of the potential benefits although estimates of the actual effects will not be possible until sufficient equipped vehicles are in service to permit robust retrospective analysis of accident data using statistical techniques.

For this study, we have had to make some major assumptions relating to the potential benefits of the different systems. These are summarised in Table 8.2.

Table 8.2: Percentages of accidents prevented by each option, split by accident severity

	Options		
Injury severity	**Collision warning**	**C/W + haptic feedback**	**Automated collision avoidance**
Fatal	10 to 40%	30 to 60%	50 to 80%
Serious	20 to 50%	40 to 70%	60 to 90%
Slight	25 to 55%	45 to 75%	65 to 95%

In preparing Table 8.2, it has been assumed that:

- It is not possible to estimate specific percentages in each case; a range of values has been specified.
- The automated collision avoidance system would not prevent all injuries as some accidents are likely to be impossible to mitigate.
- The potential benefits (in terms of percentage avoidance) would increase with decreasing levels of injury.
- The differences in injury savings between the system types are proportional to the performance of the system.

8.7.3 *Analysis*

In order to calculate the cost-benefit ratio, it is necessary to estimate the timing of the introduction of the equipment. It is known that new technology traditionally enters the market in the luxury car sector followed by the executive and then the upper medium, ultimately being implemented in the mass market mini sector. In order to provide a suitable timeframe, it has been assumed that the timings for the introduction as specified in Table 8.3, based upon experience of past history of the introduction of electronic systems.

Table 8.3: Estimated implementation timescales (years), and market proportions, split by car category

Car category	Share of the new car market (%)	Options		
		Collision warning	C/W + haptic feedback	Automated collision avoidance
Mini	1.65	+13	+14	+18
Super-mini	38.38	+11	+12	+16
Low or medium	33.33	+9	+10	+14
Upper medium	21.01	+7	+8	+12
Executive	5.01	+2	+3	+7
Luxury	0.62	0	+1	+5

The table shows, for each car category, the number of years after the initial fit to the luxury end of the market where collision warning systems are now available, hence the value 0. In estimating the benefits in terms of accident savings, the following assumptions have been made:

- the casualty valuations (Department for Transport, 2005) have been used both for the UK and EU25. These are shown in Table 8.4 below.
- the proportions of fatal accidents involving pedestrians, both for the UK and EU25, have been taken from Table 8.1. Proportions of serious and slight injury accidents have been estimated from GB data (Department for Transport, 2005).
- the percentages of accidents prevented are as given in Table 8.2. It has been assumed that these proportions of accidents are prevented completely with no accidents reduced in severity to a lower level of injury (for the reason given in Section 8.7.2).
- for each car category, the benefits occur in full as soon as each safety device is introduced to newly registered cars; retrofitting to used cars (which may be feasible but probably very expensive) is not included in this analysis.
- the proportions of new registrations in each car category are taken as unchanged year-by-year, as given in the table above.
- the savings for Europe (EU25) have been derived from the UK figures using a multiplication factor determined from Table 8.1 (its value is 12.2).
- only car/pedestrian accidents will benefit from the collision avoidance options described in this section of the report. It has been assumed that the benefits will be in the same proportion as car to all vehicle accidents (i.e. 0.651 of all fatalities, 0.662 of all serious casualties and 0.765 of all slight casualties) (Department for Transport, 2005).

Table 8.4: Casualty Valuations (2004 values)

Casualty Severity	Valuation (€m)
Fatal	2.04372
Serious	0.22964
Slight	0.01770

The savings for each of the scenarios are shown in Figures 8.7 to 8.10.

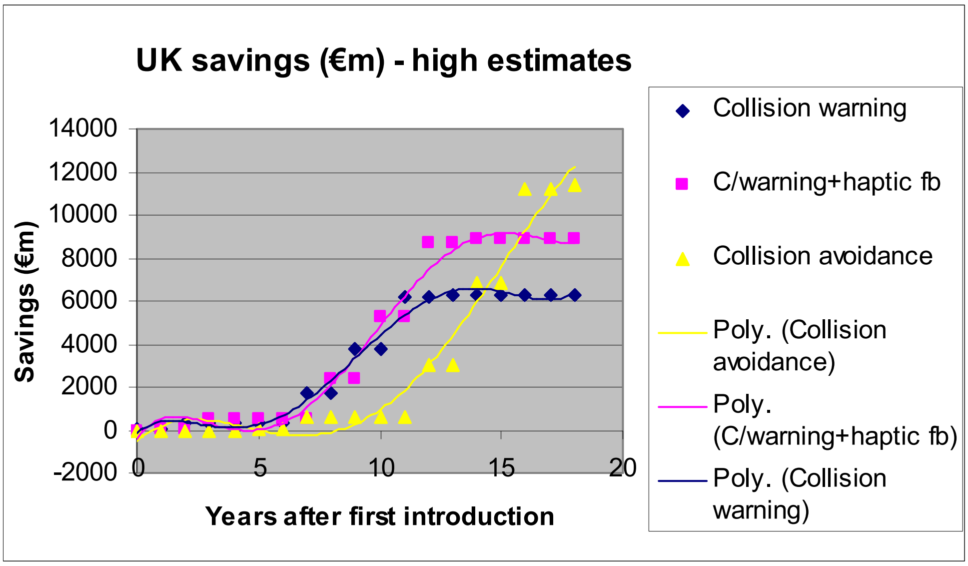


Figure 8.7. Car-pedestrian accidents – potential savings from collision prevention devices [UK high estimates]

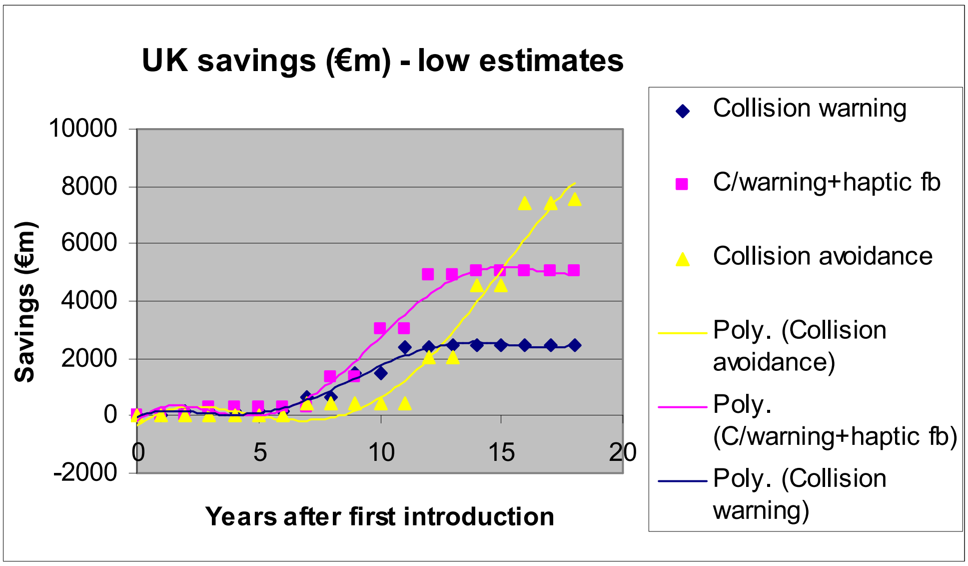


Figure 8.8. Car-pedestrian accidents – potential savings from collision prevention devices [UK low estimates]

The UK savings have been estimated for the collision warning option to lie in the range (15.3 to 39.2 €m) in year 0 but to have increased to between 2461 €m and 6288 €m by year 18. The savings for collision warning with haptic feedback become substantially more than for collision warning by year 12 (the point at which the 'super minis' begin to benefit). Savings for the full collision avoidance option begin to rise steeply from year 12 (the point at which the 'upper medium' cars begin to benefit). From year 16 onward, the savings have been estimated to rise well above those for collision warning plus haptic feedback.

The equivalent figures for EU25 follow the same pattern of savings (as they are simply the UK values factored appropriately). Estimated annual savings for the collision avoidance option have been estimated to lie in the range 92400 €m to 139200 €m by year 18.

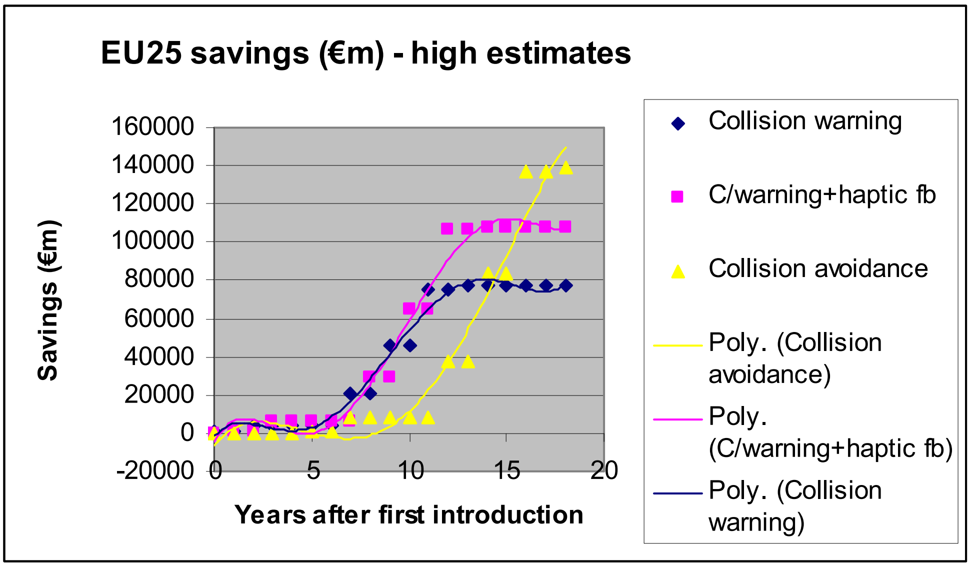


Figure 8.9. Car-pedestrian accidents – potential savings from collision prevention devices [EU25 high estimates]

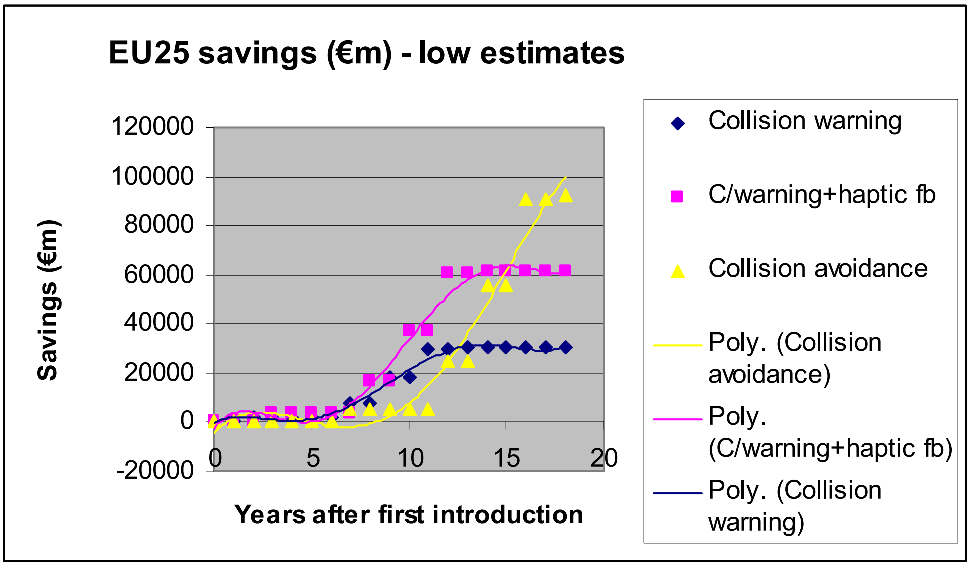


Figure 8.10. Car-pedestrian accidents – potential savings from collision prevention devices [EU25 low estimates]

8.7.4 *Costs*

Estimates of the likely costs of fitting the collision avoidance systems on new vehicles has been based on experience of some areas of existing technology used for adaptive cruise control systems that are currently fitted to luxury and high performance cars. For example, a typical ACC application using a radar system to detect the forward path of the vehicle costs the car manufacturer about €2,250 with a final cost to the purchaser of approximately €4,500. This type of system contains similar sensing technology to that needed for the collision warning and avoidance systems. However, these systems will require additional high reliability processors, controllers and actuators with appropriate high reliability software. Estimated costs of these systems are shown in Table 8.5.

Table 8.5: Estimated system costs for collision mitigation (per vehicle)

System	Cost to manufacturer	Cost to purchaser
Collision warning system only	€3,350	€6,700
Collision warning with haptic feedback	€4,000	€8,000
Automated collision avoidance with braking and steering	€4,500	€9,000

In estimating the costs, the following assumptions have been made:

- for each car category, the costs occur in full as soon as each safety device is introduced to newly registered cars; retrofitting to used cars is not included in this analysis.
- the proportions of new registrations in each car category are taken as unchanged year-by-year, as given in Table 8.3 above.
- the costs for Europe (EU25) have been derived using the same methodology as used for estimating the UK figures but using an appropriate number of new car registrations.

8.7.5 *Cost-benefit analysis results*

Because the costs of fitting the equipment are assumed to occur in the same year-by-year sequence as the savings, the trends of costs follow similar patterns to those shown in the figures displaying savings. Figure 8.11 shows the annual costs for the UK. A consequence of the similar patterns is that, for each option, the ratio of savings to costs is constant over the years following introduction, with different values for the UK and for EU25.

Table 8.6 shows the values of the ratio of savings to costs.

For the UK, the maximum estimated savings/costs ratio is 1.16 but 2.21 for Europe. The reason for this striking difference for the two locations follows from the data used for road traffic accident (RTA) deaths and new car registrations. Table 8.7 shows the data.

The ratio of RTA deaths and new car registrations is nearly twice as high for EU25 as for the UK. Compared with the UK, savings for Europe increase by a factor of about 12.3 whereas the costs increase by a lower factor (6.40). It should be emphasized that this result depends on the assumption made in the study that the proportions of accidents saved as a result of the introduction of the new equipment are identical for the UK and Europe.

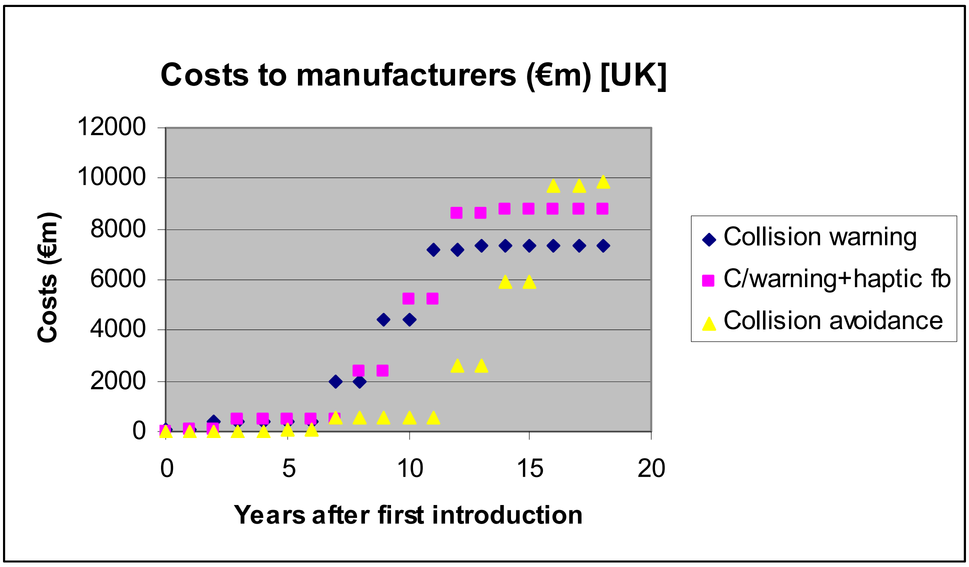


Figure 8.11. Costs to manufacturers of the collision prevention devices [UK]

Table 8.6: Ratios of casualty savings to costs to manufacturers for the three options

Location	Proportions of accidents saved	Options: Collision warning	C/W + haptic feedback	Automated collision avoidance
UK	High estimates	0.86	1.01	1.16
	Low estimates	0.34	0.57	0.77
EU25	High estimates	1.64	1.93	2.21
	Low estimates	0.64	1.09	1.47

Table 8.7: Annual numbers of RTA deaths & new car registrations (UK and EU25)

Location	RTA deaths	New car registrations	RTA deaths/(new car registrations x10^{-6})
UK	3368	2187813	1539
EU25	41383	14000000(1)	2956
EU25/UK	12.29	6.40	-

Note: (1) Data for EU15 have been used

It is very important to note that the cost-benefit analysis results reported here are provisional and highly tentative. They are based on estimates for (1) the percentages of accidents likely to be prevented by the various systems (see Table 8.2) and (2) the likely timing of their introduction (Table 8.3). In addition, the possibility of reducing the severity of accidents has not been taken into account owing to the initial nature of the cost-benefit analysis.

Finally, it should be borne in mind that the savings/costs ratios reported in Table 8.6 are based on costs to manufacturers (not to the purchasers). If the latter were used, all the benefit/cost ratios would be halved in value.

It will be possible in time to make substantial improvements to the benefit and cost estimates and thereby reduce the current uncertainties contained in this first cost benefit analysis.

8.8 Conclusions

1. Brake assist systems have been shown to have the potential to complement proposals for secondary safety pedestrian protection measures, such that as a package the combined measures outweigh the predicted benefits of phase two of the pedestrian protection Directive. However, test procedures and performance standards need to be developed if BAS is to be incorporated in any regulatory requirements.
2. It was found that BAS varied considerably in the manner in which it operated and there was limited evidence of how these differences affected real world performance. This allows the possibility that systems could potentially be optimised in future to improve real world performance.
3. Further developments of the brake assist concept have been made with the introduction into some production cars of enhanced brake assist systems and collision mitigation systems that use radar to identify the need for emergency braking and either control the brake assist function and/or autonomously brake the vehicle when a collision has become inevitable. Currently, these systems do not reliably detect pedestrians and so, cannot be considered as a pedestrian protection measure at this time.
4. Sensing systems capable of identifying imminent collision with pedestrians and activating safety measures are being developed by tier one suppliers and offer the potential to provide notable additional benefits.
5. Various forms of collision avoidance systems (including autonomous cruise control, collision warnings and full braking and steering avoidance systems) are either available or under development, at least at the concept stages. Systems in current production do not reliably detect pedestrians although this capability is likely in future.
6. All of these systems offer a future potential to have substantial benefits for pedestrian protection but considerable technical development of the products and the test methods and performance requirements for them will be required before they can be considered as candidates for mandatory fitment. This technical development should be encouraged.
7. This was supported by a speculative cost benefit analysis that, based on the major assumptions made, suggested that collision avoidance devices (especially the automatic collision avoidance system) have the potential to have substantially positive benefit to cost ratios. However, there is a very wide range of uncertainty which will need to be considered in more detail when better information is available. It is worth noting that such systems appear to be more promising in a Europe-wide context than within the UK alone. This is because of the relative numbers of RTA fatalities compared with new car registrations within the UK and EU25, which may continue to be true in the future.

9 Discussion

To be of benefit, improved test methods must 'save' more pedestrians than the pedestrian protection required by current legislation and to achieve this they must also be suitable for use in regulations. In this context 'save' means to prevent injuries or reduce the injury severity.

Options to save more pedestrians than current legislation, by providing vehicle based protection are to:

- extend the scope
- protect at a higher accident speed
- improve the test methods
- improve the test tools
- improve protection criteria

Based on the very approximate estimate in Section 7.2, expanding the scope of the current EC Directive to cover all or most of the M and N vehicles over 2.5 tonnes would result in savings of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive's savings.

The different interactions of pedestrians with these larger vehicles are likely to lead to problems in using the Directive's test tools and methods. Suggestions have been made as to how the current test methods could be adapted for testing larger M1 and all N1 vehicles. However, the operation of the amended test procedures should be checked by marking-up and testing a sample of these large vehicles.

As well as expanding the scope of current legislation to cover more vehicles, significant additional savings can be made by including the windscreen and windscreen frame within the scope of improved test methods.

Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. Although increasing the protection speed to 50 km/h would provide significant additional savings - nearly doubling the number of fatalities that might be saved - it will make providing the protection far more difficult. Therefore for regulatory use it is important to take into account the feasibility of providing the protection when selecting the maximum speed that the protection should be effective for.

In serious road accidents pedestrians are often likely to suffer injuries that result in death, disablement or mental impairment. Therefore the protection criteria should be set at an injury risk level which could be seen to provide benefit. However, the difficulty in providing vehicle based protection and the additional margin of safety over and above regulatory minimums that vehicle manufacturers provide, should be considered when setting these levels.

For improved pedestrian test methods it should be noted that scope has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.

The literature review has identified a lot of information pertinent to developing improved test methods and tools; however, important information is missing or of insufficient quality in some key areas. This is particularly apparent in the areas of lateral knee joint stiffness for live humans and the impact conditions for the bonnet leading edge and the head.

When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures. This often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

The legs of pedestrians are the most frequently injured body region in accidents with cars, so testing with an improved bumper test tool could potentially result in the prevention of a significant number of additional leg injuries. Although the EEVC WG17 lower legform impactor has been established as a regulatory sub-system test tool for many years it has some limitations and therefore there is scope for improvement. The Flex-PLI is being developed as that next generation of test tool and is undergoing development and evaluation currently.

A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Once the final version of the Flex-PLI is available, it should be assessed to determine if it is satisfactory for regulatory use against an agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability. The potential of the Flex-PLI for regulatory use can only be found once a finalised specification and impactor are available.

Several recommendations have been made for new studies to support the development of improved test methods. Any new work to support new test methods, such as new tools with improved biomechanical specifications, etc. should ideally be accepted by international experts, particularly those within IHRA PSWG and the UNECE Informal Group on Pedestrian Safety, before being used in legislation. Given the difficulties and high cost of developing alternative impactors or of revising the test parameters and acceptance criteria, the issue of acceptability should be borne in mind when deciding which option to develop. The relevant working groups should preferably be involved in selecting the option(s) that are further developed.

Brake assist systems have been shown to have good potential to complement proposals for secondary safety pedestrian protection measures.

Sensing systems capable of identifying imminent collision with pedestrians and activating safety measures are being developed by tier one suppliers and offer future potential to provide notable additional benefits.

Various forms of collision avoidance systems are either available or under development. All of these systems offer a future potential to have substantial benefits for pedestrian protection but considerable technical development of the products and the test methods and performance requirements for them will be required before they can be considered as candidates for mandatory fitment. This technical development should be encouraged.

10 Conclusions

10.1 Key conclusions

1. To be of benefit, improved test methods must 'save' more pedestrians than the pedestrian protection required by current legislation and they must also be suitable for use in regulation.

2. Options to save more pedestrians than current legislation are to extend the scope, protect at a higher accident speed, improve the test methods, improve the test tools and improve protection criteria.

3. Based on a very approximate estimate, expanding the scope of the current EC Directive to cover all or most of the M and N vehicles over 2.5 tonnes would result in savings of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive's savings.

    - The interactions of pedestrians with these larger vehicles are likely to lead to problems in using the Directive's test tools and methods. Suggestions have been made as to how the current test methods could be adapted for testing larger M1 and all N1 vehicles.

4. As well as expanding the scope of current legislation to cover more vehicles, significant additional savings could be made by including the windscreen and windscreen frame within the scope of improved test methods.

5. Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. Increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be saved. Because it will make providing the protection far more difficult, it is important for regulatory use to take into account the feasibility of providing the protection when selecting the speed.

6. In serious road accidents pedestrians are often likely to suffer injuries that result in death, disablement or mental impairment. Therefore the protection criteria should be set at an injury risk level which could be seen to provide benefit. However, the difficulty in providing vehicle based protection and the additional margin of safety over and above regulatory minimums that vehicle manufacturers provide, should be considered when setting these levels.

7. The scope has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.

8. The literature review has identified a lot of information pertinent to developing improved test methods and tools; however, important information is missing or of insufficient quality in some key areas. This is particularly apparent in the areas of lateral knee joint stiffness for live humans and the impact conditions for the bonnet leading edge and the head.

9. When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures. This often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

10. The legs of pedestrians are the most frequently injured body region in accidents with cars. Although the EEVC WG17 lower legform impactor has been established as a regulatory sub-system test tool for many years, it has some limitations and therefore there is scope for improvement. The Flex-PLI is being developed as the next generation of test tool and is undergoing development and evaluation currently.

11. A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Once the final version of the Flex-PLI is available, it should be assessed to determine if it is satisfactory for regulatory use against an agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability.

12. The potential of the Flex-PLI for regulatory use can only be found once a finalised specification and impactor are available.

13. Several recommendations have been made for new studies to support the development of improved test methods. Any new work to support new test methods, should ideally be accepted by international experts, before it is used in legislation. Given the difficulties and high cost of developing alternative impactors or of revising the test parameters and acceptance criteria, the issue of acceptability should be borne in mind when deciding which option to develop. The relevant working groups should preferably be involved in selecting the option(s) that are further developed, and obviously funding for the work will have to be provided.

14. Brake assist systems have been shown to have good potential to complement proposals for secondary safety pedestrian protection measures.

15. Sensing systems capable of identifying imminent collision with pedestrians and activating safety measures are being developed by tier one suppliers and offer future potential to provide notable additional benefits.

16. Various forms of collision avoidance systems are either available or under development. All of these systems offer a future potential to have substantial benefits for pedestrian protection but considerable technical development of the products and the test methods and performance requirements for them will be required before they can be considered as candidates for mandatory fitment. This technical development should be encouraged.

10.2 Prospects for the Flex-PLI to bumper test

10.2.1 General

1. Although the EEVC WG17 lower legform impactor has been established as a regulatory sub-system test tool for many years it has some limitations and therefore there is scope for improvement. The Flex-PLI is being developed as that next generation of test tool and is undergoing development and evaluation currently.

2. The legs of pedestrians are the most frequently injured body region in accidents with cars, so testing with an improved bumper test tool could potentially result in the prevention of a significant number of additional leg injuries.

3. A number of recommendations have been made to produce a specification for a flexible legform that is considered appropriate by independent experts. Once the final version of the Flex-PLI is available, it should be assessed to determine if it is satisfactory for regulatory use against the agreed specification and with regard to the other requirements important for regulatory impactors including robustness and repeatability.

4. Due to the slippage in the development of the Flex-PLI it is not clear if the GTR Flex-PLI Subgroup will be able to complete a sufficiently thorough assessment of the final version to show if it is suitable for regulatory use. If the GTR group are not able to carry out a full assessment then it is recommended that this assessment be carried out by appropriate experts.

10.2.2 Biofidelity

5. When considering biofidelity it should not be overlooked that a sub-system test method is intended to protect a range of statures and this often justifies simplifications that would be unacceptable if the impactor was only intended to assess protection for the stature it represents.

6. A number of benefits of using a flexible legform impactor have been identified and in some cases these are likely to result in more appropriate protection. It is clear that the flexible long bones of the Flex-PLI give it greater biofidelity than the EEVC WG17 impactor in this respect.

7. It is recommended that a review be carried out by appropriate biomechanics experts to determine definitive physical targets for a flexible legform impactor to be developed and assessed against. Ideally such a review should be carried out under the auspices of an acknowledged group of experts, such as EEVC WG12 (Biomechanics). Although the authors do not anticipate that such a review would result in any significant revisions of the targets selected by EEVC WG17 it is recommended to review and finalise them before effort is put into producing a finalised flexible legform impactor design.

8. It will be important for a new flexible legform to have appropriate moment of inertia and centre of gravity because these will have a significant effect on the impactor's interactions with the vehicle structure during the impact.

    c. The centre of gravity and moment of inertia of the current Flex-GTα version of the flexible legform are not considered to be acceptable. To obtain acceptable values would require significant redistribution of mass. If JARI choose to correct these properties, then there may be a significant delay in producing a finalised version.

    d. Unless compromises in the current Flex-PLI design, such as not meeting the centre of gravity requirement, are resolved they might negate the potential benefits of the flexible legform impactor.

10.2.3 Lateral knee joint stiffness

9. For lateral knee bending stiffness the biomechanical corridor proposed for the Flex-PLI is far lower than the stiffness chosen by EEVC WG17 because WG17 included an allowance for muscle tension.

e. Taking into account the knee geometry and ligament extension properties it seems reasonable to conclude that the lateral knee stiffness in a living human is a combination of stiffness due to muscle tension and knee ligament extension.

f. The available data for muscle effect from mathematical simulation suggest that the effect could be significant.

g. The latest version of the Flexible legform has higher knee stiffness than indicated by PMHS tests; it is assumed that this is a pragmatic estimated correction for the effects of muscle tension.

10. Before further work is undertaken to refine the Flex-PLI it is strongly recommended that a study be carried out to determine the effects of muscle tension on lateral knee joint stiffness.

10.2.4 Protection criteria

11. To date, only some tentative protection criteria (acceptance levels) have been proposed for the tibia and knee ligaments of the Flex-PLI. It will be necessary to produce injury risk curves for the final version of the impactor.

12. Ideally, both the methods used to produce the injury risk curves and the suitability of the data selected should be reviewed and confirmed by an acknowledged group of experts, such as EEVC WG12 (Biomechanics), in order to provide definitive injury risk curves which can then be used to select the vehicle protection criteria.
13. Protection criteria based on a 50 percent risk of injury have been proposed. However, as knee injuries are likely to result in long-term disability, it is recommended that the protection criteria for the knee be set at a 20 percent injury risk.

10.2.5 Feasibility

14. For areas on a vehicle where providing full protection may be difficult, a concept of relaxation zones has been introduced in the pedestrian Directive 2003/102/EC for which the impactor must have some over-range capability. It will not be clear until the protection criteria are finalised whether the over-range capacity of the Flex-PLI knee will be sufficient.

15. The feasibility of providing protection to meet a flexible legform test will be sensitive to both the injury risk values selected and the knee joint and long bone stiffness. At present it is not possible to come to any conclusions regarding feasibility because the protection criteria and lateral knee bending stiffness have not been finalised but there are sufficient data to be concerned about feasibility at 40 km/h due to the low knee bending stiffness of the current biomechanical corridor.

10.2.6 Robustness

16. Earlier versions of the Flex-PLI have been tested and have been shown to lack robustness and knee joint deformation capacity in impact severities such as those which would be expected in regulatory test environments. Since then significant changes have been made to improve robustness, but currently the robustness of the latest version of the Flex-PLI at the required test speed has yet to be proven.

17. It is recommended that before the final version of the Flex-PLI is considered for regulatory use it should be made available for sufficient time for its robustness to be assessed by the interested parties.

10.2.7 Certification

18. Certification tests are considered a good method of controlling the aspects of the impactor that could affect test results. This includes both physical aspects such as component lengths, masses, centres of gravity, etc. that are set in the specification as well as dynamic aspects that may change depending on, friction, wear, aging, tuning adjustments, etc.

19. The proposed pendulum method of certifying the complete mechanical parts of the Flex-PLI is thought to be suitable and recommendations have been made to improve its reproducibility.

    h. A certification test is also needed for the skin and flesh because they are not tested (not fitted) in the pendulum test.

    i. It is thought that individual certification tests may also be needed for the long bones and knee. These might make use of the biomechanical tests already used to assess their biofidelity and suggestions are made for how this could be done.

10.3 High bumper

1. Based on the currently available data it would appear that there are two options for a high bumper definition:
   a. Continue with the EEVC WG17 high bumper definition.
   b. Permit some flexibility for the manufacturer to nominate whether to use the lower or upper legform test for bumpers at the higher end of the ‘normal height’ bumper definition as proposed in the draft GTR. This is to take account of the off-road use ground clearance feasibility issue.
      iii) However, although reducing the high bumper transition point, as permitted in the draft GTR high bumper test, is reasonable in response to feasibility issues for off-road vehicles, it would be safer for pedestrians to place the transition height where biofidelity considerations require it.
      iv) The relationship found by Matsui (2004) between injury risks for injuries not directly measured by each impactor (lower or upper legform) suggests that for high bumpers meeting the protection criteria of either test will improve protection (but not necessarily meet a specific ‘safe’ speed target).

2. Use of a flexible legform impactor for testing high bumpers:
   a. An upper body mass must be added that correctly represents the human upper body, but it should be noted that adding a suitable upper body mass is likely to require a comprehensive research and development programme in itself.
   b. The JARI Flex-PLI has the advantage over the EEVC WG17 legform that both lower and upper leg bending moments are measured directly on the instrumented flexible bone cores (as well as measuring knee ligament extension). However, there are a number of outstanding issues regarding the Flex-PLI impactor. If these issues are resolved, then fitting it with a suitable upper body mass would appear to offer the best solution for testing high bumpers.

c. Instrumentation between the upper body mass and the joint where it is attached to the legform 'hip joint' might also be used to assess the risk of fractures within the pelvis. This combination would make it very suitable for testing a wide range of bumper heights from very low to very high.

d. If the Flex-PLI proves to be unsatisfactory for use as a regulatory tool then the possibility of further developing the WG17 impactor to be suitable for testing high bumpers could be considered.

3. Improvements to the current high bumper test and feasibility issues:

   a. The EEVC WG17 high bumper definition is such that the lower legform test applies to many off-road vehicles.

   b. Vehicles intended for off-road use need to allow for a greater ramp angle in order to negotiate rough terrain. This ramp angle constraint means that off-road vehicles have high bumpers, which give rise to a feasibility issue because this is in conflict with the protective measures needed to pass the lower legform to bumper test.

   c. Changing test methods to permit vehicle manufacturers to switch to the upper legform to high bumper test at a lower bumper height than currently specified by WG17 would resolve the feasibility problem. It remains to be shown at what bumper height a switch to the upper legform is desirable in terms of suitability of the lower legform impactor, but this change would be a pragmatic solution to the feasibility issue.

   d. It should be noted that both the EC Directive and the draft GTR have some allowance for switching to the upper legform tests for bumpers below the high bumper definition to address this issue.

   e. A further feasibility issue raised by vehicle manufacturers is that the bumper crush depth needed to meet the EEVC WG17 high bumper test is too large to be easily accommodated.

   f. Taking into account the link that Matsui found between the force found in the high bumper to upper legform test and the injury risk to the lower leg and knee, retaining the EEVC WG17 high bumper protection criteria would reduce the risk of knee joint injury.

10.4 Bonnet Leading Edge

1. A number of accident studies have reported a considerable reduction in the injuries caused by the bonnet leading edges of cars of modern design.
2. Studies have also reported that the EEVC WG17 upper legform to bonnet leading edge test fails most current cars, effectively predicting high injury risks that are inconsistent with the accident data for recent car designs.
3. The upper legform impactor and the bonnet leading edge test have been criticised by experts for their lack of biofidelity. However, it has not been demonstrated whether poor biofidelity is the cause of the high predictions of injury risk.
4. Proposals were made previously for changes to the upper legform impact energies and to the acceptance criteria. However, it has not been demonstrated that these would be adequate to bring the test results into line with data from accidents involving recent car designs.
5. A number of concepts for a replacement impactor and bonnet leading edge test procedure have been identified and the advantages and disadvantages of each have been discussed.
6. Any replacement bonnet leading edge test should ideally be accepted by international experts, particularly those within IHRA PSWG and the UNECE Informal Group on Pedestrian Safety, before it is used in legislation. Given the difficulties and high cost of developing any alternative impactor or even of revising the test parameters and acceptance criteria, the issue of acceptability

should be borne in mind when deciding which option to develop. The relevant working groups should preferably be involved in selecting the option(s) that are further developed.

7. The option involving the least change to the current test would be to review the test parameters and acceptance criteria, while retaining the current upper legform impactor.
   a. Computer modelling should be used to determine the required parameters.
   b. The pedestrian model used should be a very detailed and biofidelic FE model such as THUMS. Ideally this should be further improved by adding muscle tension effects, to simulate live pedestrians, in key parts of the model.
   c. The model should be used to find out which parameters of car shape are best correlated to the impact severity and these should then be used in the test procedure.
   d. The modelling should include a range of pedestrian sizes, as a minimum a 5th percentile female as well as a 50th percentile male.
   e. Modelling should be used to make a direct comparison between upper legform and pedestrian impacts, to check that the new test parameters should give more realistic estimates of injury risk.
   f. Additional accident reconstructions should be carried out to improve the injury risk curves. Ideally, each injury risk curve should be derived using data concerning the appropriate type of injuries.
   g. Changes to the test parameters and acceptance criteria based on such a study may still not be adequate to bring the test results into line with data from accidents involving recent car designs, as the impactor has an inherent lack of biofidelity in certain respects. Also, a test procedure that retains the current impactor may obtain limited support from experts.
8. A number of concepts have been suggested for a replacement and more biofidelic sub-system impactor to test the bonnet leading edge. These options would require a look-up method to obtain the test parameters, similar to the current method; the values would be obtained from computer modelling. These concepts would retain many of the benefits of a sub-system test, such as using a relatively compact and light-weight impactor that can easily be propelled into a vehicle. These concepts could be used to test the prominent bonnet leading edge to protect those statures at greatest risk for any given vehicle height.
9. A number of concepts have been presented for combining the bumper and bonnet leading edge tests, using impact devices ranging from a lower legform with an upper body mass to a full pedestrian dummy. These would impact the vehicle front horizontally at a fixed speed and would then simulate the initial impact in a biofidelic manner to generate automatically the correct impact into the bonnet leading edge. These would all involve a large and heavy impact device such that it might be easier to propel the vehicle into the test device rather than the test device into the vehicle. The test device would represent one specific stature of pedestrian.
10. Another option considered for the bonnet leading edge was a legislative test using computer modelling instead of an impact device. This option is considered to be premature for this test at this time, though it could be an option for the future once such methods have been used in less complex legislative tests.

10.5 Headform

1. Accident data show that protection for the head should be given the highest priority for reducing serious and fatal pedestrian accident injuries.
2. To be of benefit, improved test methods must save more pedestrians than current legislation and to achieve this they must also be suitable for use in regulations.

3. Options to save more pedestrians by providing vehicle based protection (suitable crush depth and stiffness, etc) are to: extend the scope, protect at higher accident speed, improve the test methods, improve the test tools and improve protection criteria.
4. Increasing the scope to cover vehicles not covered by the pedestrian Directive (2003/102/EC), using either the test method specified in the Directive or new improved test methods will obviously result in additional savings.
   a. A further option to increase the scope is to require protection on more of the injury causing areas of vehicles, including the windscreen. Accident data show that providing protection in these areas could be very effective in reducing serious and fatal head injuries.
   b. These areas were excluded from the European Directive because no feasible protection measures for the area as a whole were ready for use at the time of its introduction. In future protection here may become feasible.
5. Although the central area of laminated windscreen glass away from the support frame and underlying structures is normally considered safe, a test to confirm this would be of benefit and can also be used to test underlying components such as the top of the dashboard, which are likely to cause serious head injuries if too rigid.
   a. Before a protection requirement could be placed on the glass itself it would be necessary to show that the properties of the laminated glass are repeatable and that there is a feasible method of adjusting its failure properties to provide the necessary protection.
   b. Because the windscreen is initially rigid, until cracking is initiated, then it may be more sensitive to headform properties than deformable components like the bonnet top. As the headform does not take account of the deformable and frangible nature of human skull or the decoupling of the mass of the brain then it may not cause realistic crack initiation in the windscreen. Therefore head injury criterion results from windscreen impact tests may not be appropriate.
6. It should be noted that the scope for pedestrian test methods has significant implications on the complexity and possibly the number of the tests and test tools needed in a test method. As the head impact conditions are influenced by the accident scenario it is important that the scope of any improved tests should be decided first and then suitable test methods and tools can be developed to meet that scope.
7. N2 and N3 vehicles cause a disproportionately high number of pedestrian fatalities compared with the number of serious injuries. Therefore, consideration should be given to including these vehicles along with all M1 vehicles and possibly all N1 vehicles in the scope for future test methods.
8. Current regulations are aimed at providing protection that is effective at a car impact speed of 40 km/h. Accident data show that increasing the protection speed to 50 km/h would provide significant additional savings, nearly doubling the number of fatalities that might be prevented. However, going beyond 40 km/h would probably only be feasible using new technologies such as pop-up bonnets.
9. In real life, each pedestrian accident is unique in some way so that there are an almost infinite number of real accident situations. When the range of statures and other accident variables are taken into account, it can be concluded that the area of the car that potentially can be contacted by the head is so large that that the only feasible test method is one that is based on a sub-system test approach (real or mathematical).
10. Currently, deployable (pop-up bonnet or airbag) pedestrian protection solutions are triggered by bumper contact. Whole-body physical dummy testing will be useful in testing the trigger and the interaction between the body of the pedestrian and the bonnet during deployment. However, the deficiencies of current dummies, particularly the overly stiff shoulder make interpreting these

results difficult. Testing with improved, more biofidelic, pedestrian dummies (physical or mathematical) of different statures would offer improved information.

11. It is thought very likely that at some time in the future, virtual testing techniques will have developed to such a standard that they could be used in regulations. However, even then there will be problems over confidentiality of manufacturer's car models, controlling improvements and versions of the pedestrian models and auditing the approval process. Therefore, it is recommended that the next generation of test methods will use physical headform tests but that the impact conditions used will be based to some extent on computer simulation.

12. To simulate a pedestrian-vehicle collision, different tools can be used; these are PMHS tests, physical dummy testing, sub-system tests and numerical simulation. However, these tools will not have perfect biofidelity. Therefore, it becomes important to consider the behaviour that would be expected from a living human subject with respect to what is observed from tests using the alternatives.

13. To evaluate pedestrian head protection levels for regulatory enforcement, it is generally accepted that sub-system testing represents the most robust solution, particularly in terms of repeatability, reproducibility and cost. However, for the sub-system tests to be representative of the real world situation the impact conditions need to be determined.

    a. The IHRA group have chosen to increase the head test area to include the windscreen and windscreen frame. They have therefore conducted a lot of work to determine appropriate impact conditions for their test method. This activity has been based on numerical simulation.

    b. Recent reviews of the human body models that have been used in the simulations have raised concerns over their biofidelity. In particular, the interaction of a stiff shoulder with the bonnet of the vehicle protects the head (reducing the impact velocity) in a manner which would not be expected with a human.

    c. These concerns are also true for the pedestrian dummy, Polar, which also has poor lateral shoulder biofidelity.

    d. Conversely, one cannot take the results of PMHS tests to be representative of a living human as they lack muscle tone, and as such are less stiff than a living human would be. It is uncertain how this would affect the global kinematics during an impact.

    e. It is clear from this review that further work is needed in the area of the dummy pedestrians used in numerical simulation and physical testing.

14. Advanced human body models could reduce the concerns over the biofidelity of pedestrian models. Numerical simulation could be used with these improved models to generate the impact conditions for improved head test methods (velocity, direction and possibly effective mass).

    a. These human models could be used along with appropriate vehicle models to generate impact conditions for the headform.

    b. Before this position is reached, a decision would have to be taken by the relevant expert groups that a particular simulation tool was suitable for this function.

    c. Alternatively, a matrix of pedestrian statures could be run with a mathematical model for each individual vehicle model to be tested to determine tailored impact conditions.

        - However, in practice this might prove very difficult.

    d. To avoid these issues, it may be better for a suite of simulations to be run covering the necessary vehicle styles and shapes from which look-up tables could be generated for the sub-system tests. This process will also have difficulties associated with it, such as provision of the human body model for research, development and regulatory enforcement purposes as well as provision of vehicle models.

15. Accident data show that child head impacts start at a wrap around distance of about 1000 mm and end at 1700 mm and for adults head impact starts at about 1400 mm and ends at 2400 mm. For a test method overlapping of the child and adult zones will result in an area that is safe for both child and adult head impacts.
16. There is some debate as to whether in a test method the child and adult zones should overlap or have a step change. This may be become less important if the scope of a new test method is expanded as it is likely to result in more sub-wrap around zones to reflect different statures and vehicle shapes.
17. Most accidents involving impacts to the head are likely to involve a combination of linear and rotational acceleration. However, in practice, it is not thought feasible to include this in a test method and, in real life, it may not be important as the solutions for a linear acceleration criterion will also be effective in reducing rotational acceleration.
18. Given that for pedestrian sub-system testing a protection criteria based on rotational injury risk is not thought to be feasible, then continuing to use the well accepted HIC is considered to be the best option. One option to improve head protection would be to reduce the protection criteria from the current HIC 1000 used in the EC Directive. However this option is not thought necessary given that car manufacturers are known to apply an additional margin of safety on top of regulatory requirements.
19. In the authors' opinion it is feasible, with conventional designs, to provide protection effective at 40 km/h to meet a protection criterion of HIC 1000. It may not be feasible with conventional designs to achieve significant protection in excess of this due to the increase in crush depth needed.
    a. However, new protection technologies such as deployable systems (airbags, pop-up bonnets, etc.) may well be able to provide the additional crush depth needed for protecting at 50 km/h.
    b. Nevertheless, there are likely to be difficult areas in most designs where different features combine to make the structure too stiff. For these areas it is thought that there will be a continuing need for some relaxation of the protection requirements as included in the EC Directive.

10.6 Scope

1. A very approximate estimate of the savings of an expanded scope to cover all or most of the M and N vehicles over 2.5 tonnes is of savings of the order of an additional 15 percent for serious casualties and 30 percent for fatalities of the current Directive's savings.
2. A number of options to extend the scope of the Directive to include larger vehicles have been identified. These include an extension for M1 vehicles to 3.5 tonnes GVW, to 2.5 tonnes unladen or the removal of the weight limit. For N1 vehicles, options include retaining the restriction of testing only N1 vehicles derived from M1 vehicles, extending to N1 vehicles of similar basic shapes to M1 vehicles or extending to all N1 vehicles.
3. The interactions of pedestrians with these larger vehicles and potential problems in using the test tools and methods have been discussed.
4. The current test methods could be adapted for testing larger M1 and all N1 vehicles with the minimum set of changes summarised below. However, the operation of the amended test procedures should be checked by marking-up and testing a sample of large vehicles.
    a. References to direction should be clarified where necessary.
    b. When necessary, raise the straight edge used to determine the upper bumper reference line.
    c. When necessary, make the straight edge used to determine the bonnet leading edge reference line more vertical, and in extreme cases do not determine the reference line.

   d. When necessary, raise the straight edge used to determine the bonnet leading edge reference line. A maximum limit on the wrap around distance at which the headform test area starts is also suggested.

   e. Where the bonnet is more vertical than horizontal, change the orientation of the straight edge used to determine the side reference lines.

5. The following further changes might be implemented or considered relatively quickly:

   a. Change the headform impact angle to 25° from the horizontal for flat-fronted vehicles. These vehicles could be defined as those where the bonnet angle is within 25° of the vertical.

   b. Consider whether there should be a mandatory pass requirement in the upper legform to bonnet leading edge test for vehicles with a bonnet leading edge beyond a certain height.

6. A number of suggestions have been made for a longer term research programme, if this is needed in order to provide the best possible test procedures and hence VRU protection. These include accident study, biomechanical testing, improved simulations, and possibly development of additional impactors to represent other body parts. However, extension of the vehicle scope should not be delayed until the results are available; any improvements arising from the research should be used in a second phase of test procedures.

7. An extension of vehicle scope to larger vehicles including N1 vehicles will result in an improvement in the safety of VRUs. However, based on GB data, N1 vehicles have a lower involvement in fatal and serious pedestrian accidents over their lifetime than do cars. Also, it is expected that the cost of developing a safer N1 vehicle model will typically have to be shared over a smaller model run. A rough estimate is that the costs will be about the same as the benefits.

8. For some low-volume vehicles the costs of protecting VRU would be disproportionate to the benefits. Consideration should be given to exempting such vehicles.

10.7 Newer technologies

1. Brake assist systems have been shown to have the potential to complement proposals for secondary safety pedestrian protection measures, such that as a package the combined measures outweigh the predicted benefits of phase two of the pedestrian protection Directive. However, test procedures and performance standards need to be developed if BAS is to be incorporated in any regulatory requirements.

2. It was found that BAS varied considerably in the manner in which it operated and there was limited evidence of how these differences affected real world performance. This allows the possibility that systems could potentially be optimised in future to improve real world performance.

3. Further developments of the brake assist concept have been made with the introduction into some production cars of enhanced brake assist systems and collision mitigation systems that use radar to identify the need for emergency braking and either control the brake assist function and/or autonomously brake the vehicle when a collision has become inevitable. Currently, these systems do not reliably detect pedestrians and so, cannot be considered as a pedestrian protection measure at this time.

4. Sensing systems capable of identifying imminent collision with pedestrians and activating safety measures are being developed by tier one suppliers and offer the potential to provide notable additional benefits.

5. Various forms of collision avoidance systems (including autonomous cruise control, collision warnings and full braking and steering avoidance systems) are either available or under development, at least at the concept stages. Systems in current production do not reliably detect pedestrians although this capability is likely in future.

6. All of these systems offer a future potential to have substantial benefits for pedestrian protection but considerable technical development of the products and the test methods and performance requirements for them will be required before they can be considered as candidates for mandatory fitment. This technical development should be encouraged.

7. This was supported by a speculative cost benefit analysis that, based on the major assumptions made, suggested that collision avoidance devices (especially the automatic collision avoidance system) have the potential to have substantially positive benefit to cost ratios. However, there is a very wide range of uncertainty which will need to be considered in more detail when better information is available. It is worth noting that such systems appear to be more promising in a Europe-wide context than within the UK alone. This is because of the relative numbers of RTA fatalities compared with new car registrations within the UK and EU25, which may continue to be true in the future.

11 Recommendations and Priorities

On the basis of the study reported here, a number of recommendations are made for further research and development, to the European Commission and to the wider research community. These are placed in a priority order. The highest priorities, based on the necessary short timescales, are given to work needed to support the proposed revision of the European phase two requirements and to the implementation of a global technical regulation. Thereafter, research will essentially be concerned with developing second-generation test procedures and systems. Of these the highest priority is given to supporting the development and introduction into legislation of the Flex-PLI, as the development phase is scheduled to end this year (2007). Thereafter, the priorities are based more on the potential for saving additional injuries rather than on external time constraints.

Action priority 1 – Brake Assist linked to the revised phase two of the EC pedestrian regulation

With BAS ready for use in the field of Pedestrian Protection it is now required that finalised test procedures and performance standards should be fully developed to ensure proper levels of quality and performance.

Action priority 2 – Vehicle scope linked to the revised phase two of the EC pedestrian regulation and to the global technical regulation

Some changes to the test procedures are likely to be necessary to accommodate an increased vehicle scope in the legislation. It is recommended that the changes listed in this report be considered. These include: changes in the way reference lines are determined, a maximum limit on the wrap around distance at which the headform test area starts, changing the headform impact angle on flat-fronted vehicles and further consideration of the need for a bonnet leading edge test on vehicles with a high bonnet leading edge.

It is also recommended that the operation of the amended test procedures be checked by marking-up and testing a sample of large vehicles.

Action priority 3 – Support of development and introduction into legislation of Flex-PLI

Considerable efforts are being made currently, mainly by JARI, to develop the Flex-PLI as a test tool that could be used in legislation. For it to be used as a legislative tool a number of important decisions will have to be taken, such as whether it is adequately meets the requirement for a test tool, the derivation of injury risk curves and the setting of acceptance criteria. It is important that the wider research community is fully involved in reviewing the impactor and the associated test procedure. Because many of these decisions may be taken relatively soon this topic is given a high priority here.

Before further work is undertaken to refine the Flex-PLI it is strongly recommended that a study be carried out to determine the effects of muscle tension on the lateral knee joint stiffness.

A number of other recommendations have been made in this report, including that:

- a review be carried out by appropriate biomechanics experts to determine definitive physical targets for a flexible legform impactor to be developed and assessed against
- the Flex-PLI should be assessed to determine whether it is satisfactory for regulatory use, including assessing its robustness and repeatability
- it will be necessary to produce injury risk curves for the final version of the impactor
- the protection criteria for the knee should be set at a 20 percent injury risk
- a certification test is also needed for the skin and flesh because they are not tested in the pendulum test. Individual certification tests may also be needed for the long bones and knee.

Action priority 4 – Further development of newer technologies for the benefit of vulnerable road users

Technical development of collision mitigation and collision avoidance systems and their application to the safety of vulnerable road users should be encouraged.

Action priority 5 – Further development of headform test procedures including extension of the test area to the windscreen and windscreen frame

Further work is needed in the area of the mathematical models or physical dummies used in numerical simulation and physical testing, to improve the biofidelity of their kinematics and response to impact with a vehicle.

The headform test parameters should be kept under review as numerical simulations are refined.

Consideration should be given to including the windscreen and windscreen frame within improved test methods. The limitations of what is feasible should be regularly reviewed as technologies develop. The appropriateness of the current headform and using the head performance criterion should be demonstrated before they are used in a regulatory windscreen test.

New protection technologies such as deployable systems may be able to provide the additional crush depth needed for protecting at higher vehicle speeds, so this speed should be kept under review.

As pedestrian dummies are developed, they should be used to test deployable (pop-up bonnet or airbag) pedestrian protection solutions.

It is recommended that the next generation of test methods will use physical headform tests, but that the impact conditions used will be based to some extent on computer simulation.

Action priority 6 – Further extension of vehicle scope

A number of suggestions have been made for a longer term research programme, to provide the best possible test procedures, and hence protection of vulnerable road users, for vehicle types not covered currently. These suggestions include accident study, biomechanical testing, improved simulations, and possibly development of additional impactors to represent other body parts.

Action priority 7 – Development of a new or revised test for the bonnet leading edge

It is recommended that a new or revised bonnet leading edge test be developed for legislative use. Accident data should be used to determine scope of vehicles that should be tested and to ensure that vehicles that don't cause real-world injuries are not failed by the test.

Several suggestions for modifying the current upper legform impactor and the bonnet leading edge test procedure, or for developing a completely new impactor, have been made in this report. Given the difficulties and high cost of developing any of these alternatives, the issue of acceptability should be borne in mind when deciding which option to develop and the relevant working groups should be involved in selecting the option(s) that are further developed.

Action priority 8 – Development of a new high bumper test

It is recommended that a new impactor and test procedure for high bumpers be developed.

The use of a legform impactor with an additional upper body mass is considered to be the best option. The upper body mass needs to represent adequately the effects of the human upper body in this impact. This is likely to require a comprehensive research and development programme in itself.

If the Flex-PLI is successfully developed for testing standard height bumpers then fitting it with a suitable upper body mass would appear to offer the best solution for a high bumper impactor.

Instrumentation between the upper body mass and the original legform 'hip joint' should be considered, to assess the risk of fractures within the pelvis.

Feasibility considerations may conflict with obtaining the full benefit of an improved test procedure. The limitations of what is feasible should therefore be kept under review as technology develops.

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