A study on the feasibility of measures relating to the protection of pedestrians and other vulnerable road users

by G J L Lawrence, B J Hardy, J A Carroll, W M S Donaldson, C Visvikis and D A Peel

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PROJECT REPORT

TRL Limited

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A STUDY ON THE FEASIBILITY OF MEASURES RELATING TO THE PROTECTION OF PEDESTRIANS AND OTHER VULNERABLE ROAD USERS

by B J Hardy, G J L Lawrence, J A Carroll, W M S Donaldson, C Visvikis and D A Peel (TRL Limited)

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Executive summary

In most countries, including those of the European Union, 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 supported the development of test methods and test tools suitable for requiring certain standards of pedestrian protection by the European Enhanced Vehicle-safety Committee Working Groups 10 and 17. Most experts agree that requiring full compliance with EEVC WG17 in one step would be too demanding. Therefore, following consultation with those concerned, a two stage Directive (2003/102/EC) was approved by the European Parliament and by the Council on the 17th of November 2003. The first stage required pedestrian protection to be provided in new car designs using an adaptation of the EEVC WG17 test methods that are less demanding. Following a feasibility assessment study, a higher level of pedestrian protection could be provided by a second phase. TRL Limited were contracted to carry out this the feasibility study over the period 18th December 2003 to 9th June 2004 (Lawrence *et al.*, 2004a – see document http://ec.europa.eu/enterprise/automotive/pagesbackground/pedestrianprotection/pedestrian_protection_study.pdf).

Following completion of the original feasibility study (Lawrence *et al.*, 2004a), a meeting of the EC's Pedestrian Protection Monitoring Committee (26th July 2004) was held where presentations were made of the feasibility study and other studies carried out for or by the car industry on feasibility. The benefits of the second stage of the Directive and the benefits of fitting brake assist systems to all vehicles were presented. At the meeting the industry expressed concerns about the feasibility of meeting the original phase two requirements. The issues raised had been addressed to some extent by proposals made in the feasibility study, but it was not clear that the changes proposed were sufficient to meet the industry's feasibility concerns. It was also clear that the estimates of benefits made in the feasibility study and by industry were very different. The main point of disagreement was that industry produced a higher estimate of the benefits of brake assist. When these were combined with the industry's estimate of a small increase in benefits when going from phase one to phase two, industry concluded that brake assist with phase one was more effective than phase two. It was clear that these conflicting estimates made it difficult to come to any decision on what the final form of the second stage should be.

Following the Monitoring Committee meeting it was agreed that details would be exchanged on the methods and data used to make the estimates on the benefits of various levels of passive protection and the benefits of brake assist in the two studies. This would enable a better understanding of both methods and their limitations, and enable improvements to be made to the calculation methods making use of the new data provided. At about the same time, following discussions between the EC (DG Enterprise and Industry) and industry, an alternative proposal for revising phase two of the Directive was forthcoming. Therefore, revised benefit calculations which included new estimates of the benefits of the original phase two and the improved proposal along with a more detailed estimate of the benefits of brake assist were made. This work was reported as an addendum to the original feasibility report (Hardy and Lawrence, 2005). The addendum describes the additional work carried out and the information provided by ACEA and TUD. However, this resulted in a rather untidy situation where two documents had to be read in conjunction and the main report did not reflect the latest alternative proposal.

More recently a proposal for a global technical regulation for pedestrians and other vulnerable road users has been drafted under the United Nations Economic Commission for Europe (UN/ECE) 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 authors understand that the GTR, with the additional requirement for brake assist systems to be fitted to all cars, is likely to form the basis for an EC proposal for legislation to replace the current Directive (2003/102/EC).

The Directive requires that if, as a result of the feasibility assessment, it is considered necessary to adapt the provisions of phase two, to include a combination of passive and active measures, it must achieve at least the same level of protection as the existing provisions of phase two. Further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of "at least the same level of protection" of the Directive. Since TRL's original proposals (Lawrence *et al*. 2004a) did not find any support from the experts in the area, they are no longer pursued and therefore this report only considers the costs and benefits of the present proposal.

The European Commission has contracted TRL to consolidate and update the original feasibility study, and in particular the cost-benefit analysis, to produce this updated report. The scope of this update includes taking account of the draft GTR and, as far as is possible, more recent data.

Accordingly, this document brings together the present levels of understanding and removes issues of opinion, thus providing an evaluation of the present position vis-à-vis phase two of the Directive. In particular, some of the options for feasibility proposed in the earlier study (Lawrence *et al.*, 2004a) are not included in the cost-benefit comparisons in this report, but instead alternatives proposed by the GTR group are included.

The updated cost-benefit analysis compares the benefits of the current phase two requirements with those of phase one plus brake assist and the EC proposal which also includes brake assist.

Again, the authors co-operated with ACEA over the benefit analysis and other issues. ACEA has arranged with the GIDAS Steering Committee for TRL to be provided with car frontal and car non-frontal pedestrian accident samples, in addition to the data provided by GIDAS in 2004. The GIDAS non-frontal sample has been used to estimate the benefit offered by brake assist in non-frontal accidents (mainly corner and glancing side-swipe type accidents). Without these accident data, the authors had not been able to estimate the benefits of brake assist in non-frontal accidents before. However, the analysis will reflect the characteristics of the GIDAS data and their data collection methods.

The updated report has a number of conclusions:

The original feasibility study and cost-benefit analysis carried out for the European Commission (Lawrence *et al.*, 2004a) has been consolidated and updated to produce this new report. The scope of this update includes taking account of the draft GTR and, as far as is possible, more recent data. The updated cost-benefit analysis compares the benefits of the current phase two requirements with those of phase one plus brake assist and what the authors understand to be the EC proposal for phase two which also includes brake assist. The Directive requires that if, as a result of the feasibility assessment, it is considered necessary to adapt the provisions of phase two, to include a combination of passive and active measures, it must achieve at least the same level of protection as the existing provisions of phase two. Further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of "at least the same level of protection" of the Directive. Since TRL's original proposals (Lawrence *et al*. 2004a) did not find any support from the experts in the area, they are no longer pursued and therefore this report only considers the costs and benefits of the present proposal. Accordingly, this document brings together the present levels of understanding, thus providing an evaluation of the present position vis-à-vis phase two of the Directive.

The original study of alternative test methods (Lawrence *et al.*, 2004a) has been updated to take into account new data and the current understanding with regard to feasibility issues and a number of recommendations have been made for revising phase two of the Directive. The author's understand that the draft GTR, with the additional requirement for brake assist systems to be fitted to all cars and possible expansion of the vehicle types covered in the scope is likely to form the basis for an EC proposal for legislation to replace the current Directive (2003/102/EC). If this proposal is accepted for a revised phase two then the following are recommended:

- Those parts of the proposals by Lawrence *et al.* (2004a) that were regarded as improvements to the test procedures, rather than feasibility adjustments, should also be included in the revised test procedures.
- The bonnet leading edge test should at least be retained as a monitoring only test.
- The changes to the second phase should be kept under review with regard to real-world injuries caused by the bonnet leading edge of cars meeting phase one or phase two requirements for the bumper, once sufficient accident data are available.

It is thought that it may be beneficial to have two tibia accelerometers fitted to the lower legform test tool; however, this is not recommended for phase two of the Directive, as more research is needed. It is recommended that permanent towing eyes be set back by at least 150 mm from the front face of the bumper. Although the bonnet leading edge test is aimed at protecting the adult male it could also be effective in providing some protection for smaller adults and children. Nevertheless, given the level of criticism of this test method and the feasibility issues of meeting the protection requirements it is recommended that more work should be carried out in this area.

- It is clear that a better understanding of the bonnet leading edge contact is needed to refine or replace the current test.
- In the mean time it is therefore considered more prudent to retain the current test for monitoring purposes rather than leaving a potentially significant load path with no future protection requirement.

The main differences between the current phase two requirements and the draft GTR have been summarised and discussed and the following observations and recommendations have been made:

- The most significant difference is that the draft GTR proposes a head test speed of 35 km/h whereas the current Directives phase two requirement is 40 km/h. However, the effect of the reduction in velocity on protection will be smaller than might be anticipated due to the normal manufacturers' practice of exceeding regulatory protection requirements by about 20 percent.
- It is recommended that a definitive study be carried out to determine what range of bumper heights the lower legform impactor is appropriate for. Until this is done a well justified high bumper definition cannot be produced.

A number of options to extend the scope of the Directive to include larger vehicles have been identified and potential problems in using the test tools and methods, for vehicles they were not necessarily designed for, have been discussed. It has been suggested that problems in using these rules are almost certain to be found when they are used on larger vehicles. It would, therefore, be essential to undertake a study of large vehicles to develop workable new rules for the current test methods to be applied to large vehicles. Ideally, new test methods and rules should also be developed for these larger vehicles.

A study has been made of new technologies that might be used to avoid a pedestrian accident or mitigate its effects in terms of injuries. One technology was identified, pop-up bonnets, as already being used on certain new vehicles in order to meet phase one of the Directive. The following observations were made with regard to this system.

- Test of a pop-up bonnet system on a mule vehicle, showed that it deployed the bonnet as intended and was fully deployed before the predicted pedestrian head contact. Testing of the deployed system on a mule vehicle showed that it provided considerable benefit over the original vehicle and passed the phase two Directive head protection requirements in many places despite using the original vehicle bonnet which had not been optimised for this use.

- Testing with pedestrian dummies by Fredriksson *et al.* (2001) showed that a pop-up bonnet system tested remained in a raised position until the head impacted the bonnet. This confirmed that the lifting mechanism could support the torso of a pedestrian for the required period as opposed to sinking before the head impact occurred.
- Testing of a bumper with a trigger system for a pop-up bonnet show that it is important to use a trigger test tool that is appropriate for the detection system being used.
- It is thought that, by their nature, there is likely to be less confidence that pop-up bonnet systems will always work as intended compared with protection by vehicle deformation; they are also likely to have higher costs. Therefore, for both cost and confidence reasons it is thought that pop-up bonnets solutions would not applied to the whole fleet but instead would normally be reserved for sport or executive type vehicles where simpler vehicle deformation solutions are not practical due to restricted crush depth.

A study of brake assist has been carried out and the conclusions were:

- There is evidence that BAS will have a beneficial effect on accidents generally and pedestrian accidents specifically. However, there is still uncertainty with respect to accurately quantifying the magnitude of that benefit.
- The evidence available suggests that it is reasonable to assume that BAS will result in a reduction in pedestrian fatalities of greater than zero and less than 12 percent. Within this estimate it is likely that the true answer will lie somewhere in the mid-range of values. However, it must be noted that with the data currently available, any estimate of benefits that aims to produce a more specific single answer within that range will carry a substantial risk of either under or over estimating the real benefits of the system in pedestrian accidents. Further accident research will be required in order to increase confidence in the results and to narrow the range of benefits that can be confidently predicted.
- A variety of different brake assist systems are currently available and there are at least two fundamentally different operating principles. No published research was identified that compared the effectiveness of different brake assist systems with different operating principles or different activation thresholds.
- The only BAS test procedure identified, for inclusion with the other test procedures, was that proposed by ACEA. Only two variants of the brake assist system were covered within the scope of that procedure and these were treated as being equally effective, which is not proven. The procedure only enforces a minimum standard for one aspect of performance (minimum amount of brake boost over and above demand). Performance in relation to the emergency detection criteria or the trigger thresholds was not considered for speed sensitive devices and was not worded as compulsory for force activated systems.
- A range of values within which the trigger threshold must lie could be added to the procedure for pedal speed activated systems in order to make it more robust and the procedure for force activated systems could be re-worded to enforce the range of forces already quoted. This could be implemented almost immediately. Further research could compare the effectiveness of different brake assist systems with different operating principles in order to find optimal operating conditions. This information could potentially be used to develop an enhanced BAS test procedure that ensured a higher standard level of performance in service than exists now, thus potentially offering greater benefits than the current mix of systems. This could be implemented in a relatively short time frame.

- In the long term, enhanced brake assist and collision mitigation systems could offer further benefits to pedestrians but these systems still require considerable research and technical development before they can be proven to be effective and reliable pedestrian protection systems.

The original review of technical restrictions by Lawrence *et al.* (2004a) has been updated and the most important inclusions are:

- Sub-systems tests do not take account of an earlier contact which might in some circumstances compromise protection intended for a later contact. This may be of particular concern for pop-up bonnets which are very likely to be more poorly supported than conventional bonnets. Therefore a protocol, to determine if deployable systems work as intended, should include an assessment of the risk of earlier contacts compromising protection for later contacts.
- The situation regarding the lateral knee joint bending stiffness has been discussed and the authors have concluded that EEVC WG17 requirement is more appropriate to represent the living human than the lower stiffness selected for the Flex-PLI legform impactor. Nevertheless, if a lower stiffness is chosen for a new regulation then this would have consequences for feasibility. A sensitivity study appears to suggest that reducing the knee stiffness would make it far more difficult for manufacturers to meet the protection requirements. Therefore before any changes to the knee bending stiffness are made it is recommended that a study of the effects on feasibility be carried out.

Guideline manufacturing costs for the ‘EC proposal’ have been produced by selecting slightly different combinations of costs from the earlier feasibility study and these guideline costs have been used in the updated cost-benefit study.

An updated cost-benefit study has been carried out and the conclusions were:

- The financial benefits estimated for the secondary safety elements of the Industry and EC proposals, and including consideration of BAS and for the latter proposal an increase in scope to cover heavier vehicles, as a percentage of those of the current phase two, are 174 percent and 182 percent respectively.
- BAS offers significant benefits to many vulnerable road users. Whereas the passive safety measures cannot protect against injuries caused by the ground or by non-tested areas, BAS can reduce the impact severity and hence injury risk for all contact areas.
- BAS can also provide significant benefits in non-frontal impacts. The estimated indicative financial benefits of BAS in non-frontal impacts, for the EC proposal, corresponded to 37 percent of the financial benefits of the current phase two.
- Current BAS cannot provide any benefits in the roughly half of pedestrian accidents where the driver was unable to brake before impact.
- The estimates of the effectiveness of BAS are for a change in the fitment rate of BAS from zero to 100 percent.
- It is recommended that if fitment of BAS becomes part of a package of changes to the phase two requirements then minimum standards for BAS should be agreed.
- It should be noted that the estimated benefits of brake assist systems must be regarded in the light of the uncertainties discussed, as insufficient data have as yet become available to accurately gauge their benefits for vulnerable road users. Nevertheless, brake assist systems are capable of providing valuable additional benefits for pedestrians and other road users.

The recommendation is therefore strongly made that brake assist systems should be mandated as part of the package of requirements for phase two.

1 Introduction

In most countries, including those of the European Union, 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 supported the development of test methods and test tools suitable for requiring certain standards of pedestrian protection. These test methods were first developed by the European Enhanced Vehicle-safety Committee Working Group 10 (EEVC WG10) and then further refined by EEVC Working Group 17 (EEVC WG17). The European Union has been considering requiring car manufacturers to comply with these test methods for some time; however, providing pedestrian protection will require significant changes to the way cars are made, both to the outer skin and to some parts of the underlying structure.

Most experts agree that requiring full compliance with EEVC WG17 in one step would be too demanding. As a result, car manufacturers and others (including EEVC WG17) have suggested that some form of phasing-in of the pedestrian protection requirement would be more reasonable. Therefore, following consultation with those concerned, the European Commission and the main car manufacturer's associations that supply cars to the European market (ACEA, JAMA and KAMA), developed a two-stage approach. The first stage required pedestrian protection to be provided in new car designs using an adaptation of the EEVC WG17 test methods that are less demanding. Following a feasibility assessment study, a higher level of pedestrian protection could be provided by a second phase. The car manufacturers offered to commit themselves to meeting these protection requirements without legislation. However, the European Parliament decided, in their resolution of 13th June 2002, that a Directive should be drafted to require protection. Therefore a draft Directive laying down the application dates, the goals to be achieved and the methods to monitor their application, based on the commitment made by the industry including the feasibility assessment of the second phase, was produced by the Commission. The Directive 2003/102/EC was approved by the European Parliament and by the Council on the 17th of November and published in the Official Journal of the European Union on the 6th of December 2003 (European Parliament and Council of the European Union, 2003).

In parallel with the above process, the European Commission produced a specification for the feasibility study for the second phase of the Directive (the Directive has a commitment to have independent experts carry out such a study by 1st July 2004). TRL Limited were subsequently contracted to carry out a feasibility study over the period 18th December 2003 to 9th June 2004 (Lawrence *et al.*, 2004a – see document http://ec.europa.eu/enterprise/automotive/pagesbackground/pedestrianprotection/pedestrian_protection_study.pdf).

The second phase of the EC Directive consists of three principal test procedures each using different sub-systems 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 of the bumper.
- An upper legform impactor representing the adult upper leg and pelvis to record bending moments and forces caused by the contact of 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, see Figure 1.1.

These test methods replicate an impact with a pedestrian and for the bumper and bonnet leading edge tests they represent the statures more vulnerable to injury (adults). Measures introduced to protect pedestrians will also be of benefit to other vulnerable road users, particularly for pedal cyclists. It is for this reason that vulnerable road users are included in the title of the EC Directive.

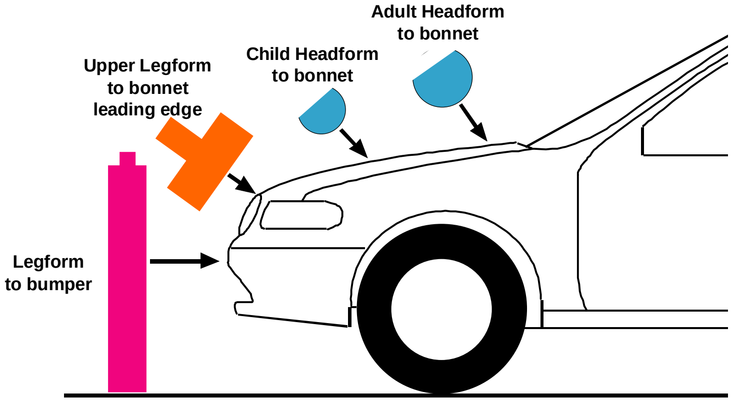


Figure 1.1. The sub-systems tests used in the second phase of the EC Directive

1.1 Introduction to 2006 report

Following completion of the original feasibility study (Lawrence *et al.*, 2004a) a meeting of the EC's Pedestrian Protection Monitoring Committee (26th July 2004) was held where presentations were made of the feasibility study and other studies carried out for or by the car industry[1] on feasibility. The benefits of the second stage of the Directive and the benefits of fitting brake assist to all vehicles were presented.

At the meeting the industry expressed concerns about the feasibility of meeting the original phase two requirements. The issues raised had been addressed to some extent by proposals made in the feasibility study, but it was not clear that the changes proposed were sufficient to remove concerns with the lack of feasibility.

It was also clear that the estimates of benefits made in the feasibility study and by industry[1] were very different. The main point of disagreement was that industry produced a higher estimate of the benefits of brake assist. When these were combined with the industry's estimate of a small increase in benefits when going from phase one to phase two, industry concluded that brake assist with phase one was more effective than phase two. It was clear that these conflicting estimates made it difficult to come to any decision on what the final form of the second stage should be.

Following the Monitoring Committee meeting it was agreed that details would be exchanged on the methods and data used to make the estimates on the benefits of various levels of passive protection and the benefits of brake assist in the two studies. This would enable a better understanding of both methods and their limitations, and enable improvements to be made to the calculation methods making use of the new data provided. At about the same time, following discussions between the EC (DG Enterprise and Industry) and industry, an alternative proposal for revising phase two of the Directive was forthcoming. Therefore, revised benefit calculations which included new estimates of the benefits of the original phase two and the improved proposal along with a more detailed estimate of the benefits of brake assist were made. These estimates made use of newer accident data provided by industry from the GIDAS accident database and were reported in an addendum to the feasibility study. Within the constraints at the time, it was only possible to report this work as an addendum to the main (original) feasibility report (Hardy and Lawrence, 2005). The addendum describes the additional work carried out and the information provided by ACEA and TUD. However, this resulted

[1] ACEA's contractor for their benefit and brake assist system (BAS) effectiveness study (Hannawald and Kauer, 2004a) was the Technical University of Dresden (TUD).

in a rather untidy situation where two documents had to be read in conjunction and the main report did not reflect the latest alternative proposal.

More recently a proposal for a global technical regulation for pedestrians and other vulnerable road users has been drafted under the United Nations Economic Commission for Europe (UN/ECE) 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 authors understand that the GTR, with the additional requirement for brake assist systems to be fitted to all cars, is likely to form the basis for an EC proposal for legislation to replace the current Directive (2003/102/EC).

The existing Directive requires that if, as a result of the feasibility assessment, it is considered necessary to adapt the provisions of phase two, to include a combination of passive and active measures, it must achieve at least the same level of protection as the existing provisions of phase two. Further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of “at least the same level of protection” of the Directive. Since TRL’s original proposals (Lawrence *et al.* 2004a) did not find any support from the experts in the area, they are no longer pursued.

The European Commission has contracted TRL to consolidate and update the original feasibility study, and in particular the cost-benefit analysis, to produce this updated report. The scope of this update includes taking account of the draft GTR and, as far as is possible, more recent data.

Accordingly, this document brings together the present levels of understanding and removes issues of opinion, thus providing an evaluation of the present position vis-à-vis phase two of the Directive.

The updated cost-benefit analysis compares the benefits of the current phase two requirements with those of phase one plus brake assist and the EC proposal which also includes brake assist.

Again, the authors co-operated with ACEA over the benefit analysis and other issues. ACEA has arranged with the GIDAS Steering Committee for TRL to be provided with car frontal and car non-frontal pedestrian accident samples, in addition to the data provided by GIDAS in 2004. The GIDAS non-frontal sample has been used to estimate the benefit offered by brake assist in non-frontal accidents (mainly corner and glancing side-swipe type accidents). Without these accident data, the authors had not been able to estimate the benefits of brake assist in non-frontal accidents before. However, the analysis will reflect the characteristics of the GIDAS data and their data collection methods.

2 Overview of current research, development and vehicle performance

To carry out the original study the authors contacted the following associations to obtain information on the current position of research and development regarding pedestrian protection pre-accident (active) and in-accident protection (passive). As the expressions ‘active’ and ‘passive’ are often used in a different context to that given in the previous sentence, a more detailed definition of the use of these words in this report is given in Section 6.

- The association representing the European, Japanese and Korean motor vehicle manufacturers (ACEA, JAMA and KAMA respectively)
- The association representing the European tier one automotive suppliers (CLEPA)

The authors also:

- had discussions with industry and supplier experts
- undertook examination of known ‘good’ cars
- used their existing knowledge and experience gained in testing and developing improved pedestrian protection

It was found, at that time, that manufacturers were mostly concentrating on providing pedestrian protection to meet phase one of the EC Directive (European Parliament and Council of the European Union, 2003).

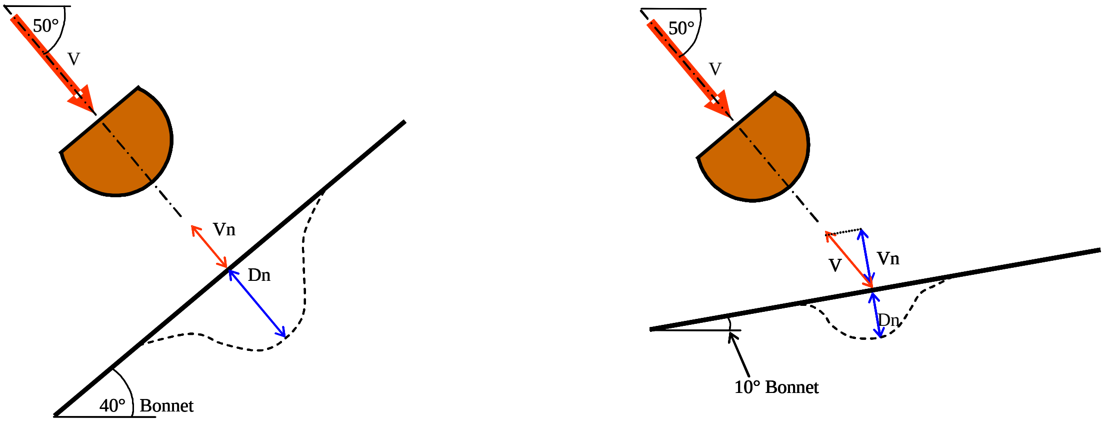
To update the report two further meetings with ACEA were held. Additional accident data and a number of new documents were reviewed, including the proposed global technical regulation for pedestrians and other vulnerable road users.

2.1 Concept of passive pedestrian protection

The head injury risk criteria used in this test in both the EEVC and EC Directive test methods is the ‘Head Performance Criterion’ (HPC). This may lead to some confusion because the most frequently used criterion for head injury risk is the ‘Head Injury Criterion’ (HIC). However the formula used to calculate ‘HPC’ is identical to that used to calculate ‘HIC’. The reason for using a HPC rather than HIC within these two pedestrian test procedures is so that the formula is fixed. This prevents any subsequent change to the HIC calculation method causing an involuntarily change to the criterion used in these test methods. Within this report ‘HPC’ will be used. Note, however that the draft GTR uses HIC.

In general, the approaches used for passive pedestrian protection (deploying and non-deploying) may be simplified into three key considerations, crush depth, stiffness and force distribution. For the headform impactor the HPC criterion is a complex calculation but it is a function of acceleration and time (force can be obtained from mass and acceleration). The force criterion for the upper legform can be applied directly to the maximum stiffness of the car structure, and the legform acceleration and knee shear displacement can also be converted into an equivalent force if a value for the effective mass of the legform, with its deformable knee, is estimated. Therefore to absorb the kinetic energy of the impactor, crush depth and appropriate vehicle stiffness are necessary. However, the additional criteria of bending moment and knee bending angle for the upper legform and the legform impactors respectively also place requirements on the distribution of force along the length of the impactor.

To simplify the arguments below, first only the crush depth and stiffness are considered. It is clear that the distance from the outer surface of the vehicle to any hard immoveable objects must be sufficiently big to allow absorption of the energy of the impact. This depth, the crush depth, along with appropriate crush stiffness can then be used to absorb the energy of the impact. The efficiency with which the energy is absorbed is dependent on the level of contact force the vehicle structure exerts on the pedestrian test tool throughout the impact. As discussed above, to meet at least one of the performance criteria for each tool this force must not exceed a certain value. Ideally, to absorb the energy efficiently the car must exert a force, just below that required by the criterion for that tool, throughout the impact. If the impacted area is too stiff then it will fail the test. If it is too soft then it will require a larger crush depth than the minimum necessary to meet the criterion. In practice most vehicle structures that pass the test will provide a varying force level throughout the impact, meaning that the efficiency of energy absorption will also vary throughout the impact. Therefore, depending on the average or overall energy absorbing efficiency that can be achieved in practice with the car structure, larger crush depths will be necessary than the theoretical minimum. For the legform and the upper legform the impact will be approximately normal to the surface, so that the estimates of the necessary crush depth can be calculated using the appropriate impactor criteria and an energy absorption efficiency factor. For the headform test, depending on the local angle of the bonnet, the impact will often not be normal to the surface; in this case a reduced crush depth will be required, as illustrated in Figure 2.1.



If V = 11.1 m/s

Then Vn = 11.1 m/s

Assuming HIC target of 800
and energy efficiency of 80%
Then Dn = 99 mm

If V = 11.1 m/s

Then Vn = 9.61 m/s

Assuming HIC target of 800
and energy efficiency of 80%
Then Dn = 67 mm

Figure 2.1. Reduced crush depth due to non-normal headform impact (child)

Through tailoring of the stiffness and crush depth of the vehicle and taking into account absorption efficiency, those impactor criteria relating to force can be complied with.

Complexity is added for the upper legform and legform impactor where the force distribution along the length of the impactor must also be controlled. To control the knee bending angle for the legform, the contact forces at the bumper, spoiler and possibly the bonnet leading edge need to have appropriate stiffness and relative position. For the upper legform the force must be distributed to some degree along the length of the femur section.

2.2 Pedestrian protection in the bumper area

2.2.1 The bumper tests

The bumpers of most vehicles are at such a height that they contact the average adult leg below the knee. Current cars with this height of bumper are likely to fracture the leg bones below the knee (the tibia and fibula) in moderate to severe accidents. The tibia acceleration limit in the legform test is aimed at saving these fractures by requiring that the bumper deforms; however, without additional measures this would result in a switch to injuring the knee joint instead. Therefore, although knee joint injuries are currently infrequent, the 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.

Some off-road type vehicles have bumpers so high that they contact the average adult at or above the knee and in this case the upper legform impactor is a more appropriate test tool. However, a high bumper that is safe for the femur (meets the upper legform to high bumper protection requirement) is still likely to injure the knee joint. Knowing that the upper legform to high bumper test requires more crush depth than the legform test and that, although less appropriate for high bumpers, the legform impactor is very likely to fail a dangerous high bumper, EEVC WG17 decided to retain the option for high bumpers to be tested with the legform impactor. The reasoning for allowing either test was that a high bumper that passed the legform test was overall less likely to result in disabling injuries than one that passed the upper legform test, because bone fractures (away from joints) are less likely to result in disablement than are serious joint injuries. This, combined with the assumption that manufacturers would normally opt for protection that requires less crush depth, would encourage manufacturers to design to meet the legform test rather than the upper legform test and therefore result in more pedestrian friendly designs.

2.2.2 Current position on providing protection – bumper area

The current solutions for bumpers are aimed at meeting phase one of the Directive or to achieve some points in the European New Car Assessment Programme (Euro NCAP). However, as the only difference between phase one and phase two of the Directive is a reduction in the maximum permitted tibia acceleration and lateral knee bending angle (with the same knee shear limit in both phases) it can be concluded, with some caution, that all that is needed to meet phase two is a more thorough application of the same protective principles. (The current phase two of the Directive uses the EEVC WG17 test methods and Euro NCAP tests also use an adaptation of these test methods (Euro NCAP, 2004).)

Current plastic bumper faces are already highly flexible and need no significant change or development in their ability to deform. Therefore, the properties and the solutions needed to meet the requirements of both phase one and phase two of the Directive are:

- Sufficient crush depth:
    - Many current cars have insufficient crush depth to meet the pedestrian protection requirements.
        - Additional crush space is being released by moving the hard bumper beams back or by making them stronger and thinner. Alternatively thinner and weaker bumper beams can be used with an additional link between the chassis rails, in front of the sub frame for example, to maintain the necessary link between the chassis rails needed to provide offset frontal crash performance. However, this is complicated by a combination of factors which are discussed in Section 10.
- Appropriate deformation stiffness:
    - Current bumper faces without pedestrian protection may be too soft without additional energy absorbing material behind.
        - Additional energy absorbing material is often used to enhance crash protection and insurance ratings. The width, height and stiffness of energy absorbing material are now being optimised to meet the pedestrian legform impactor acceleration criterion. That is, for the deformation stiffness to give a tibia acceleration within the maximum permitted tibia acceleration criterion

even if the distance between the bumper face and immovable objects behind is limited.

- Appropriate force distribution:
    - Currently most bumper profiles are deep (top to bottom edge) and include an integrated air-dam or spoiler. In normal modern cars, these spoilers are set at or behind the main bumper face but are less evident with older designs of cars that also had narrow bumpers. The deep bumper and air-dam or spoiler styling changes are beneficial in distributing the contact force onto the pedestrian and the legform impactor.
        - Therefore, only small changes in bumper shape and spoiler position are needed from current styles and this is particularly true for the bumpers of the sports version of saloon cars.
    - The other important quality of a bumper to control the force distribution on the leg is the distribution of stiffness in the bumper from the top to the bottom edge.
        - The change found here is a general stiffening of the lower edge either by minor changes to an existing under-tray or splash guard or by introduction of a support bar. However, it is possible to make the lower edge of the bumper too strong, which would result in unnecessary injuries at about ankle level in real life. Unfortunately, the legform test does not detect excessive lower edge stiffness, nevertheless some manufacturers have already identified this risk from their simulation results and are limiting bumper lower edge stiffness to safe levels; this is discussed further in Section 10.

A method of managing the energy resulting from an impact to the bumper that is currently employed by one vehicle manufacturer (Honda) uses a combination of deforming loop and crush cans on the front face of the bumper armature at each end where it is attached to the main chassis rails. This arrangement consists of a two-stage energy management system. A loop of metal strip in front of a rectangular crush can section absorbs energy during a pedestrian legform impact by a rolling plastic bending mode with the deformed loop material going into the hollow centre of the rectangular section as it is pushed back. The stronger rectangular section (crush can) has an indented crease around it that allows it to crush at higher loads than generated in a pedestrian leg impact. Un-deformed, there is a small gap between the plastic bumper facia and the metal loop, the facia only contacts the metal loop during an impact. A different solution was used for the central area of the bumper of this car where a large crush depth (larger than the minimum required by the acceleration criterion) was combined with a low bumper stiffness to allow the leg to penetrate the bumper and engage the spoiler and bonnet leading edge, thus distributing the contact force. The results from legform tests to the Honda Civic (Lawrence *et al*. 2002) are shown in Table 2.1 with the impact points identified in Figure 2.2. Figure 2.3 shows these points in relation to the underlying structures of the bumper. Figure 2.4 shows pre-test and post-test images of the deformable loop and crush can combination, with the loop clearly deformed following the test.

It is clear that other manufacturers are also using, or considering using combinations of shape and stiffness to provide leg protection. For example, the new Volvo S40 has a thinner high-strength bumper beam combined with improved bumper and spoiler shapes, with the spoiler positioned more forward than normal. These are combined with a deformable plastic box behind the bumper facia and an energy-absorbing under-tray (closure) to support the spoiler. It is understood from discussion with Volvo that the aim of these and other changes was to provide as much pedestrian protection as possible within the constraints of carry-over features in the underlying platform and to achieve a good performance.

Figure 2.2. Legform test sites

Figure 2.3. Underlying points for the legform impactor tests

Table 2.1: Legform test results

Test point	Location ‡	Impact velocity (m/s)	Knee angle (°)	Shear displacement (mm)	Tibia acceleration (g)
L01	Over left strut, 477 mm from C/L	11.11	15.1	4.6	164
L02	218 mm to left of C/L, midway between verticals at centre & corner of headlight	11.13	14.4	1.9	112
L03	1 mm to right of centreline	11.13	9.0	2.2	102
L04	Just off the inner corner of the headlight, 386 mm to right of centreline	11.12	15.8	2.7	181

‡ Dimensions are target locations, not necessarily precisely the actual impact locations.

Undamaged right hand crush loop **Damaged left hand crush loop**

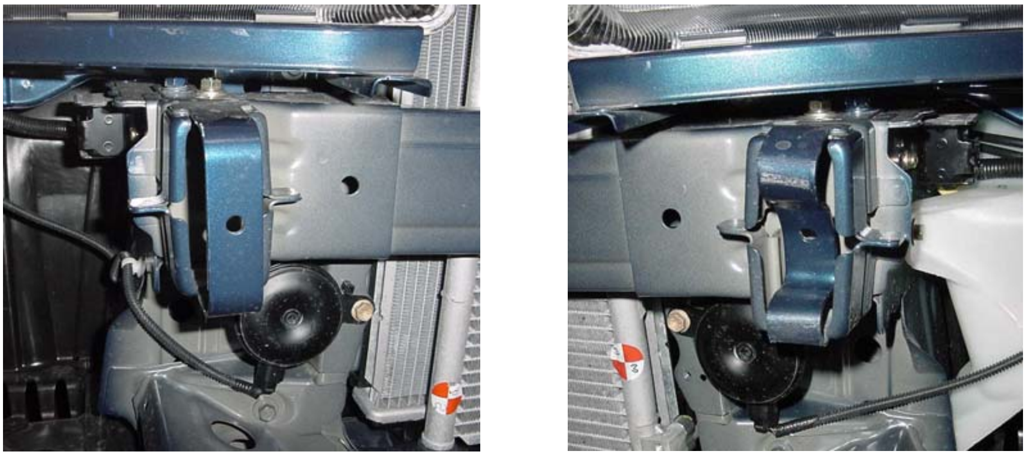


Figure 2.4. Bumper armature damage post test, L01

2.2.3 Summary of protection in the bumper area

The study has shown that car manufacturers and some of their tier one suppliers understand well the protective principles for the legform to bumper test. They are now actively working to provide the correct combination of compliance in the bumper to control tibia acceleration and knee joint shear to meet the phase one requirements of the Directive. The shape and stiffness profile of the bumper and spoiler are being used to control the force distribution on the legform, which in turn limits the lateral knee bending angle. Finite element simulation and component testing are being used to help understand and refine the pedestrian protection properties of the vehicle and determine the interaction between pedestrian protection features and styling, functionality and crash protection. With the protection standards now enshrined in phase one of the Directive it appears reasonable to conclude that vehicle manufacturers consider protecting to phase one to be feasible (if demanding). It may also been concluded, with some caution, that all that is needed to meet phase two is a more thorough application of the protective principles found to meet phase one; however, this may raise some feasibility issues which are discussed in Section 10.

2.3 Pedestrian protection in the bonnet leading edge area

2.3.1 The upper legform tests

For a given speed in an impact between a vehicle and a pedestrian, the severity of the contact between the bonnet leading edge (BLE) and the part of the pedestrian’s body hit, in terms of change in velocity, angle of contact and pedestrian effective mass is dependent on the shape of the vehicle. For streamlined car shapes the impact will be of low severity and for tall upright shaped cars the impact will be of higher severity. In order to simply reproduce this effect in the upper legform to bonnet leading edge test, three look-up graphs are used so that appropriate test velocity, energy and impact angles can be looked up for the shape of vehicle under test. Energy and velocity are specified rather than mass and velocity because it is easier to define the test severity precisely in this way (the impactor mass is then calculated from velocity and energy).

The combination of both femur bending and total force measurements and their performance requirements in phase two of the Directive is the means of requiring protection for both the femur and pelvis.

2.3.2 Current position on providing protection – bonnet leading edge area

In phase one of the Directive the bonnet leading edge has target performance values combined with monitoring of the results.

The properties and the solutions needed to meet the requirements of phase two of the Directive are:

- Sufficient crush depth:
  - Theoretically there is sufficient room for the bonnet leading edge to deform in most current cars for them to meet the pedestrian protection requirements before contact is made with immovable objects such as the engine. However, in practice the combined strength and positions of the following features all combine to restrict crush depth:
    - Rigid mounting required for vibration free headlamps.
    - The upper cross-member which includes the bonnet lock and upper fixing for the cooling pack and forms the necessary link between the upper load paths in the inner front wing area.
    - The strength and positioning of components such as the headlamps and radiator.
    - Some manufacturers have started to release additional crush space by moving back the upper cross-member and bonnet support buffers leaving the bonnet front edge free to deform. However, this is complicated by a combination of factors which are discussed in Section 10.
- Appropriate deformation stiffness:
  - Currently the bonnet leading edge may be too strong because it is shaped so that it is loaded in its strongest mode and also receives support from the upper cross-member, as illustrated in Figure 2.5. To address this, changes in styling are being used;
    - By adopting a more curved shape on the front edge of the bonnet a more gentle transition between the bonnet top and the front face of the vehicle may be achieved. This, along with a smaller distance between the outer surface and the inner under frame of the bonnet and moving back the upper cross-member all means that the tested area of the bonnet is more easily deformed, see Figure 2.6.
    - Alternatively, within the overall vehicle shape the plastic front face components (bumper, headlamp, grill and grill surround) are being extended more rearwards so that the opening bonnet edge is tending to be behind the upper legform test area with the main test area being to a relatively soft plastic front nose. This type of styling feature can be seen in the Volvo S40 and S50, see Figure 2.7. The two BMW models that are shown in Figures 2.8 and 2.9 also show this change in style with the older 5 Series having an extended metal bonnet forming a metal nose and the more recent 6 Series having a plastic nose. These changes in styling are not thought to be driven by pedestrian protection but they could be used to help meet the pedestrian protection requirements. It is possible that this styling trend could be taken further if necessary to move the metal parts further away from the legform and upper legform test area. This has been illustrated by adding a red-line on the photograph of the BMW 6 Series to indicate a new more rearwards switch from plastic to metal parts, see Figure 2.10.

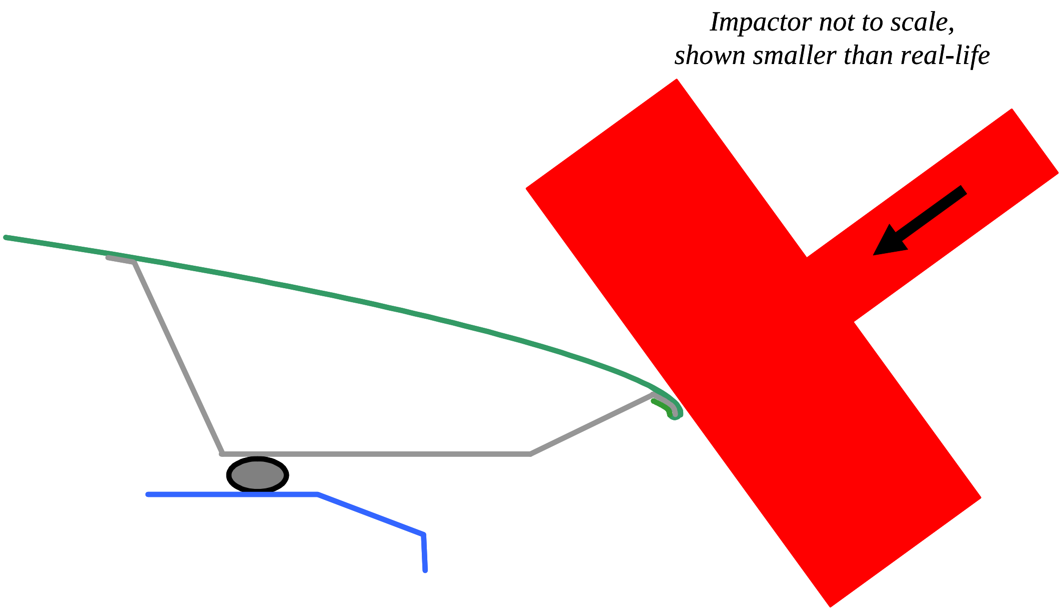


Figure 2.5. Typical current bonnet leading edge

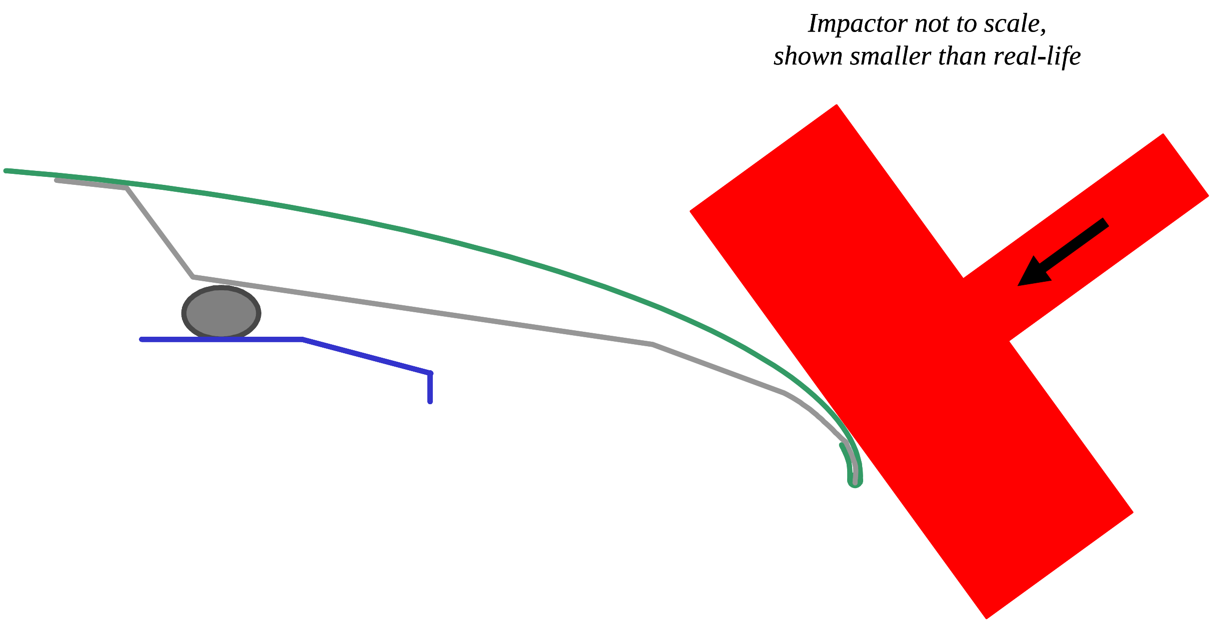


Figure 2.6. Bonnet leading edge with pedestrian protection

Figure 2.7. Volvo S50, with plastic front face components extending into the conventional ‘bonnet’ surface

Figure 2.8. Changes in styling - older style BMW 5 Series with steel bonnet leading edge

Figure 2.9. Changes in styling – new style BMW 6 Series with bumper/grill extending into bonnet, with more rounded edge

Figure 2.10. Possible adaptation or enlargement of styling change by extending plastic parts back towards red-line

- Depending on the styling of a vehicle, the headlamp ‘glass’ may effectively form the outer bonnet leading edge or the complete light units may support the front edge of the bonnet. These can be adapted to deform by the use of plastic in place of the glass and the lamp housing can be made deformable or frangible. Examples of this can be seen in the Honda Civic and the Volvo S40.

- Bonnet leading edge to upper legform force distribution:
  - As with providing the ability to deform, changes in styling are being used to control the force distribution
    - By providing greater radii of curvature for the shape on the front edge of the bonnet, it means that the force of the impact can be better distributed and the necessary crush depth reduced.

2.3.3 Summary of protection in the bonnet leading edge area

From the investigations for this study, it has been found that, presently, car manufacturers have tended to put less work into considering the upper legform to bonnet leading edge test than for the legform or headform tests. Perhaps as a result of the target requirements in phase one of the Directive, the reaction to the potential requirements is certainly less measured for some manufacturers than it is for the legform to bumper test. Whilst it appears that experimental and numerical simulation work is occurring to cover the bonnet leading edge area, it is apparent from discussions with manufacturers that they believe the requirements of phase two of the Directive are not feasible in this area. There will always be a battle in the bonnet leading edge area to marry the reduced stiffness of structures required for the pedestrian test with the structural rigidity necessary at joints in this area. These feasibility issues are discussed in Section 10. Another approach is to increase the bonnet leading edge clearance from underlying structures by raising it; however, this 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. The scope for design changes in this region is linked to feasibility issues and is discussed further in Section 10.

2.4 Pedestrian protection in the bonnet area

2.4.1 The headform tests

In phase one of the Directive, the bonnet top is tested with just one type of headform. This headform represents the head of a child or small adult and has a mass of 3.5 kg. The test is performed at an impact speed of 35 km/h and the limits for passing the test are that the HPC shall not exceed 1000 over 2/3 of the bonnet test area and 2000 for the remaining 1/3 of the bonnet test area.

For phase two of the Directive two different headforms are introduced instead of that used in phase one: one of the headforms represents the head of a child (impactor mass 2.5 kg) and the other of an adult (impactor mass 4.8 kg). The headforms are used in two distinct test areas covering the bonnet top based on the stature of the pedestrians that the headforms represent. Presently, both of the headform tests are to be performed at an impact speed of 40 km/h and the pass or fail criterion is that the HPC shall not exceed 1000 for the whole of the bonnet test area. Discussion of the justification for these tests and potential revisions are presented in Section 3 and application of the test zones and pass or fail criterion further discussed as feasibility issues in Section 10.

To an even greater extent than was the case for the legform tests, the protection for pedestrian heads as assessed by the headform tests can be broken down into the two fundamental considerations. Firstly, the stiffness of the impacted structure, the bonnet or the wing edge; and secondly, the available depth to rigid underlying structures such as the engine, bulkhead / firewall and structural beams such at the upper longitudinal beam (rail).

2.4.2 *Current position on providing protection – bonnet top and supporting areas*

The properties and the solutions needed to meet the requirements of phase two of the Directive are:

- Sufficient crush depth:
    - Sufficient crush depth is required under the bonnet to attenuate the energy of the impactor before contact is made with immovable objects, such as the engine, bulkhead / firewall, suspension tower or underlying structural beams such as the upper longitudinal beam. There are a four basic principles that can be used for achieving the required crush depth which can be used in any combination:
        - Locally modifying the design to remove rigid high points, moving hard assemblies down or by making underlying components lower through more compact designs.
        - Modifying hard structures to make them crush, shear off, or push down on collapsible brackets.
        - By changing (raising) the bonnet line, to obtain more clearance over immovable or rigid elements, providing space into which the bonnet can deform. However, the height of the bonnet is fundamental to the styling of the vehicle.
        - By introducing deployable systems such as pop-up bonnets to increase crush depth.
- Appropriate deformation stiffness:
    - The deformation of the bonnet should be considered with regard to the underlying skin(s) and reinforcing elements:
        - The introduction of additional clearance between the inner and outer skins can tailor the stiffness of the bonnet as a whole.
        - Reinforcements under the bonnet may be made more deformable. One method for achieving this is the changing of the cross-section of the reinforcing beams (see Figure 2.11 and Figure 2.12).
        - Development of a more homogeneous bonnet support system avoiding the use of stiff reinforcement beams. Mazda Motor Corporation has developed the 'Shock Cone Aluminium Hood', which has a structure aimed at enhancing pedestrian protection. Instead of a framed structure, the Shock Cone Aluminium Hood has an inner panel that is shaped with numerous craters, similar to cones (Mazda, 2004).

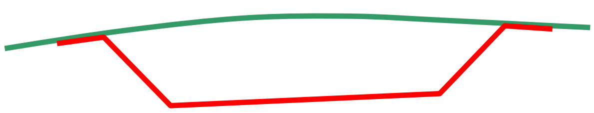


Figure 2.11. Current reinforcement cross-section

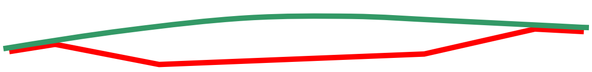


Figure 2.12. Proposed new reinforcement with a more readily deformable cross-section

    - It may be impractical to raise the bonnet level over certain features of a vehicle that are found in the engine bay, to provide sufficient crush depth. As an alternative, these features may be made to deform under loading to absorb energy. This strategy can then be used with many features that may cause high deceleration levels for a headform. The height and stiffness of deformable elements may need to be optimised to be within the maximum permitted HPC, particularly if the distance between the bonnet and immovable objects underneath is limited:

- Fluid reservoirs may be supported by deformable brackets.
- The wings may have deformable edge supports as opposed to strong rigid protrusions to rest on (see Figures 2.13 and 2.14).

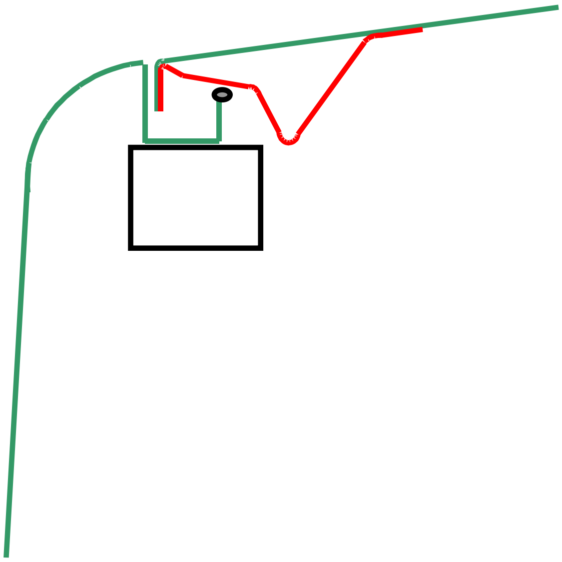


Figure 2.13. Bonnet edge with strong underlying support mounted on the wing

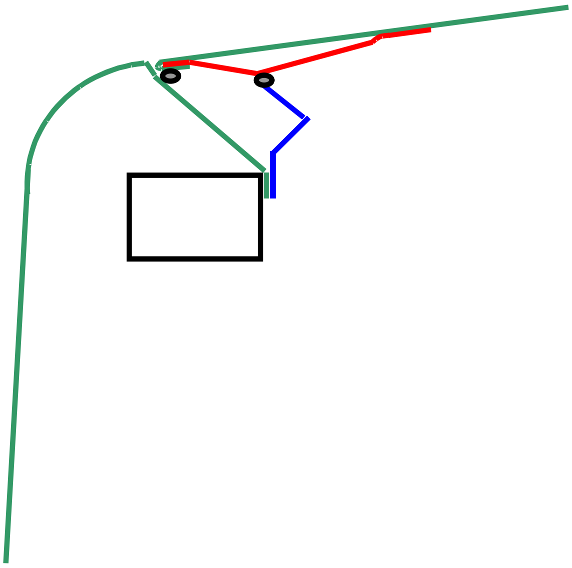


Figure 2.14. Possible bonnet edge with a more deformable wing support

- The bonnet hinges may be designed to deform under a head impact (see Figures 2.15 and 2.16).

o For head protection at the rear of the headform test area measures may include:

- Adding deformable or shear-off systems for the wiper spindles and linkage.
- Weakening of the bulkhead and firewall.

2.4.3 Summary of protection in the bonnet area

To date, the concepts described above for providing protection for pedestrian heads are thought to be at least sufficient to solve the requirements for phase one of the Directive. However, it is not clear from current data if the degree of change necessary to meet phase two of the EC Directive will be feasible for the whole of the bonnet top test area; this is discussed in Section 10.

2.5 Performance of current production cars

Since October 2005 new car approvals have to meet the first phase of the pedestrian Directive. Some new car models are evaluated to more stringent requirements to provide consumer information in the Euro NCAP programme. In the lead-up to the implementation of phase one of the Directive, Euro NCAP testing has included cars with some pedestrian protection features incorporated and these show that manufacturers are making progress.

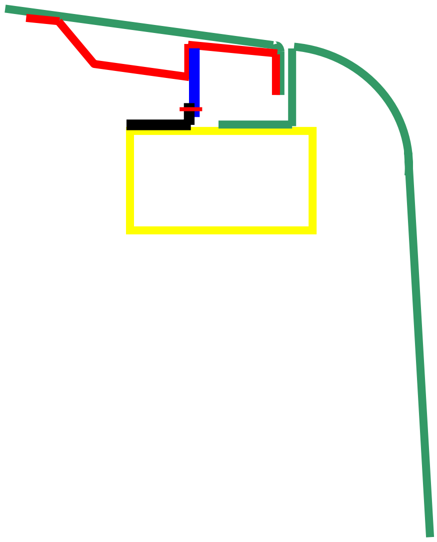


Figure 2.15. Bonnet mounted with a conventional hinge

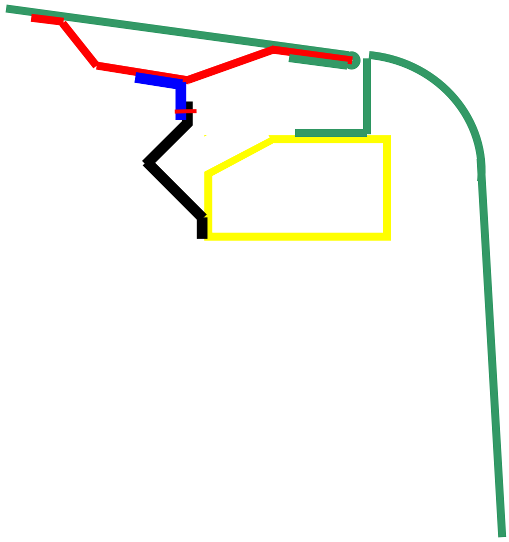


Figure 2.16. Bonnet mounted with a more deformable hinge structure

More recently in late 2005, Euro NCAP tested the Citroen C6, which is understood to be the first car they have tested that was designed specifically to meet phase one of the Directive. The car achieved the first four star rating for pedestrian protection. Although the Euro NCAP protocol is not identical to the current phase two of the EC Directive, the results showed that in many areas it passed the requirements of phase two of the Directive and in the remaining areas it came close to passing. However, the combination of vehicle styling and the high technology pop-up bonnet solution used for the C6 may not be applied to the whole range of vehicle types and variants popular in Europe without undue cost, and aesthetic or design (shape) restriction. Also by their nature, there is likely to be less confidence that pop-up bonnet systems will always work as intended when compared with non-deploying energy absorbing protection (normal vehicle deformation). This combined with the higher cost means that high-tech solutions, such as pop-up bonnets are only likely to be used for sport or executive type vehicles where simpler solutions are not practical. This is because for these vehicles the requirement for the vehicle to be low and streamlined results in a low seating position, which in turn results in minimal under-bonnet clearances in order to achieve the required drivers' view angle. Therefore, for both cost and confidence reasons it is thought unlikely that pop-up bonnets solutions would be applied to the whole fleet despite it possibly being an easier method of providing protection than by vehicle deformation alone. In the authors' opinion the performance of the C6 cannot be read directly across to the other types of vehicles in terms of the feasibility of meeting phase two of the current Directive.

2.6 Research vehicles

Meeting the requirements for crash safety in both frontal impact protection and pedestrian protection was an objective of the project reported by Bosma *et al.* (2001). New concepts for a vehicle front with enhanced safety features were developed and incorporated into their demonstration vehicle called the 'Ecofront'. This vehicle front consisted of a bonnet, wings and a bumper designed to satisfy the EEVC pedestrian protection requirements, whilst also taking into account styling and packaging.

A first exterior design was used to make an initial assessment of the pedestrian safety of the vehicle shape, which was performed using MADYMO multi-body techniques and MADYMO models of the EEVC pedestrian impactors. Based on the results of the conceptual studies, design recommendations were made to provide space underneath the bonnet to avoid contact with rigid engine parts and between the bumper skin and aluminium bumper. As the hinges of the bonnet normally create local stiffness in the impact zone, which makes achieving the EEVC pedestrian requirements for head impacts difficult, the hinges were placed outside of the impact area, to the sides of the A-pillars.

The bonnet was assessed through performing several child headform impact simulations. The bonnet consisted of a steel outer surface with a Bulk Moulded Compound (BMC) layer on the inside. In the area with less curvature, the stiffness of the bonnet was tuned by placing a PVC foam between the outer surface and the BMC. This produced a bonnet that for most areas achieved HPC values below 1000. An area of the bonnet produced HPC values from 1100 to 1200, which was stated as being due to the styling feature, curvature, of the bonnet in that region. By smoothing the bonnet surface, the values from this area were reduced to less than 1000.

With just the bumper skin made out of PolyPropylene (PP), it was shown to be impossible to achieve a proper balance between the bonnet leading edge, bumper and spoiler area. Therefore special energy absorbing elements, also made from PP were added behind the bumper surface. This allowed the stiffness of each of the three main areas to be tuned separately.

For all impact locations considered by Bosma *et al.*, the EEVC pedestrian requirements were found to be satisfied according to the simulations. However, the styling of their Eco-front dictated certain design features for the vehicle, for example, having the bonnet hinges to the side of the A-pillars.

At the Institut für Kraftfahrwesen Aachen (IKA), modifications were made to an existing car to improve the pedestrian protection offered by the front of a vehicle (Kalliske and Friesen, 2001). A representative small family car was selected for the investigations. It was first tested un-modified according to the procedures proposed by the EEVC WG17 and then, based on the results, modifications were made to the vehicle aiming to improve the pedestrian protection when tested again.

In order to achieve the required deformation distance under the bonnet to absorb enough energy to pass the child and adult headform tests, the bonnet was raised, ‘popped-up’. A lifting mechanism was developed by means of which the rear edge of the bonnet was actively raised, by 80 mm, in the event of an accident. As the contact sensors required to trigger the raising of the bonnet were not developed within this study, the headform tests were conducted with the bonnet already in the raised position. Additionally, the thickness of the bonnet outer surface was reduced by a third. Following these modifications, clear improvements as regards HPC values were achieved at all test locations. Two adult and two child headform test locations still failed the HPC value of less than 1000 criterion, although it was suggested that these results could be improved through better selection of the spring stiffness in the bonnet raising mechanism, particularly for the adult headform tests.

The upper legform to bonnet leading edge test area was modified by using a bonnet latch that did not prevent downwards movement of the locking bracket in the case of impact. Clear improvements were seen in the vehicle performance, although the performance criteria limits were still exceeded.

The bumper of the vehicle was brought forward by 20 mm, the standard production plastic bumper was made more elastic and a foam-core inserted between the cover and cross members. The lower edge of the bumper was brought 10 mm forward with respect to the upper edge. The shearing displacement of the knee was within the performance limit, about 4 mm for the improved vehicle. The knee bending angle was also improved but remained above the performance limit and the tibia acceleration was also above 150 g for one test.

Further revisions were made to the bumper by introducing more crush depth and stepped padding between the cover and the cross member. The three specified limit values were then found to be fulfilled.

Kalliske and Friesen (2001), in contrast to the study by Bosma *et al.* (2001), started from an existing vehicle model. It is therefore not surprising that they had greater difficulty in achieving the requirements of the EEVC WG17 test procedures. However, both studies have shown the potential to achieve the requirements in the bonnet region and the bumper. The requirements for the bonnet leading edge, according to Kalliske and Friesen, remain unfeasible.

2.7 Conclusions from current research and development

Ideally, the consultations carried out within the overview of current research and development would have provided detailed information of the position of the manufacturers with respect to meeting the requirements of phase two of the EC Directive. However, as the vehicle design work in this regard is still at an early stage with the manufacturers, there was insufficient detail available to gauge the present position.

Depending on the effort made by the various manufacturers to incorporate pedestrian protection into current vehicle designs, the test results from Euro NCAP pedestrian evaluations could be used as a baseline for vehicles with little or no pedestrian protection or for some specific vehicles as an example of what can be achieved. However, unlike occupant protection, protection for pedestrians was not until recently thought to have been given high priority by most car manufacturers or car buyers and although research vehicles appear to show that it could be possible to meet phase two of the EC Directive. These research vehicles do not represent the full range of sizes, styles and variants now produced and much work has to be done to provide the required improvements.

3 Alternative test methods and tools (review of state of development and availability)

The European Enhanced Vehicle-safety Committee (EEVC) set up a pedestrian working group in 1987 (EEVC WG10) and the International Organisation for Standardisation (ISO) set up a pedestrian working group in 1988. The EEVC and ISO working groups worked in parallel sharing some experts and information, so it is difficult to accurately credit either group with the development of the test tools and methods. However, put simply, the EEVC working group (WG10) was more active and by 1994 had developed a complete set of draft test methods and tools. EEVC Working Group 17 was set up in May 1997 to up-date and finalise the test methods and by 1998 the EEVC methods and tools were essentially complete. They consisted of separate tests to the bumper, the bonnet leading edge, and the bonnet top up to and including the base of the windscreen. These test methods, used in conjunction with their performance criteria, were drafted at the request of the European Commission in a form suitable for inclusion in a regulation to require certain standards of pedestrian protection. As a result, the EC Directive 2003/102/EC (European Parliament and Council of the European Union, 2003) currently uses the test methods drafted by EEVC Working Group 17, though most of the detail of the test methods is in a separate document (Commission of the European Communities, 2004).

To date the ISO working group have produced two test methods, one for the bumper and one for the bonnet top. The ISO test methods are very similar to the EEVC ones and in many respects they are based on them. However, they are not identical and in general the ISO test methods are less specific because they were intended for research and development rather than regulatory use. More recently, in 1997, the International Harmonised Research Activities committee (IHRA) also set up a pedestrian safety working group. The aim of this group is to build on the work of EEVC and ISO to produce improved harmonised test methods suitable for a wider range of vehicles shapes and to develop test methods and tools for all pedestrian contacts with the front of the vehicle. Some members of the IHRA group are also members of the ISO and EEVC pedestrian working groups. The EEVC methods have been limited to the front of the vehicle up to and including the base of the windscreen because these were the only areas that were thought to be feasible to improve. As the central unsupported area of the windscreen is thought to be safe this only leaves the windscreen glass close to supports, the A-pillars, the upper windscreen frame and roof, with no EEVC test method. Therefore, to meet their aim of testing all areas likely to be contacted by a pedestrian in an accident, the IHRA Pedestrian Safety Working Group will also need to develop test methods for these areas.

More recently, at the request of the Japan Ministry of Land, Infrastructure and Transport (Japan MLIT), the IHRA working group provided the Ministry with their best estimates of head impact conditions based on selected simulation results. The Japan MLIT, with the help of the Japan Automobile Manufacturers' Association, Inc. (JAMA) and the Japan Automobile Research Institute (JARI, who are also members of the IHRA working group), has developed a pedestrian head test method and protection requirement. The Japanese test method uses the ISO headforms and a variation on the IHRA head test method, and it will be applied to passenger cars and to trucks with GVW (Gross Vehicle Weight) ≤ 2.5 t derived from passenger cars, from 1 September 2005 for new models and from 1 September 2010 for existing models.

The UN ECE (United Nations Economic Commission for Europe) Working Party on Passive Safety (GRSP) has the task of developing a pedestrian Global Technical Regulation (GTR) based on existing and updated research (they are doing no new research). The GTR informal working group, under GRSP, on pedestrian safety group has recently produced a proposal for a pedestrian GTR (Informal Working Group on Pedestrian Safety, 2006). The draft GTR is important to the debate on pedestrian protection. The proposal is essentially based on the work of EEVC, ISO, IHRA and Japanese MLIT test methods. It has not been fully discussed in detail here, under alternative test methods and tools, but in the following section, Section 4.

3.1 Alternative test tools

3.1.1 Legform

For evaluating car aggressiveness to the lower extremities of a pedestrian, the EC Directive specifies a legform impactor which consists of a simplified rigid femur section, a knee joint and a simplified rigid combined tibia and foot section. The specification is that developed by EEVC WG17. As part of his research work for EEVC WG17, Lawrence developed a legform impactor to meet this specification; the current version of this impactor was assessed by Lawrence and Rodmell (2000) and found to meet the EEVC specification. The knee joint was designed to reproduce the bending moment of a human knee under lateral loading; however, the mechanism used to achieve this does not mimic a human knee. The EEVC legform and knee joint was designed to be simple, repeatable and robust and includes instrumentation that accurately measures knee shear and lateral bending. The legform, associated equipment and consumable parts have been available for several years.

ISO have produced a specification for a legform impactor, but no impactor to meet it. Therefore, as there is no ISO test tool available, it is not discussed below as an alternative test tool. However, it is interesting to note that, with the exception of the knee, the biomechanical requirements of the impactor specification are very similar to those of the EEVC.

Japanese car manufacturers and research groups JAMA and JARI have begun development of a more complex legform able to simulate the human long bone flexibility and possessing a mechanical knee joint that is a closer replication of a human knee. This legform is known as the Flexible Pedestrian Legform Impactor called Flex-PLI. However, it should be noted that this impactor is still under development.

As this is the only alternative legform impactor the following sections compare this impactor with the EEVC WG17 legform impactor.

Unfortunately, within the time available to update this report it was not possible to obtain sufficient information to comment in full on the latest version, therefore the comments below apply to the Flex-PLI 2003 and not the current version, called the Flex-PLI GTα, unless stated.

3.1.1.1 Biomechanics (Flex-PLI 2003)

The long bone structure of the Flex-PLI consists of a flexible core of glass-reinforced polymer pressed between hard urethane and the core binder, which is compressed by screws through the exterior housing segments. The exterior housing segments are separated along the length of the long bone by rubber spacers. The knee joint includes simulated femoral condyles and a tibial plateau, with coil-spring tensioned wire cables representing four knee ligaments. The whole legform is enclosed within flesh that comprises a layer of rubber sandwiched between two layers of neoprene.

Dynamic three-point bending tests have been carried out to assess the biofidelity of the Flex-PLI. Direct comparison of the thigh biofidelity with that from human thigh bone tests could not be made because the PMHS (Post Mortem Human Subject) had the flesh removed before testing, however, once the flesh on the Flex-PLI was crushed the force deformation slope was of the same order as the PMHS test selected for comparison. The lower leg bone of the Flex-PLI compared well with results from three point bending tests with lower leg PMHS tests selected for comparison. A four-point loading test of the knee was used to evaluate the biofidelity of the Flex-PLI, which demonstrated a bending behaviour similar to that of the PMHS tests selected for comparison, see Figure 3.1. It can be seen from Figure 3.1 that the highest PMHS knee bending moment recorded was about 160 Nm, which is far lower than the maximum value of about 450 Nm specified by EEVC WG17 for the legform knee bending moment.

There is a considerable quantity of biomechanical data for the knee joint obtained from tests of PMHS; however, the results vary widely. The cause of this variation is thought to be due to a combination of factors including the use of PMHS of elderly persons, errors due to inertial effects of moving the leg to load the knee and the visco-elastic properties of the ligaments, which result in low stiffness at low loading velocities and higher stiffness at higher velocities. In the more recent PMHS knee study used by Konosu (Bhalla *et al.*, 2003), efforts were made to isolate the lateral stiffness of the knee joint. However, the loading method forced the knee to deflect about a pre-determined plane, which would have prevented the knee joint from rotating slightly, as it would have done in real life to share the loading between the collateral and cruciate ligaments under tension; this may have resulted in a lower stiffness and premature failure. This forced knee loading was caused by the use of the rollers at each end of the sample; the line contact of the roller would have inhibited axial rotation between the tibia and femur, see Figure 3.2.

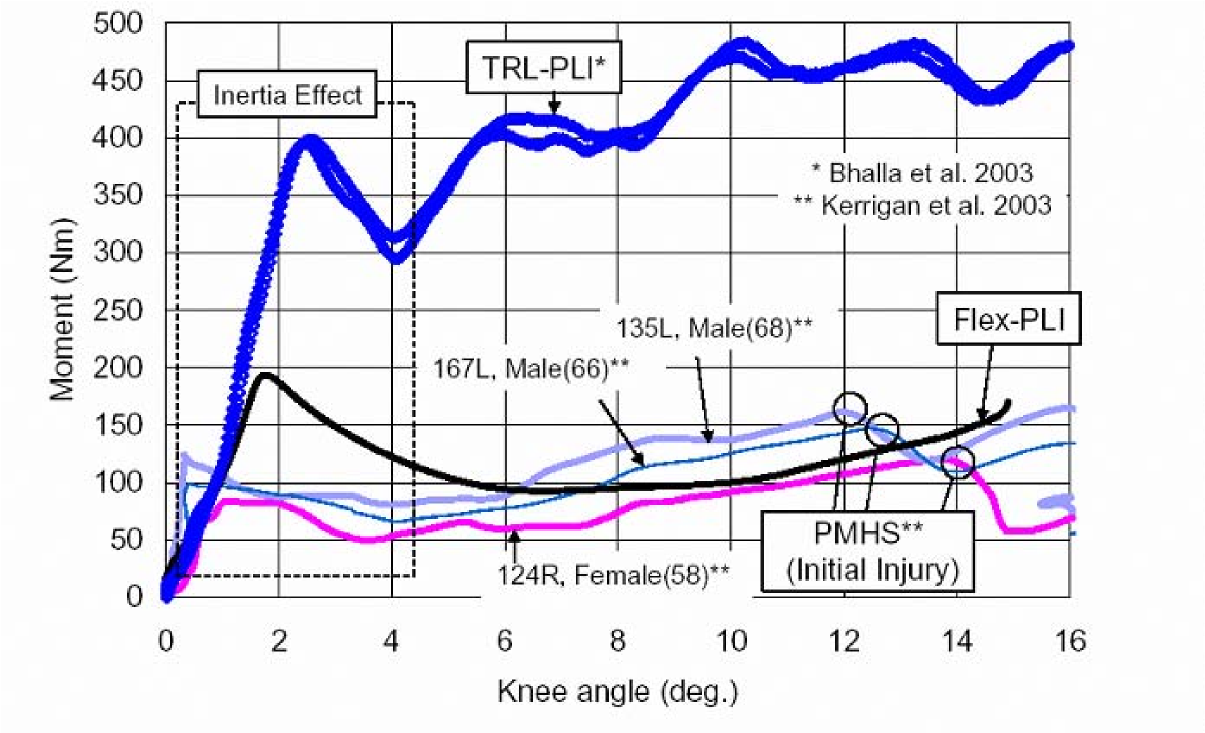


Figure 3.1. Dynamic four-point bending test for knee joint of PMHS by Bhalla *et al.* (2003) compared with similar tests of the Flex-PLI and TRL-PLI legform impactors (Konosu and Tanahashi, 2003a)

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 H, 2001), see Figure 3.3.

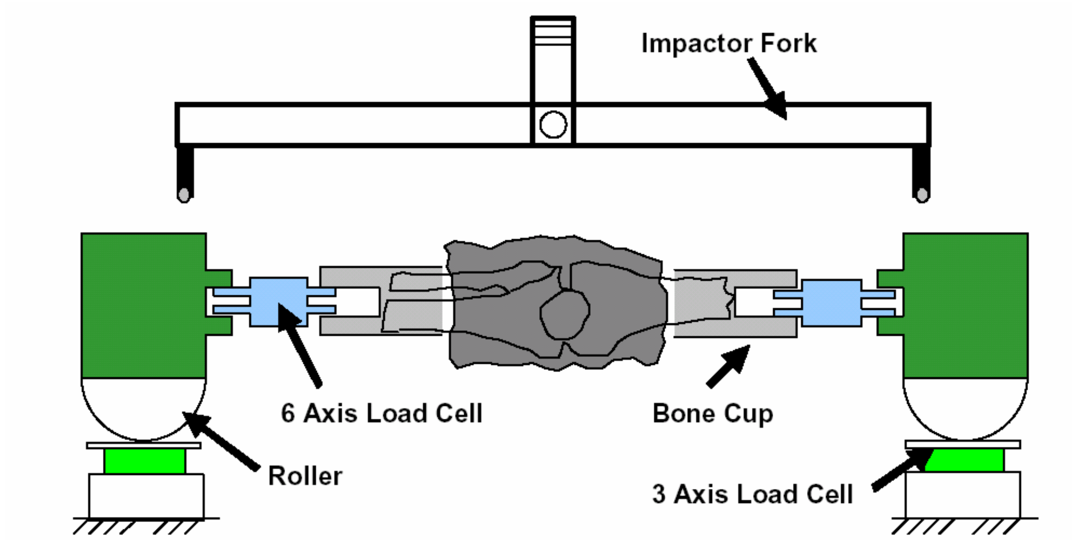


Figure 3.2. Schematic of the four-point knee bending test set up used in PMHS tests (Bhalla *et al.*, 2003)

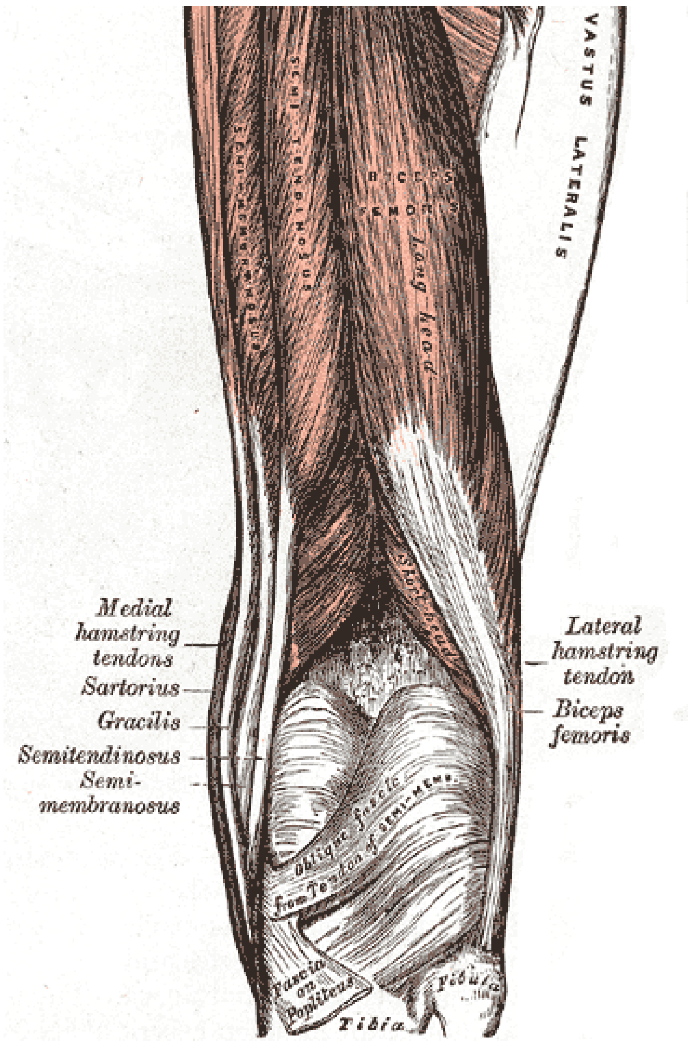


Figure 3.3. Muscles and tendons of the knee (Gray, 1918)

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.*. The average peak bending moment measured in the Kajzer *et al.* bending tests was 388 Nm (Kajzer *et al.*, 1997). Konosu and Tanahashi in their ESV paper (Konosu and Tanahashi, 2003b) question 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.

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. This method was used by Matsui (2003) when he used the EEVC WG17 legform impactor to reconstruct real pedestrian accidents. This method has the advantage that the measured outputs can be compared with the accident injuries to obtain injury risk curves for living humans. These results are discussed further in Section 3.3.1.4, however, 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. This conflicts with the far lower knee bending moment found in PMHS knee tests.

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 cadaver 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 have been contacted for further clarification on how this conclusion relates to knee shear and bending performance.) 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 answer.

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 for the Flex-PLI legform impactor.

Increasing the strength and pre-tension of the springs acting on the wire ropes that represent the collateral ligament 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 may seem strange that there is debate and disagreement about the most appropriate biomechanical values to be used for the knee of the legform impactor; however, it is in practice very difficult to make measurements in live and PMHS subjects. It is reassuring to note that similar debates exist about most biomechanics requirements used in safety regulations; however, applying these regulations has resulted in significant improvements in vehicle safety despite these uncertainties.

Like the EEVC legform impactor, the Flex-PLI has ‘bones,’ sections of a simplified cylindrical shape which are much larger in diameter and heavier than the femur and tibia of a human, and the flesh in both impactors is comparatively lightweight and of uniform thickness. 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. However, in the case of the Flexi-PLI, which is intended to have greater biofidelity than the EEVC impactor, it must be questioned why bone flexibility was considered more important than mass distribution and the de-coupling of the muscle mass.

It is clear that the flexible long bones of the Flex-PLI give it greater biofidelity than the EEVC WG17 impactor; however, as discussed above, the biofidelity of the Flex-PLI knee for living humans is not proven.

3.1.1.2 Physical and mechanical properties and instrumentation (Flex-PLI 2003)

The legform specification for the EC Directive (European Parliament and Council of the European Union, 2003) as detailed in the Commission Decision (Commission of the European Communities, 2004) includes length, mass, centre of gravity and moment of inertia requirements. All these properties were derived by EEVC WG17 from those of a 50th percentile male, by making suitable adjustments to take account of the simplified shape of the impactor.

The physical measurements from (or design specification for) the prototype Flex-PLI 2003 are given by Konosu and Tanahashi (2003a). A comparison of these two sets of measurements is provided in Table 3.1. Two properties have no corresponding values from the Flex-PLI as none are available in the literature.

Table 3.1: Comparison of the EEVC / EC Directive requirements and the Flex-PLI 2003 characteristics

Property	EEVC legform	Flex-PLI 2003
Total length	926 ± 5 mm	926 mm
Femur mass	8.6 ± 0.1 kg	8.4 kg
Tibia mass	4.8 ± 0.1 kg	5.6 kg
Total mass	13.4 ± 0.2 kg	14.0 kg
Femur centre of gravity (from knee centre)	217 + 10 mm	223 mm
Tibia centre of gravity (from knee centre)	233 ± 10 mm	234 mm
Femur moment of inertia	0.127 ± 0.01 kg.m^{-2}	
Tibia moment of inertia	0.120 ± 0.01 kg.m^{-2}	

From Table 3.1 it can be seen that the lengths of the Flex-PLI conform to the requirements set out in the EC Directive. However, apart from having no information on the moments of inertia for the legform, the masses of the Flex-PLI are not within the design requirements. In particular, whilst the femur mass is slightly too light, the tibia mass is far greater than that of EEVC, ISO and the provisional IHRA specification and that of the 50th percentile human. Part of the increased tibia mass could be justified as an allowance for the mass of a shoe, which is not allowed for within the EEVC specification. When questioned on the lack of moment of inertia information for the Flex-PLI, Konosu replied that based on numerical simulations the moment of inertia was not thought to affect the test result (Konosu, 2004). Although this argument might be accepted for small differences in moment of inertia, the effect in this case cannot be judged due to the absence of data.

It is also important that an impactor used for regulatory testing should be robust and have accurate transducers with a suitable frequency response. The EEVC WG17 legform impactor has proved its robustness over many years and the accuracy of the transducer system has also been examined throughout the impactor development and has been shown to have acceptable accuracy and frequency response (Lawrence and Thornton, 1996; Lawrence and Rodmell, 2000). The robustness of the Flex-PLI has yet to be proven, however, its complexity is thought likely to make it less robust and possibly less repeatable. Repeatability of the Flex-PLI knee shearing mechanisms is thought likely to be poor because the stiffness is produced by a combination of several factors including the joint friction, the interlocking action of knee components and the ligament tension. In the EEVC knee the bending and shear mechanisms are independent and repeatable. The knee ligament extension is measured in the Flex-PLI by ‘string operated potentiometers’, which is a relatively low accuracy and frequency response system, whereas the EEVC legform shear and bending potentiometers are directly driven by the displacements, thus providing high accuracy and frequency response.

The Flex-PLI has a maximum of 15 measurement channels that can measure the strain on the long bones, elongation of each ligament and the knee condyle compression forces on both the lateral and medial sides. The outputs of knee ligament extension are directly related to knee injury, however, on their own it is difficult to determine the combination of bending and knee shear that has caused them. The addition of condyle force measurements, which are not directly related to injury, help give an understanding of the knee joint deformation. In the WG17 legform impactor the knee transducer outputs measure separately knee shear and bending deformation, which are used to determine injury risk but also give direct information on the nature of knee loading.

As one of the vehicle measures that helps to reduce knee lateral bending is the introduction of a low load path in the bumper, early in the impact (a strong spoiler), ideally 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 mean that it is possible to determine the loading profile along the full length of the tibia. 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).

The measurement channels on the femur of the Flex-PLI mean that it could potentially be used to test high bumpers to determine the risk of femur fracture and in addition contribute towards the measurement of the risk of knee joint injury. This would have an advantage over the current EEVC high bumper test, which only measures the risk of femur fracture. However, to be realistic for this use the Flex-PLI would need a simplified upper body mass to be added.

At the time of the 2004 feasibility study (which is being up-dated here) JARI had stated that they hope to finish development and arrange production of the Flex-PLI by 2005, however, their latest target is the end of 2007. To be a valid alternative tool for possible use in phase two of the EC Directive a test tool must, amongst other things, be finalised. Ideally it should also be commercially available. However, as the performance of the final version of the Flex-PLI will need to be independently assessed before it could be adopted for phase two of the Directive, currently it must be regarded as not complying with these requirements.

3.1.1.3 Testing of the Flex-PLI G version (currently this is the penultimate version)

The informal group on pedestrian safety responsible for developing the pedestrian GTR has set-up a Flex-PLI Subgroup to assess and develop the legform. Their aim is to assess the legform’s performance and identify any shortcomings so that JARI can refine the design with the aim of producing a version suitable for legislative use by about the end of 2007. As part of the activities of this group the German research laboratory BASt carried out a study titled ‘Examination of the handling and the repeatability of tests with the Flexible Pedestrian Legform Impactor (G-Level)’ (Lorenz and Zander, 2005).

3.1.1.3.1 Summary and conclusions of BASt’s work

BASt’s work was reported in the form of a presentation to the GTR group and EEVC WG17. This presentation is summarised below. The conclusions and outlook below have been taken directly from the presentation (PowerPoint).

Two cars with ‘pedestrian friendly bumpers’ were selected by BASt for testing with the Flex-G, a Mercedes A-Class and a VW Golf. The vehicles were selected as having ‘pedestrian friendly bumpers’ on the basis of their Euro NCAP scores. The bumper of the A-Class showed that it had an all green bumper and the Golf bumper was green in the main central area (a green Euro NCAP rating shows it complies with the current Directive phase two protection requirements and a yellow shows that it fails, but only by a small margin).

Originally it was intended to do a few low speed tests with the Flex-G followed by full speed (40 km/h) tests. However, a low speed test at 24 km/h on green areas of the bumper of each car showed that they both exceeded the failure criteria and the capacity of the MCL ligament extension instrumentation.

BASt then modified the bumpers to try to make them softer by removing and / or adding padding behind the bumper face. The vehicles where modified in two stages and tested with the Flex-G at a range of speeds up to a nominal 40 km/h and with the EEVC WG17 legform at 40 km/h. The results with the Flex-G at 40 km/h showed that the improved vehicles were still exceeding the MCL output criteria. The MCL output for the modified Mercedes A-Class was 19.2 mm, which was just inside the 20 mm measurement capacity of the legform. The MCL output for the modified VW Golf just exceeded the measurement capacity at 21.8 mm. In the tests using the WG17 legform, the results had indicated that the modifications had improved the protection.

The conclusions from this study were:

- Flex-G seemed to be less sensitive to environmental influences because it does not use Confor-foam – further research is needed.
- The tested “pedestrian friendly” cars (according to Euro NCAP, using TRL-PLI) can marginally meet the Flex-G proposed protection criteria at a speed of 25 km/h
- Modified cars allowed first information about the repeatability of test results
- Improved test results with Flex-G on modified cars were confirmed by tests with the TRL PLI (impact height (foot end) 50 mm above ground reference)
- A bumper that was pedestrian friendly according to Euro NCAP / EEVC WG 17 could be too hard to be tested with the Flex-G without modifications at an impact speed of 40 km/h
- Under ‘Outlook’ it was noted that further research was needed including tests on pedestrian friendly vehicles of different shapes, durability and repeatability and with different examples of the Flex-G to examine reproducibility, and that the way forward was uncertain.

3.1.1.3.2 Interpretation of the BASt’s findings

Two conclusions could be drawn from these results:

- pedestrians need far more protection than previously thought i.e. the current Directive phase two test tool and protection criteria are insufficient to require a truly pedestrian friendly bumper

- or the biomechanics being used to specify the Flex-G impactor are either inappropriate or are missing some important elements such as muscle tension across the knee joint.

The WG17 legform impactor's outputs had produced statistically significant correlation between injury and car properties (see Section 3.1.1.1) in JARI reconstructions of real (live) pedestrian accidents (Matsui, 2003) so it was reasonable to assume that the cars tested with the Flex-G impactor (identified as pedestrian friendly by Euro NCAP testing to WG17) were in fact really pedestrian friendly. As the Flex-G's protection criteria were exceeded in tests at a lower speed than used by Euro NCAP it can be surmised that some important properties of a live human are not included in the Flex-G impactor. One property that is currently missing in the Flex-PLI legform (including the latest GTα version) is the effect of muscle tension on the knee; this may be significant. This has already been discussed in Section 3.1.1.1. A second property that is different (in both the EEVC WG17 and the Flex-PLI) is that much of the mass in a human leg is in the muscle whereas in the impactors most is concentrated in the 'bone'. Therefore in the impactors most of the mass, that represents the muscle, is effectively part of the 'bone' whereas in the human the muscle is more loosely attached. This could mean that the effective mass of the impactor (the mass seen by the car) is higher that that in an impact with a pedestrian.

The tests by BASt show that using the Flex-PLI and meeting its protection criteria would require car manufacturers to provide more extensive protection. Therefore if it were to be used in a regulation with the current knee stiffness then it would cause some feasibility concerns; this is discussed in Section 10.3.

Following discussions of the BASt assessment in the GTR Flex-PLI Subgroup it was decided to increase the bending capacity of the knee of the Flex-PLI and a new version was developed which amongst other changes included more bending capacity. The new version of the Flex PLI the legform is called the Flex-PLI GTα.

3.1.1.4 Description and physical properties of the Flex-PLI GTα

The long bone structure of the Flex-PLI GTα is complex, consisting of a series of segments around a flexible rectangular core (the original core was circular). The bone segments are made from aluminium surrounded by nylon and are separated by rubber spacer washers which allow them to articulate. The segments are effectively square in section, however, the nylon 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. Depending on the amount of slack in the wires they tend to force the bone to bend by compressing the rubber spacer washers on the compression side by preventing extension on the tension side, ultimately, when the rubber washers are fully compressed they act as bending limit stops for the long bone assembly. The knee joint includes simulated femoral condyles and a tibial plateau, with coil-spring tensioned wire cables representing four knee ligaments found in the human. As well as doubling the length of the springs used to represent the human knee ligaments the Flex-PLI GTα now uses a total of eight sets of cables and springs to represent the collateral ligaments, four for the rope and spring assembles representing the medial collateral ligament and four representing the lateral collateral ligament. 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.

The main driving force for most of the changes and improvements for previous versions have been to improve the robustness and reliability. For the Flex-PLI GTα version the main change was to increase the ligament extension to so that the impactor can provide useful data, without hitting stops (springs going coil-bound), when testing vehicles that do not meet the proposed Flex-PLI impactor protection criteria. This design change was in response to the BASt tests discussed above.

In developing the Flex-PLI, priority has been given to meeting biomechanical requirements that relate to the bending, deformation or extension of components such as the long bones, flesh and ligaments. However, other properties such as mass, centre of gravity and moment of inertia are also important in order to obtain realistic loading of the mechanical knee. Table 3.2 shows the physical targets set by

EEVC WG17, which are used in the Directive, compared with the properties for the Flex-PLI GTα where available.

Table 3.2: 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.

Although the values for the GTα version have been estimated by JARI they are probably reasonably accurate outputs from the CAD system used. It can be seen that there are some large deviations from the target values, however, this is to be expected at this stage of the development. Once the design of key components has been fixed in terms of satisfactory impactor performance, some adjustment of dimensions and materials (to which the impactor performance will be insensitive) can be made to come closer to the mass targets. However, it may well be difficult to reduce the mass of the tibia sufficiently. Correcting the centre of gravity and moment of inertia may be even more difficult to achieve. Obtaining an acceptable centre of gravity would require a significant redistribution of mass which may be difficult and the moment of inertia is unlikely to be correct if the centre of gravity is not. 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 once the Flex-PLI has been shown to be acceptable in other respects but eventually similar tight tolerances will be needed.

As mentioned in Section 3.1.1.2, to be a valid alternative test tool for possible use in the second phase of the EC Directive the tool must, amongst other things, be finalised. It should also be commercially available. JARI and the GTR Flex-PLI Subgroup intend to complete their evaluation and development programme by the end of 2007. Currently the FLEX-PLI described above does not comply with these requirements. The GTR informal working group on pedestrian safety have come to the same conclusion and currently propose to use the same impactor as specified in the EU Directive; the EEVC WG17 impactor. However, in the future when / if the Flex-PLI or a similar impactor has been developed and shown to be suitable for regulatory use then consideration should be given to amending the Directive, GTR etc. in order to use it.

3.1.2 Upper legform impactor

No alternative to the EEVC WG17 upper legform impactor test tool has been found.

As discussed in Section 3.1.1.2 the addition of an upper body mass to the Flex-PLI legform impactor might make it suitable for use in testing high bumpers. It is possible that if a hip force transducer was also fitted in the joint between the leg and the upper body mass that it might also be suitable for testing the bonnet leading edge. However, this would take both time and funding for the development programme, which means that this is not currently a viable alternative.

3.1.3 Headform

As discussed in Section 1 of this report, the EC pedestrian protection Directive has a two-stage approach. For the first phase a 3.5 kg child / small adult headform is used to test the whole bonnet surface at a speed of 35 km/h. For the second phase, the front part of the bonnet top is tested with a 2.5 kg child headform and the rear part of the bonnet top is tested with a 4.8 kg adult headform, both of which are at a test velocity of 40 km/h. This second stage uses the EEVC WG17 test methods and tools unaltered; however, before this second stage is adopted it must be subjected to the feasibility study described in this report.

Headform impactors to the EEVC WG17 specification (2.5 kg and 4.8 kg) have been supplied for many years by First Technology Safety Systems (FTSS). A 3.5 kg headform impactor was not available at the time that ACEA (*Association des Constructeurs Européens d' Automobiles*) proposed the two stage approach now included in the EC Directive, so ACEA produced a specification for a 3.5 kg headform based on the ISO specification and arranged for FTSS to develop a headform to meet this specification. This was achieved by modifying the EEVC WG17 adult headform design. The ACEA 3.5 kg headforms have been available from FTSS for about three years.

As noted in Section 3 above, ISO WG2 has produced a sub-system head test method. This also 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, the 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. 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. 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 of 0.3 kg.

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, however, 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. Therefore it is difficult to make a case for choosing between the available headform masses on the basis of effective mass alone. As discussed in Section 10, recommendations for the adult headform mass are possible when the test methods and feasibility issues are considered together.

The ISO headform specifications were used as the basis of the draft International Harmonised Research Activities – Pedestrian Safety – Working Group (IHRA-PS-WG) 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.

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 but no examples of 3.5 kg child and 4.5 kg adult headforms complying with the ISO / IHRA specification existed. Therefore the Japan Automobile Manufacturers' Association, Inc. (JAMA) in conjunction with the Japan Automobile Research Institute (JARI) developed prototypes of new child and adult headform impactors, designed specifically to meet both the requirements of the ISO specification and the specification proposed, and later included, in the Japan MLIT requirement (Matsui *et al.*, 2003). These impactors are referred to as the JAMA-JARI child and adult headform impactors. These new headforms meet the ISO and Japan MLIT specification and can be used in performance assessment tests conducted by the Japan MLIT and J-NCAP. The specification of the JAMA-JARI 3.5 kg child headform is such that it also meets the requirements of the first stage of the EC Directive with the exception that different certification methods are used. Certification tests are used to test the complete impactor system and show that its performance is as intended. In the case of the JAMA-JARI child headform, although the certification method is very different from that in the first stage of the EC Directive it is thought that the impactor is likely to meet or come close to meeting the EC certification limits; any differences could probably be resolved by using a head skin with a slightly different formulation of raw materials. Therefore, if found necessary, there would be no problem in adopting this headform for use in the EC Directive. With the exception of the headform mass and related properties the adult JAMA-JARI headform specification is very similar to that of the adult in the EC Directive. However, the adult JAMA-JARI headform has a different certification method to the EC Directive. Therefore, if found necessary to adopt this headform for use in the EC Directive minor changes would have to be made in the specification and either certification limits would have to be found and set for a 4.5 kg headform using the EC certification method or the JAMA-JARI certification method would have to inserted into the EC Directive.

Like the EEVC WG17 and ACEA headforms the JAMA-JARI child and adult headform impactors consist of an aluminium hemispherical core with an outer synthetic rubber 'skin'. The headform skin represents the flesh covering of a pedestrian's head. The JAMA-JARI child and adult headform cores are available from S•Tech Co. Ltd., Japan (http://www.s-techinc.co.jp) and the skins are available from JASTI Co. Ltd., Japan (http://www.jasti.co.jp).

A 4.5 kg headform is also available from First Technology Safety Systems (FTSS) that meets the ISO and Japan MLIT specifications. Alternative 3.5 kg and 4.5 kg headform impactors are also available from JASTI Co. Ltd., Japan. Information on the FTSS and JASTI headforms can be found in a report by Lawrence (2005).

As mentioned in Section 3.1.1.2, to be a valid alternative tool for possible use in the second phase of the EC Directive a test tool must, amongst other things, be finalised. Ideally it should also be commercially available. It can be seen that the alternative headforms (JAMA-JARI, JASTI and ACEA) described above comply with these requirements.

3.1.4 Pedestrian dummy

Pedestrian dummies might appear to be a more obvious choice for a regulatory test and they do have a number of benefits, which include a simple test method, and impact conditions for each main contact with the car that automatically adapt to vehicle shape and stiffness. However, they also have significant disadvantages:

- The repeatability of tests using pedestrian dummies is relatively poor, small variations in the initial dummy set-up will have an increasing influence on the impact severity and position on the car of dummy body parts, as the impact progresses.
- If pedestrian dummies were used then a range of pedestrian dummies of different stature would be required to test all areas likely to be hit in real life. This is because the impact locations for key body parts such as the head are very dependent on the stature of the pedestrian, as well as the position of first contact across the width of the vehicle and the motion of the pedestrian before contact. It would also be very difficult to predict and control the impact locations of dummy body parts to test selected danger points accurately, particularly for the head.
- To give appropriate results the biofidelity of the whole pedestrian dummy must be correct.

For test methods intended for legislative use, as in this case, sub-system test methods overcome these disadvantages. Sub-system tests have the following advantages over full-scale dummy tests:

- 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 for the car manufacturers to design to 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.
- They can include corrections in the test conditions for the limitations in the biofidelity of the pedestrian dummies used to develop them.

However, they also have some disadvantages:

- They require the test method to specify the impact conditions, this gets more difficult to predict as the contact progresses from the leg, to the thigh / pelvis, to the upper body and then head.
- They do not take account of an earlier contact which might in some circumstances compromise protection intended for a later contact. One example of this is that a shoulder might collapse a bonnet before the head contact, thus removing the protection for the head. However, the shoulder contact is likely to reduce the severity of the subsequent head impact so this may not be a problem in real life.

Of these two disadvantages the first is probably the most important. When EEVC set up WG10 they considered that the experts appointed had sufficient knowledge to predict subsequent impact conditions and the approach was taken that by protecting for a ‘reasonable’ worst case it would provide sufficient protection in the majority of accidents. Therefore, the mandate for EEVC WG10 was to develop sub-system test methods and, as already noted, these test methods were subsequently reviewed and updated by EEVC WG17.

Whilst it may not be practical to use dummies in regulatory tests they are very valuable for research purposes, to help understand the kinematics and injury mechanisms and to review the overall effects of pedestrian protection measures. A pedestrian dummy called Polar has been developed recently in a joint collaboration between GESAC Inc., Honda R&D and JARI (Akiyama *et al*., 2001). The latest version of the dummy, known as Polar II, includes a human-like representation of the knee, a flexible tibia and more compliance of the shoulder than the Polar I. Currently the Polar II dummy is a prototype and it is not commercially available. Although it appears to provide good biofidelity when compared with the PMHS data selected, it is not clear from the reported results if all biofidelity issues have been fully addressed. For example, the lateral knee stiffness is far lower than that selected by EEVC WG17 with no allowance for muscle tension. The dummy's instrumentation is also thought to be insufficient to make it suitable for regulatory use.

The Polar II it is clearly an improvement in biofidelity over older pedestrian dummies, but it is not considered sufficiently well developed to be used in a regulatory test; nor does it overcome the other difficulties for using dummies, listed previously.

In the future, once the pedestrian dummies are sufficiently well developed and instrumented, it might be possible to use a combination of dummy tests and component tests to overcome the need for a family of dummies of different sizes. This would be facilitated by limiting testing in each area to those statures most vulnerable to injury. This principle is used in the EEVC test methods where the bumper and bonnet leading edge is only tested with adult impactors because accident data suggests that their longer limbs are more vulnerable to injury from these parts than children in accidents up to 40 km/h.

3.2 Alternative test methods

Both the Japanese MLIT and Euro NCAP methods have a tolerance not only on impact speed but also on the accuracy with which it is measured. The Japanese MLIT require "The instrument for measuring speed shall have a precision of ± 1% and a resolution of not more than 0.5 km/h". Euro NCAP require "The velocity measuring device should be able to measure to an accuracy of at least ± 0.02 m/s". The GTR proposal has a tighter tolerance on the equipment of ± 0.01 m/s. In the authors view it may be technically difficult to achieve such accuracy but, if it proves to be possible then a higher accuracy would be beneficial because it would help reduce test variability.

3.2.1 Legform test method

Only ISO have a complete alternative legform test method. The ISO legform test method is very similar to the EEVC one and in many respects it has been based on it. Although the ISO legform test method is not identical to the EEVC method there are no significant differences, therefore there would be no benefit in using the ISO test method in phase two of the EC Directive. Also, as it is less specific, written in a different style and comparatively untested, it offers no improvement over the current legform test method for phase two of the EC Directive.

IHRA are also currently developing a legform test procedure and it is essentially complete. However, the only fundamental difference between it and the EEVC WG17 method, used in the Directive, is the specification for the impactor. The IHRA specification requires a flexible tibia and femur and is effectively drawn up around a Flex-PLI type impactor. As discussed in Section 3.1 the Flex-PLI impactor development programme has not been completed and there are some questions about the knee specification. As the impactor specification is the only significant difference between the IHRA and the Directive test methods it is suggested that there is no benefit in considering it for use in the second phase of the EC Directive. If in the future the Flex-PLI or a similar impactor has been developed and shown to be suitable for regulatory use then consideration could be given to amending the Directive, GTR etc. to use it.

In reviewing the EEVC and ISO test methods one interesting point was raised in the IHRA discussions, relating to the lack of a shoe thickness allowance in both the EEVC and ISO test methods. Both the EEVC and ISO test methods require the 'foot' end of the impactor to be at ground level at impact with the car. The anthropometric data used to specify the length of the legform impactor is for people without shoes and, as most pedestrians are assumed to be wearing them, then the normal allowance of 25 mm should be added for their thickness. Therefore, the IHRA working group agreed to require the foot end of the impactor to be 25 mm above ground level, at first contact, in their test method.

3.2.2 Upper legform test method

Currently there is no alternative to the EEVC WG17 upper legform test method for the bonnet leading edge test. As discussed in Section 3.1.2 the addition of an upper body mass and a hip force transducer to the Flex-PLI legform impactor might make it suitable for testing the bonnet leading edge. If such a tool were available then the test method might simply consist of firing it horizontally into the front of the vehicle at a fixed velocity and mass. However, as this would take both time and funding for the development programme, this is not currently a viable alternative test method.

3.2.3 Headform test method

As discussed in Section 3.1.3, there are effectively three alternative headform test methods, the ISO, IHRA and Japanese MLIT methods, all three of which use 3.5 kg child and 4.5 kg adult headforms.

3.2.3.1 Test area

The ISO pedestrian safety working group (ISO TC22/SC10/WG2) believes that the information necessary to specify a narrow boundary separating the acceptable impact zones for the child or adult head impactor is not currently available. The working group has concluded that only the child head impactor should be used at wrap around distances (WAD's) of 1500 mm or less, only the adult head impactor should be used at WAD's of 2100 mm or more and that a transition zone exists within the WAD range of 1500 - 2100 mm. This transition zone is believed, by the working group, to be narrower than 600 mm in real world impacts but that there is insufficient information currently available to specify the location of the transition zone within the 1500-2100 mm WAD range. They specify that either a child or adult impactor (but not both) should be used in tests within this transition zone. The latest draft procedure for the child headform tests specifies an impact zone from 1000 mm to 2100 mm WAD (International Organisation for Standardisation, 2003a) and for the adult headform test from 1500 mm to 2100 mm WAD (International Organisation for Standardisation, 2003b). An ISO working group resolution in the draft child test procedure (International Organisation for Standardisation, 2003a) recommends that until further data are obtained or additional analyses are performed, each organisation specifying head impactor tests should use current data to determine the size and location of a transition zone within the WAD range of 1500-2100 mm.

IHRA have proposed two options for specifying the child and adult areas; the first has an overlapping child and adult zone. This option has the advantage of reproducing the accident situation where there is an area likely to be struck by both light and heavy heads. The second IHRA option is to have a sudden transition between the adult and child zones; this second method is also used by EEVC. It is used because in practice a step change in stiffness within the same vehicle structure is not feasible. Therefore to pass each side of the line with the different headform masses will result in vehicle designs having a 'safe' overlapping zone about the line. 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 Wrap Around Distance (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 wrap around distances in the EEVC method is almost in the middle of the IHRA child to adult transition zone, whereas the ISO overlap appears less appropriate, extending from 1500 to 2100 mm WAD. It can be concluded that the EEVC step change transition from child to adult is 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, for the child zone, start at a wrap around distance of 1000 mm and end at 1700 mm and for the adult zone, start at 1400 mm and end at 2400 mm (or up to the top windscreen frame for shorter vehicles). However, as noted above the IHRA working group also give the option of a sudden transition between child and adult. Unlike the EEVC method the IHRA adult test area extends beyond the base of the windscreen up to 2400 mm. This reflects the ambition of the IHRA-PS-WG to include the vehicle A-pillars, the complete windscreen and the leading edge of the roof in the test zone. However, although these areas are the cause of serious and fatal injuries in a large proportion of accidents, they were deliberately excluded from the mandate of EEVC WG10 and WG17 on the grounds of feasibility. As these feasibility issues are still pertinent it is not considered reasonable to extend the test area in phase two of the Directive to include these parts. However, the IHRA test methods for these areas will be of use in developing new solutions, such as A-pillar airbags, which might eventually overcome the feasibility issues.

3.2.3.2 Head mass

The discussion on effective mass, in Section 3.1.3, supports the masses selected by EEVC of 2.5 kg and 4.8 kg respectively to represent 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 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. With hindsight it might have been better if EEVC had chosen a heavier mass to represent the average effective head mass from the range of ages and statures striking the whole child area. In the 15th meeting of the EEVC WG17 the use of a 3.5 kg headform instead of the 2.5 kg headform was discussed. Based on similar arguments to those described above, EEVC WG17 agreed that they had no objections to adopting a 3.5 kg mass for testing the child area (this position has not been presented to the EEVC SC for their approval).

As noted earlier, the slightly heavier EEVC adult mass is supported by kinematics (body mass acting through neck) and PMHS reconstructions, however, the possible use of the alternative 4.5 kg mass is discussed in Section 10 under feasibility issues.

3.2.3.3 Impact velocity

The child (International Organisation for Standardisation, 2003a, Annex C) and adult (International Organisation for Standardisation, 2003b, Annex B) draft ISO headform test procedures contain information on the relationship between the vehicle velocity and the head impact velocity. The head impact velocity is described as being related to the vehicle velocity by the relationship shown in Equation 3.1.

$$v_{HF} = kv \qquad \text{Equation 3.1}$$

where:

v_{HF} = the head impact velocity

k = a constant

v = the vehicle velocity

From MADYMO modelling and cadaver data (three sources), the value of ‘k’ for a child is quoted as being between 0.72 and 0.78.

From Annex B in the draft ISO adult headform test document, it is stated that ‘k’ has been determined as being between 0.7 and 1.4 but to facilitate uniformity, a value of one was recommended. Since the 2004 feasibility study (which is being up-dated here) ISO have published their finalised adult head test procedure (International Organisation for Standardisation, 2006) but not their child procedure. Their latest adult test procedure 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*., 1993) commented that elbow contact reduced head impact velocities (i.e. gave a lower k value) in a number of cases.

The IHRA working group are also using mathematical simulation results to determine child and adult head impact conditions, with the aim of providing a more complex head velocity / vehicle shape / stature or wrap around distance on the car. The provisional IHRA head test velocities are from three different simulation models all simulating the same range of vehicle shapes and 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 average and the ± one standard deviation values were calculated. The IHRA provisional head impact test conditions can be seen below, in Tables 3.3 and 3.4, for a vehicle impact speed of 40 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), see in Tables 3.3 and 3.4. It is thought that much of this variation was due to the differences between the computer models used by IHRA, which utilise simplified car and pedestrian models. 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. 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 biofidelic shoulder for the IHRA computer pedestrian model (Neale *et al.*, 2005). Having, evaluated the biofidelity of improved shoulder, he made further improvements to the model 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 more biofidelic shoulder increased the head impact speed between 1.2 to 5.1 km/h. Neal also made other changes to improve the vehicle model to provide a giving it ‘safe’ stiffness characteristics. 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.

The IHRA working group (IHRA Pedestrian Safety Working Group, 2005) stated that computer simulations for a child indicated that the head impact speed equals to 80% of the car impact speed. On the other hand, a PMHS test for adult indicated that such ratio for the head impact speed against car impact speed varies widely between 80% and 150%. The values for the head impact speed related to the vehicle impact speed in simulations of a head collision with the bonnet or the windshield 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 test and simulation result data 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 believed the information is best available information at the present time. It should be noted that the child velocity in the IHRA paper was a model of a six year old. Based on this 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). As a result, an average ratio value of 0.8 was selected by the Japanese and when applied to a car velocity of 40 km/h gives the 32 km/h found in their headform to bonnet top regulation. The ratio of head impact velocity to car velocity is often referred to as the ‘k’ value.

Table 3.3: IHRA Child head impact conditions – average and ± 1 standard deviation – 40 km/h car impact speed

Shape corridor	Impact velocity (km/h)			Impact angle (°)		
	Bonnet	Windshield	BLE/Grille	Bonnet	Windshield	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 3.4: IHRA Adult head impact conditions – average and ± 1 standard deviation – 40 km/h car impact speed

Shape corridor	Impact velocity (km/h)			Impact angle (°)		
	Bonnet	Windshield	BLE/Grille	Bonnet	Windshield	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

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), before selecting a 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 against three vehicles 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 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). WG17 concluded that it was not feasible to have a test method for the child where the velocity varied depending on the shape of the vehicle and stature or wrap around distance on the car. They concluded that the head impact velocity of a child is likely to be very sensitive to the relationship between the height of the bonnet leading edge (BLE) and the height of the head. When the heights are similar then the head impact velocity is likely to be close to that of the car, when the BLE is level with the shoulder or high on the chest, head velocities are likely to be low and for taller children the velocity will again be higher. Therefore WG17 (European Enhanced Vehicle-safety Committee, 2002a) confirmed the decision made by WG10 to use a velocity of 40 km/h for the child, giving a 'k' value of 1.0.

EEVC WG17 also reviewed adult head impact velocity data, which indicated that the velocity could be as high as 1.45 times the car impact velocity (European Enhanced Vehicle-safety Committee, 2002a). However, they confirmed the WG10 decision to use a compromise value of 40 km/h. The following considerations were the main reasons for reaching this decision:

- The bonnet lengths (up to and including the base of the windscreen) of most European cars are too short to be hit by the heads of taller pedestrians. As the ratio of head velocity to car impact velocity (k) is closer to 1 for shorter adult pedestrians then a velocity of 40 km/h is appropriate.
- Depending on the bonnet length and pedestrian stature, higher impacts velocities (k values of more than 1) are likely at the rear of the bonnet / base of the windscreen. However, the crush depth needed to protect increases with the square of the velocity. The theoretical crush depth needed to achieve a HPC 1000 value in a normal impact at 40 km/h can be calculated to be about 68 mm but this increases to 167 mm at 56 km/h (1.4 x 40 km/h). It was concluded that although a k value of 1.4 would be appropriate for those few cars with longer bonnets it would not be feasible to provide the necessary crush depth in this area.
- The central unsupported area of the windscreen is normally safe for the head of a pedestrian in impacts up to 40 km/h, so this does not need testing.
- Testing the A-pillars and windscreen upper frame had been deliberately excluded from their mandate due to feasibility issues.

More recently, 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. To avoid unacceptable inappropriate activation, these methods need a reliable pre-impact pedestrian sensing and triggering system, which is currently thought to need many years of development before it may be available for use. Therefore, it is thought that it is not appropriate to have, at this time, a regulatory test for this area (see comments on test methods for this area in Section 3.2.3.1).

It can be seen that there is a wide variation in head 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 (for the shoulder see Neale *et al.*, 2003 and Neale *et al.*, 2005).

It might be thought reasonable to use the mean values for the test velocity and this approach has been used in the Japanese head test method. However, an average 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 average head velocity to 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 an average velocity of 32 km/h.

3.2.3.4 Head impact angle

The ISO child and adult head test procedures specify an 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 these graphs it has been found that the ISO simulations for the child at 40 km/h vary between 68 to 42 degrees and for the adult between 62 and 58 degrees. Since the 2004 feasibility study (which is being up-dated here) ISO have published their finalised adult head test procedure (International Organisation for Standardisation, 2006) but not their child procedure. Their latest adult test procedure recommends an average test angle of 65.4 degrees; however, as justification they provide a range of computer simulation results from two comparatively old studies (1988 and 1993). The combined data gives 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; however, a more detailed examination of the outputs might give reason to exclude some of the more extreme results as being due to atypical kinematics.

The provisional IHRA head impact angles are also given in Tables 3.3 and 3.4. For the 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 plus and 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 yet lies outside of the ISO range 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. These results peaked at 60 degrees and the bulk of them fell within a 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 percent adult female and a 6-year-old child (Janssen and Nieboer, 1990). A 5th percentile adult female is often taken to be equivalent 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.

The range of results in the ISO, IHRA and EEVC impact angle data described above is most probably representative of real life 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. It can be concluded that 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. Given sufficient data on head impact angle 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. The angle of the surface of car bonnets is not fixed and is a function of size, type and styling, however, from a small survey it is thought that 15 degrees is a typical angle for conventionally shaped car type vehicles. Therefore, if one fixed angle is selected, assuming that 15 degrees is a typical bonnet angle, then all of the population would be protected if 75 degrees was used for both tests. Indeed as this angle is higher than the current data suggests, then the net effect would probably result in an average protection level effective at speeds somewhat in excess of 40 km/h covering a slightly larger target group than intended. However, given the provisional nature of the IHRA angle data and the difficulties in providing head protection, it would appear unreasonable to increase the test severity by making the impact more normal than the test requirement currently in the second phase of the EC Directive.

3.2.4 Hybrid-test

Kuehn *et al.* (2003) discuss the relative merits and flaws with different methods of testing the protection for pedestrians afforded by cars. They state that at present, due to the lack of proper test devices, full-scale tests are not able to reproduce the pedestrian kinematics in real accidents and the reproducibility of pedestrian-car crashes is not guaranteed, and they mention the Polar II dummy as a potential test tool for the future. The discussion of component tests introduces the concept that the test may not always be representative of a pedestrian accident event and requires knowledge about accident events to interpret the results in the right way. This leads Kuehn *et al.* to the concept of a hybrid-test procedure, linking accident analysis, numerical simulation and component testing.

The proposed hybrid-test would use numerical simulation to modify the EEVC test procedures for each car tested. Vehicle specific test parameters, such as head impact velocity and impact angle for the adult and child headforms would be deduced from simulations.

This advanced procedure requires improved pedestrian models; Kuehn *et al.* mention the shoulder of the models as being too stiff and the scaled child model also needing improvement in particular.

A second option is to use a combination of pedestrian dummy and subsystem tests. For example two dummy statures could be used to test the vehicle front end (bumper, grill and bonnet leading edge) and child and adult headform sub-system tests used to test the bonnet top area. If the two dummy sizes selected match the child and adult statures most at risk of injury from the front end, then protection for in-between statures could be assumed. The need for a large family of dummy statures to test the head protection for the whole bonnet top could be avoided by a separate head sub-system test using child and adult headforms.

However, although both of the above hybrid testing ideas are interesting approaches, they clearly need further development before they can be considered as viable alternative methods for use in phase two of the EC Directive.

3.3 Proposed refinements to the EEVC test methods and criteria

Alternative test methods and the data which were used in their development are one potential source which can be used to refine the EEVC test methods used in the second phase of the EC Directive, as discussed in Sections 3.1 and 3.2. The conclusions from this are included in the sections below. A second source is research proposals criticising or suggesting improvements to the EEVC test tools, methods and criteria and these are also discussed below.

One effect of requiring pedestrian protection by legislation is that in practice car manufacturers have to achieve a higher level of protection than the minimum requirements to ensure the vehicles obtain regulatory approval. Following approval, when the vehicle is in mass production, they are required to ensure that the 'worst' combination of manufacturing and test variations would not result in a vehicle that would not achieve the performance requirements. The net effect of this is that manufacturers typically aim to be inside the protection requirements by about 20 or 25 percent. In addition, they will have to allow some extra crush depth in case the vehicle is slightly softer than intended. These manufacturer's additional tolerances are likely to mean that typically most vehicles will protect a greater portion of the population at the intended impact speed and be safe for most pedestrians at slightly higher speeds than the intended impact speed. Obviously this is not normally a problem, as it results in additional savings; however, if it is very difficult to provide the minimum protection required, then having to provide these extra margins might make a regulation less feasible. Feasibility issues are discussed further in this report in Section 10.

As noted in Section 3.2, other test procedures have a tolerance for the minimum accuracy of the equipment used to measure the velocity of all the pedestrian sub-system impactors. The use of inaccurate speed measuring equipment would have adverse implications for feasibility because, to ensure approval, manufacturers would have to assume that a vehicle could be subjected to approval tests at a higher velocity than that specified. Therefore it is recommended that for all test procedures, in phase two of the EC Directive, a tolerance should be introduced on the accuracy with which impact speed is measured. Consideration should be given to introducing the Euro NCAP tolerance of ±0.02 m/s or the tighter GTR tolerance of ±0.01 m/s, if it is thought to be feasible.

3.3.1 Legform test

3.3.1.1 Legform tool

Although, as concluded in Section 3.1.1, the Flex-PLI is unlikely to be finalised and fully assessed until after the requirements of phase two of the EC Directive are finalised, some aspects of the design might be applied to the EEVC legform. Adoption of a flexible tibia would improve the EEVC impactor; however, it is not clear if the added complexity would be worth any improvement in biofidelity. Much of the differences between the Flex-PLI and the EEVC impactor are attributed to the flexible bones of the Flex-PLI, but the authors consider this to be mainly due to the higher lateral bending moment of the EEVC knee. It would also be possible to modify the lateral bending moment of the EEVC knee to match the bending moment of PMHS knees although it is thought that the EEVC bending moment is more appropriate for live humans with muscle tension. Therefore, no changes to the EEVC test tool are recommended for phase two of the EC Directive.

Analysis of the use of tibia acceleration as an index of lower leg fracture was carried out by Konosu *et al.* (2001). They stated that the relationship between tibia acceleration in legform tests and fracture was obtained from a PMHS test series in which the impact condition was a normal bumper height and the acceleration was measured at the upper part of the tibia. However, when the impact point was changed, tibia fracture could occur even with small tibia accelerations measured at the current EEVC position (just below the knee). Konosu *et al.* went on to suggest that when the tibia acceleration is used for the leg injury criterion, the measurement point of tibia acceleration should be changed to a proper position for each test.

As already noted in Section 3.1.1.2, EEVC WG17 has recommended that the need for a second accelerometer at ankle level should be a topic for consideration / research. The use of two accelerometers rather than a movable one will be more practical and will avoid the need to know the 'proper position for each test' (the position of the underlying hardest area of each bumper under test). Although it would be comparatively simple to amend the EEVC legform impactor design to include a second accelerometer the test method would need to include suitable pass / fail limits for each or a method of combining the two outputs.

Although it might be beneficial to have two tibia accelerometers, this is not recommended for phase two of the EC Directive, as more research is needed.

3.3.1.2 Legform 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 repeatable in order to achieve constant standards. In order to achieve consistent test tools, EEVC specify both the physical and dynamic requirements. Both the legform impactor and its dynamic certification method were developed in a series of stages. The final stage of development of the current dynamic certification method was to review the results of a large number of dynamic certification tests, to 35 different legform impactors that were made to the current WG17 specification. It was found that the dynamic certification acceleration and, to a lesser extent, knee shear displacement were more variable than is ideal. The legform components are manufactured to small tolerances, so these 35 impactors are likely to have very consistent physical properties of mass, centre of gravity and moment of inertia. Also, the stiffness of the bending ligaments and shear spring are controlled by their static certification procedures. Therefore, it had been assumed that most of the differences seen in the dynamic certification results for these 35 legforms were primarily due to variation in the performance of the Confor™ foam flesh during the bottoming-out phase and the sensitivity of the certification method to this. To test this assumption, dynamic certification test results with the same impactor with different bending ligaments and flesh fitted were examined and the results support this theory (Lawrence and Hardy, 2002).

Following on from this an alternative certification test was developed with compliance built into the impact partner to more closely reproduce the loading conditions of a pedestrian-friendly bumper system. An impact partner that represents a bumper with a capacity to deform repeatably was required to achieve this. The most obvious method of achieving this would be to use deformable materials on the impact partner such as foam or aluminium honeycomb. However, it is difficult to control accurately the stiffness of such materials, particularly ones that do not recover, without using an additional test procedure. Consequently, it was decided to explore the potential of using a steel leaf spring to represent a bumper, because the elastic modulus of steel is thought to be more consistent than the stiffness of plastically deforming materials. A steel spring will also recover completely after use, provided that the elastic limit is not exceeded, so that it can be used repeatedly. The leaf spring certification arrangement is shown in Figure 3.4.

A programme of tests were carried out with this method (Lawrence *et al.*, 2004b) and the results show that the new method appears to give smaller variation in tibia acceleration, but there are still large variations in the knee shear and the variability in knee bending angle has increased. The risk of damage through the legform striking the associated equipment on rebound is also far higher in this new test. Therefore, although the new test appears to be less sensitive to variation in the performance of the Confor™ foam during the bottoming-out phase, it does not appear to be a significant improvement over the current method.

Matsui and Takabayashi examined the effects of a number of factors to try to find the main cause of variation in the dynamic legform certification results (Matsui and Takabayashi, 2004). Of these, only relative humidity was found to have a significant effect on the certification performance. It was hypothesised that changes in humidity were affecting the performance of the Confor™ foam material used to represent flesh on the legform impactor. A drop weight test for the foam within a humidity controlled chamber was devised so that the effects of humidity could be examined in isolation. These results showed a clear relationship between humidity and acceleration, in both the full legform certification test and the separate drop weight tests of the foam, with the peak acceleration increasing with increasing humidity. Changes in the mass of Confor™ specimens were recorded against time whilst they were exposed to three different relative humidity atmospheres. These showed that the foam gained weight by absorbing water and that at a humidity of less than 60 percent their weight gain of about 0.5 percent had stabilised within 50 minutes of soaking. Matsui and Takabayashi found the legform tibia acceleration to be strongly affected by humidity in the certification tests. In the drop test on the foam the drop weight accelerations increased drastically with higher humidity. He concluded that adjustment of the humidity within the test apparatus is thus one way to obtain compliance of the lower leg acceleration within the proposed EC Directive corridor.

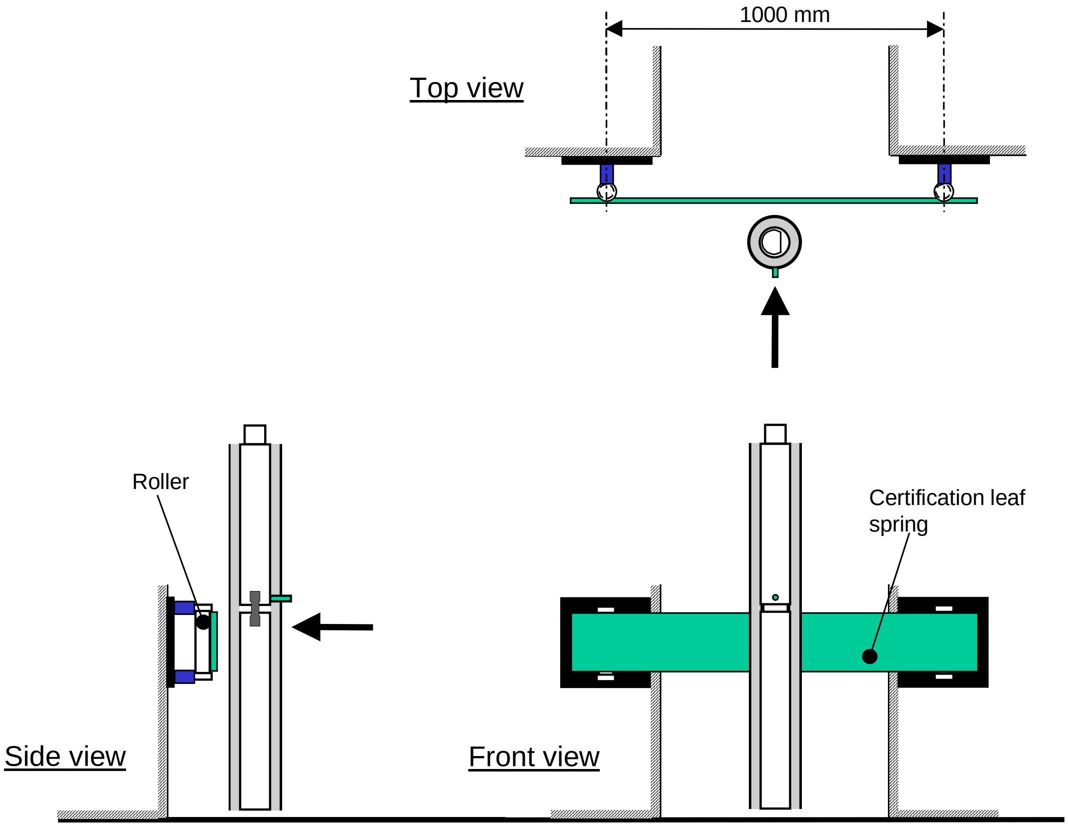


Figure 3.4. TRL alternative legform certification method

The authors have since consulted with the Senior Materials Chemist for Confor™ foam (Mr Renninger) at the manufacturers E-A-R Speciality Composites. He confirmed that the properties of Confor™ were sensitive to humidity even though only small amounts of water are absorbed. Within the microscopic structure the water acts as a plasticiser or lubricant. Confor™ foam becomes softer as the humidity increases (while this would reduce the early acceleration in an impact test, it would make the bottoming-out phase more severe, with higher peak acceleration). It would not be possible to make Confor™ foam less sensitive to humidity without affecting its desirable properties for this application. It is less sensitive to changes in humidity in the range 25 to 60 percent relative humidity, though this would relate to general properties rather than those specific to this application.

As can be seen from Matsui and Takabayashi's data in Figures 3.5 and 3.6, the humidity range 18 to 46 percent appears to give results within the corridor in the legform certification tests and this is supported by the drop weight test results. These results were presumably obtained with just one sheet of Confor™ foam, which may not be typical. Limited data obtained from records of TRL's impactor sales certification tests suggest that the upper limit of humidity for passing the certification test is higher, with several successful tests with relative humidity in the range 60 to 70 percent.

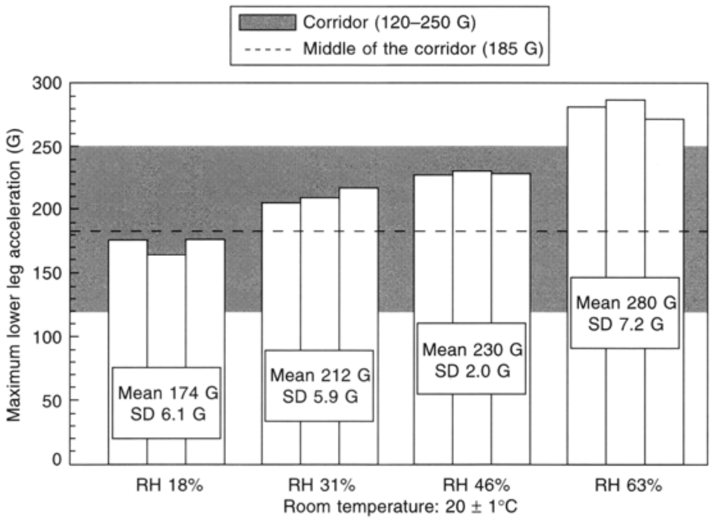


Figure 3.5. Maximum (WG17) lower leg acceleration from dynamic certification tests results at different relative humidity levels (Matsui and Takabayashi, 2004)

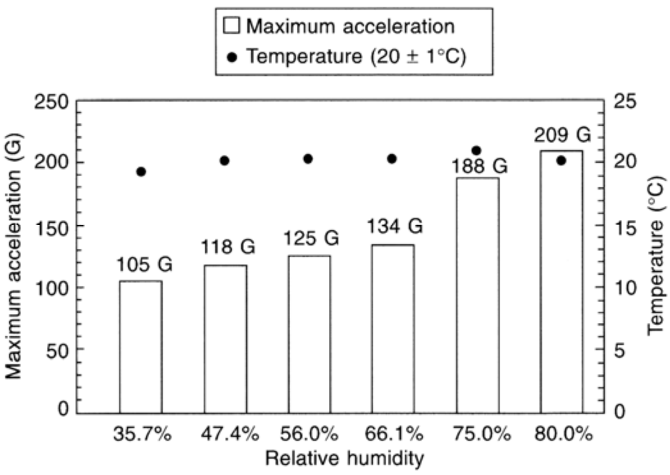


Figure 3.6. Maximum acceleration in drop tests of Confor foam specimens at various relative humidity levels (Matsui and Takabayashi, 2004)

It appears reasonable to introduce, into the EC Directive, humidity tolerances for both legform certification tests and vehicle tests. As controlling the humidity in a test laboratory would be difficult and expensive to provide, some care needs to be used in selecting a tolerance. Depending on the width of the humidity tolerance it might be possible to test in Europe without humidity control by selecting suitable days for testing, though in some countries humidity control systems would be necessary in hot and wet seasons. However, the limited data shown in Figure 3.7 suggest that a humidity-controlled environment is likely to be necessary. For tests of vehicles with a pedestrian-friendly, compliant bumper, variations in the performance of the Confor™ flesh is not thought to be critical as any differences in the energy absorbed by the foam will be small compared with the energy that the vehicle has to absorb. However, in the current certification test, the results are likely to be more sensitive to variations in the Confor™ foam flesh. Therefore it is suggested that a tolerance of 35 ±15% of relative humidity for vehicle tests and 35 ±10% for certification tests be introduced in the second phase of the EC Directive. Introducing these tolerances will contribute to improving feasibility by reducing impactor variability. It is recommended that the effect of this tolerance on the legform dynamic certification performance should be determined by a suitable study so that the pass / fail corridors can be adjusted to take account of any reduction in variability and / or change in mean values resulting from controlling humidity.

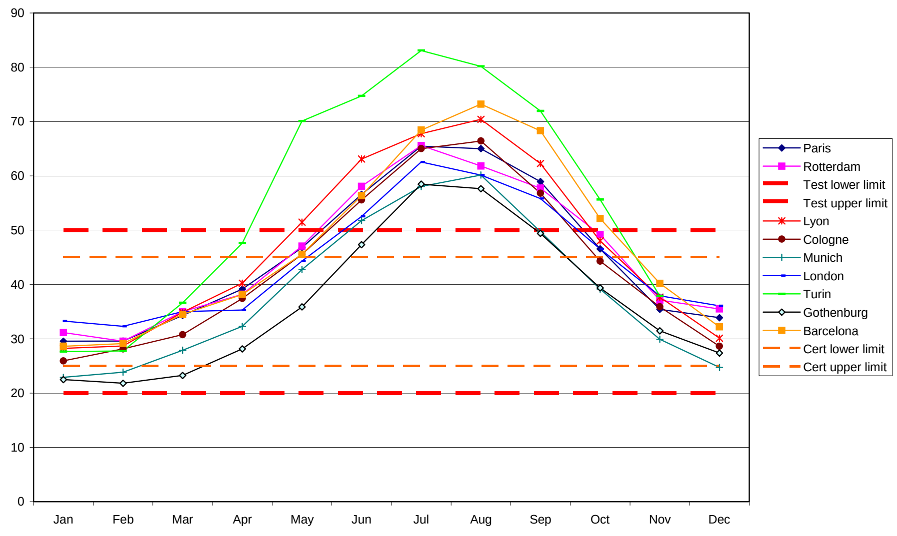


Figure 3.7. Average relative humidity for selected European cities adjusted to 20°C, assuming that the absolute humidity remains the same inside as outside (data obtained from a number of internet source)

Since the 2004 feasibility study (which is being up-dated here) Lawrence *et al.* (2005) have carried out a study of the effects of humidity on legform impactor certification results. The main objective of this new study was to investigate further the effects of humidity on the legform impactor certification results.

The conclusions of this study are summarised below:

- The sensitivity to relative humidity that was first reported by Matsui and Takabayashi was confirmed. The greatest sensitivity was in tibia acceleration; however, the results show a much lower rate of acceleration change against relative humidity than Matsui and Takabayashi.
- The tolerances previously proposed for relative humidity (35 ±10 percent in certification tests and 35 ±15 percent in vehicle tests) are supported by this study, although it would be preferable to have more data.
- The relationship of relative humidity to tibia acceleration is the end cause of two relationships; firstly the relationship between relative humidity and Confor foam stiffness, and secondly the relationship between Confor foam stiffness and tibia acceleration. Both relationships are probably non-linear. Confor foam stiffness to tibia acceleration is normally inverse (lower stiffness gives a higher peak acceleration) and non-linear due to 'bottoming out'.
- Differences in the tibia acceleration's sensitivity to relative humidity may be caused by different characteristics of Confor foam used by TRL and by Matsui and Takabayashi (such as a different stiffness at a given relative humidity) or a slightly different thickness of foam.
- Because of considerations of the cost and technical difficulty of controlling relative humidity in a large test laboratory, the use of a separate humidity controlled cabinet to condition the legform should be considered. The use of a humidity-tight transfer box could also be permitted.
- It would be useful to study the issue of soak times further, so that recommendations on the time required to condition the legform could be made with greater confidence.

3.3.1.3 Legform test method

As already noted, both the second phase of the EC Directive (EEVC WG17) and ISO test methods are essentially the same and require the 'foot' end of the impactor to be at ground level at impact with the car. However, the IHRA working group have agreed to add a 25 mm shoe allowance. It is thought that the lack of a shoe allowance was an oversight by EEVC WG17. Therefore it is recommended that in the second phase of the EC Directive the height of the lower end of the legform impactor, at first contact with the vehicle, be 25 mm above the ground reference level.

Variations in legform test results have been found which are linked to the height and orientation of the impactor. It is suggested that both the tolerance for the height of the foot of the legform and for the legform to be vertical at the time of first impact be reduced. These two tolerances are currently ±10 mm and ±2 degrees in the EC Directive. To improve repeatability, ideally the tolerances of all sensitive impact parameters should be minimised; however, they must not be made so small as to be impossible to measure and achieve. Therefore, it would be preferable to conduct a study to determine the accuracy with which that impactor height and angle can be measured and the accuracy that it is possible to achieve in practice with a 'good' propulsion system. Nevertheless, it is reasonable to consider reducing these tolerances:

- Impact height can be measured in a number of ways; one of the most practical methods is thought to be by measuring the height of a spot of wet paint, which has been transferred from the impactor to the bumper face during the test. This method is probably accurate to about ±2 mm, although paint smear may make interpretation difficult in some cases. The maximum accuracy of legform delivery is thought to be within a similar range (about ±2 mm). Overall tolerance of about ±5 mm is considered to be achievable.
- The tolerance on angular errors in legform verticality applies to errors in any direction, but it has been suggested that the test results are likely to be most sensitive to errors in the longitudinal plane. This error can be measured in a number of ways. Currently high speed video is often used to compare the legform angle with a vertical reference. This method is thought to be accurate to about ±0.25 degrees, so this method is likely to be sufficiently accurate to use with a smaller tolerance. Other measuring methods could be devised, such as recording the difference in time between the legform breaking a light beam at its top and bottom, this combined with the velocity of the legform could be used to calculate angle more accurately. It is thought that the maximum accuracy of legform delivery is within about ±0.25 degrees, although the drag of instrumentation cables may introduce some additional variability in legform angle (it is probably feasible to use in-legform recording systems). Overall, a tolerance of about ±1 degree is considered to be achievable.

As discussed above in Section 3.3.1.2, a tolerance of 35 ±15% of relative humidity for vehicle tests with the legform impactor could be considered in the second phase of the EC Directive.

3.3.1.4 Legform criteria

Konosu *et al.* (2001) applied a logistic analysis method to data from PMHS tests conducted by Kajzer *et al.* (1997 and 1999). The resulting injury risk curves for bending angle and shearing displacement of the knee gave a 50 percent injury risk at 24.2 mm and 19.8°. Konosu *et al.* provided a similar logistic analysis of the results from quasi-static tests to PMHS legs conducted by Ramet *et al.*, (1995). They then went on to suggest performance criteria based on a 50 percent risk of injury. However, as knee injuries are likely to result in long-term disability, the criteria chosen for phase two of the EC Directive are set at a 20 percent injury risk. The values pertaining to a 20 percent injury risk can be read from the injury risk curves provided by Konosu *et al.* and are 18 mm of shear displacement and 14.7 degrees of knee bending angle for the Kajzer *et al.* data and 16.4 mm and 16 degrees for the Ramet *et al.* data. However, Konosu *et al.* point out that although overall bending and shear displacements measured in such experiments will be predominantly due to deflection of the knee joint, the effect of the bones bending during impact will also contribute and is used to support the argument of Konosu *et al.* that a flexible legform impactor is needed. This conclusion resulted in the decision to develop the Flex-PLI legform impactor described in Section 3.1.1.

Further to the analysis by Konosu *et al.* (2001) on the tibia acceleration, they produced an injury risk curve for lower leg fracture. The PMHS data was taken from a test series conducted by Bunketorp *et al.* (1983). This was the same data used by EEVC to select their 20 percent injury risk value of 150 g and although a different method of analysis was used by Konosu *et al.*, this method gives an almost identical result of 152 g (scaled from the graph). Konosu *et al.* also suggest that cases where only fibula fracture occurred should be removed from the analysis. With these (two cases out of twenty) removed, the 20 percent risk increases to 188 g; however, it is thought that the large change seen in the acceleration at 20 percent risk might be partially due to the statistical method used by Konosu *et al.*, which forces the curve to pass through zero. Again, Konosu *et al.* suggest a 50 percent injury risk be used as the performance criteria because tibia fractures are not normally a life threatening or disabling injury. Accident statistics show that leg injuries occur in high numbers, for example Mizuno and Ishikawa (2001) report that leg injuries are 30 percent of the AIS 2-6 injuries in the IHRA global pedestrian accident dataset. Therefore setting a high risk level would reduce the potential injury savings significantly.

From computer simulations using a finite element model of the human lower limb, Takahashi and Kikuchi (2001) 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. The acceptance limits were found to be 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.

The suggestion by Takahashi and Kikuchi to combine the shearing displacement and bending angle is interesting. Intuitively the concept of a biomechanical relationship between bending and shearing injury modes is believable and unremarkable. The simplest means of combining the two parameters would be to consider the peak values for each. However, these may not occur at the same time and would therefore give a false representation of the extension of the knee ligaments. Instead, bending angle would need to be plotted against shearing displacement and compared against a threshold curve.

To determine injury-related factors, data obtained in impact tests using PMHS were statistically tested by Matsui (2001). Knee lateral force, knee bending moment, knee shear displacement and knee bending angle were analysed as parameters that could correlate with the occurrence of ligament injury. Additionally, to understand the biofidelity of legform impactors with respect to the PMHS performance, impact tests using the EEVC legform were conducted. In tests set up to induce shearing in the PMHS, tibia acceleration was found to significantly correlate with tibia fracture. However, the acceleration was not used for the estimation of fracture tolerance due to the means of its estimation, from film analysis. Matsui suggested that shearing displacement can be treated as a significant factor to determine the risk of ligament damage but the bending angle and bending moment cannot be used when estimating the risk of ligament damage. For the shearing set-up, he found that the EEVC legform did not exhibit good biofidelity when compared with the responses of the PMHS. Only in the bending tests conducted at 20 km/h did the EEVC legform fit with the responses of the PMHS. To obtain a scaled risk curve of impact force for the EEVC 2000 legform impactor (i.e. WG17 version with shear damping) from the tolerance of PMHS, Matsui applied a transfer coefficient of 1.38. With this scaling, using the EEVC legform, a 6.9 kN impact force produces a fracture with a probability of 50 percent. For the shearing displacement, the transfer coefficient was 0.314. This produced the value of 7.9 mm of shearing displacement as assessed by the EEVC legform, causing ligament injury with the probability of 50 percent. It should be noted that the current phase two EC Directive performance criteria were chosen with the intention of achieving an injury risk of about 20 percent; the criteria proposed by Matsui are for a 50 percent injury risk.

As discussed in Section 3.1.1.1, none of the above studies include the effects of muscle tension on knee joint lateral bending moment. However, the following comments can be made regarding the above studies:

- The legform impactor gives a different result to PMHS tests; this is not surprising since the knee bending moment as discussed in Section 3.1.1.1 is far higher in the EEVC impactor than found in most PMHS tests (EEVC WG 10 included this to account for muscle tension in live humans based on tests to the knees of volunteers (European Experimental Vehicles Committee, 1994)).
- That, as with many test tools, a transfer function can be used to take account of the necessary differences between the test tool and real life.

One alternative to obtaining biomechanical data from PMHS tests to set both impactor characteristics and performance criteria is the reconstruction of real pedestrian accidents. By reconstructing well-documented accidents with the test tool, injury risk curves for living humans can be derived. This method also has the advantage that it includes the transfer function for any differences between the test tool and humans. Where injuries are caused by metal parts of the car (such as the bonnet top or bonnet leading edge) the severity of the impact can be matched in the reconstruction by reproducing the dents found in the accident. In this case the accident investigator's estimate of the impact speed is used as a starting point, but it may be adjusted slightly up or down until the damage is matched. However, for reconstructions of bumper contacts this matching is often not possible because no permanent dents are left in the vehicle. In this case random errors in estimating accident impact velocity will reduce the confidence in the risk curves but not distort them. Any systematic biases in the estimates of accident impact speed will also produce a bias in the risk curves derived from the reconstructions.

Matsui (2003) reconstructed fifteen accident cases selected from the JARI and the Institute for Traffic Accident Research and Data Analysis of Japan (ITARDA) pedestrian accident databases using the EEVC WG17 legform impactor. The data from these reconstructions were then used to define injury risk curves for the EEVC legform. For the reconstructed legform tests, it was not possible to confirm if the legform test velocity/severity matched the real accident velocity by matching the accident damage to the car. Therefore, as noted above, any systematic errors in estimating the accident impact speed would cause errors in the reconstructions and injury risk curves derived from them.

Matsui originally intended to apply transfer coefficients to the data from these accident reconstructions to generate the scaled tolerance curve for collateral ligament injury. The need for this was based on the previous results (Matsui 2001), which indicated that comparison of the magnitudes of bending angle time histories of PMHS and the legform impactor could be misleading. However, when the tangents of the bending angle time histories were used to generate the scaling factor, they were found to be in the range 1 to 1.07. For the range of bending angles corresponding to injury risks of 0.2 to 0.5, the factor was found to be 1. As this was the region of interest for Matsui, no scaling was necessary for the collateral ligament injury risk curve derived from the accident reconstructions.

The no injury cases are as important as the injury cases in a logistic injury risk analysis. Therefore Matsui grouped the fifteen cases that he reconstructed into groups with and without knee injury and groups with and without tibia fracture. This gave him four cases with and four cases without collateral ligament injury to derive his knee bending angle / knee ligament injury risk curve and seven cases with tibia fracture and eight cases without, to derive his tibia acceleration / tibia fracture injury risk curve. As the data available seemed to be rather limited, Matsui suggested that to increase the reliability of the results, further accident reconstruction tests should be performed not only to simulate accidents reported in Japanese databases but also those investigated in other countries.

The cases selected to generate the injury risk curve for collateral ligament injury were accident cases where tibia fracture did not occur. This is important as fracture of the tibia can reduce the severity of the impact at the knee. However, it may also introduce a sample bias towards pedestrians with strong tibias or vehicles with pedestrian friendly bumper designs. As logistic regression is sensitive to sampling strategies, this would affect the injury risk curve although the extent of the effect is not known. It should also be noted that the legform bending angle in three of the four collateral ligament injury cases reached the mechanical limitation (around 30°) of the legform impactor, the effect of this would be to slightly overestimate the risk of injury at the 20 percent level with the error increasing with higher risks.

The Logistic regression injury risk curves that Matsui derived for the collateral ligament (bending angle) and tibia fracture (lower leg acceleration) for the legform impactor are shown in Figure 3.8 below. Matsui gave the 20 percent injury risk levels from these curves as 19.2° for the bending angle and 153 g for the tibia acceleration. The corresponding 50 percent injury risk values were 26.5° and 203 g respectively. The implication of these values is, for example, that the probability of a living human pedestrian receiving a collateral ligament injury is 0.2 when the EEVC legform gives a bending angle of 19.2° in a test.

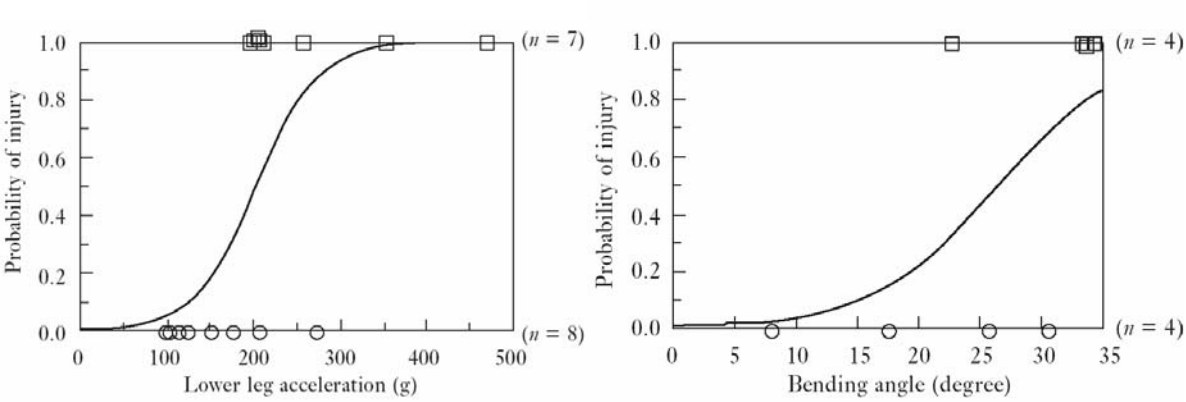


Figure 3.8. Tibia fracture and collateral ligament injury risk curves expressed by acceleration and bending angle using the EEVC legform impactor (Matsui, 2003)

As already noted, the data used to derive these curves was rather limited and any systematic bias in the reported accident speed will also have biased the risk curves. Nevertheless, it is thought important to have values that take into account the differences between live and PM humans and also to have a transfer function for the differences between the test device and a human. Therefore, overall, these reconstructions are thought to represent the best current data. As a result, it is likely that the 20 percent injury risk value of about 19 degrees is a more appropriate value (than the current 15 degrees) for use in the second phase of the EC Directive. However, given the limitations of this data it might be more prudent to select a slightly lower value or alternatively use 19 degrees as the limit and rely on the margin of safety added by manufacturers to reduce this to about 14 or 15 degrees in practice. As with the other data on tibia fracture risk, these accident reconstructions confirm the current 150 g acceleration performance criteria for the second phase. However, if account is taken of the margin of safety added by manufacturers, then the 170 g proposed in the GTR will in practice provide the protection originally intended.

3.3.2 High bumper test

The Japanese Automobile Manufacturers Association (JAMA) have expressed concern that for vehicles whose bumper position is higher than the legform impactor's overall centre of gravity, the impactor often slides under the vehicle. This is unrealistic and might result in the approval of designs that could aggravate injuries to pedestrians and other vulnerable road users if the vehicle structure is modified to comply with phase two of the EC Directive. They suggest that this "sliding" behaviour is interpreted as a better leg protection performance according to the phase two standard. In the real world it will probably not help to reduce injuries. Consequently, JAMA believes it necessary to modify the WG17 test procedure and standard values so as to select measures more appropriate for the reduction of pedestrians' leg injuries.

This matter was considered by EEVC WG17 in selecting the height of the lower bumper reference line at which the switch to the high bumper occurs. They used a study by EEVC WG10 that had shown that an upper body mass was not necessary for vehicles where the bumper impact occurred at or below the knee joint. The legform impactor emulates a 50th 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. EEVC WG17 considered these heights along with the results of the WG10 study and decided to select a lower bumper reference line at a height of 500 mm as being the appropriate point at which to switch the test to an upper legform to bumper test (European Enhanced Vehicle-safety Committee, 2002a). For cars, bumper standards such as Part 581 set out that the centre of the bumper test face used to impact the bumper is required to be at any height between 16 and 20 inches (406 to 508 mm). For cars, the bumper top edge is designed at a fairly consistent height of about 500 ±50 mm, with the depth of a typical bumper being about 100 to 200 mm. The practical effect of this is that the centreline of car bumpers will be at or below the impactor knee height and therefore no upper body mass is needed. For vehicles with high bumpers it may be argued that the switch might have been better made at a slightly lower height than the 500 mm chosen by WG17, to be sure that the lack of an upper body mass did not affect the results. However, as discussed in Section 3.3.1.3 it is recommended that at first contact, the height of the 'foot' end of the impactor above the ground reference level be increased from zero to 25 mm to allow for the typical thickness of a shoe. This will mean that the height of the knee of the impactor relative to the ground will be 519 mm (494 + 25 mm) and the height of the overall centre of gravity of the impactor will be 578 mm (553 + 25 mm). Therefore, the current switch point of 500 mm becomes more appropriate.

Currently, both the first and the second phases of the EC Directive allow the manufacturers of vehicles with 'high bumpers' to select whether the bumper is to be tested with the upper legform impactor or the legform impactor. The absence of an upper body mass on the legform impactor means that for high bumpers, the kinematics of the legform will not be the same as for a live human. Despite this the choice of test was allowed by WG17 because it was thought that measures introduced to meet the legform requirements would still be effective in reducing the injury risk of high bumpers in real life. However, taking into account the concerns of JAMA that some solutions might aggravate injuries to pedestrians and other vulnerable road users, it is suggested that the option for manufacturers to chose between using the lower or upper legform be removed leaving the upper legform as the only option for testing high bumpers with a lower reference line of 500 mm or more. In discussions with manufacturers, concerns have been expressed, about the feasibility of meeting two different tests for bumpers where some parts of the width comply with the high bumper definition and other parts do not. Taking both these points into consideration it is suggested that the switch to the upper legform to bumper test should remain at 500 mm, but a region of choice be added below this to prevent those bumpers which are just below this level migrating higher during the design process. This suggestion is in alignment with the GTR proposal.

The upper legform to bumper test requires the impactor to be centred about the bumper upper and lower reference lines. Originally the upper bumper reference line was only used to determine the bumper lead, which is used in turn to determine the impact conditions for the bonnet leading edge test. In the determination procedure, the 700 mm straight edge length and the end of the straight edge 'on the ground' requirements were introduced so that for flat fronted vehicles with no identifiable bumper, the height of the line was restricted to a reasonable bumper type area. However, when the reference line is also used in the upper legform to high bumper test, instead of always marking the top corner of the bumper on a vehicle with a high bumper, as intended, it can mark a lower point, because the top end of the straight edge makes contact rather than its face, see Figure 3.9.

For a vehicle with an extremely high bumper we could have a lower bumper reference line within 23.5 mm of the upper reference line. This would result in the upper legform to bumper test not being centred about the 'real' bumper front face. To overcome this problem the following change can be made to the test methods:

> "The Upper Bumper Reference Line identifies the upper limit to significant points of pedestrian contact with the bumper. For vehicles with an identifiable bumper structure it is defined as the geometric trace of the uppermost points of contact

between a straight edge and the bumper, when the straight edge, held parallel to the vertical longitudinal plane of the car and inclined rearwards by 20 degrees, is traversed across the front of the car whilst maintaining contact with the upper edge of the bumper.

For a vehicle with no identifiable bumper structure it is defined as the geometric trace of the upper most points of contact between a straight edge 700 mm long and the bumper, when the straight edge, held parallel to the vertical longitudinal plane of the car and inclined rearwards by 20 degrees, is traversed across the front of the car, whilst maintaining contact with the ground and the surface of the bumper. See Figure 1a."

Note that the second paragraph of 2.2.1 (in the EEVC WG17 test methods), about shortening the straight edge, is no longer necessary. We suggest that Figure 1a is changed to show the more common case of a stick not in contact with the ground.

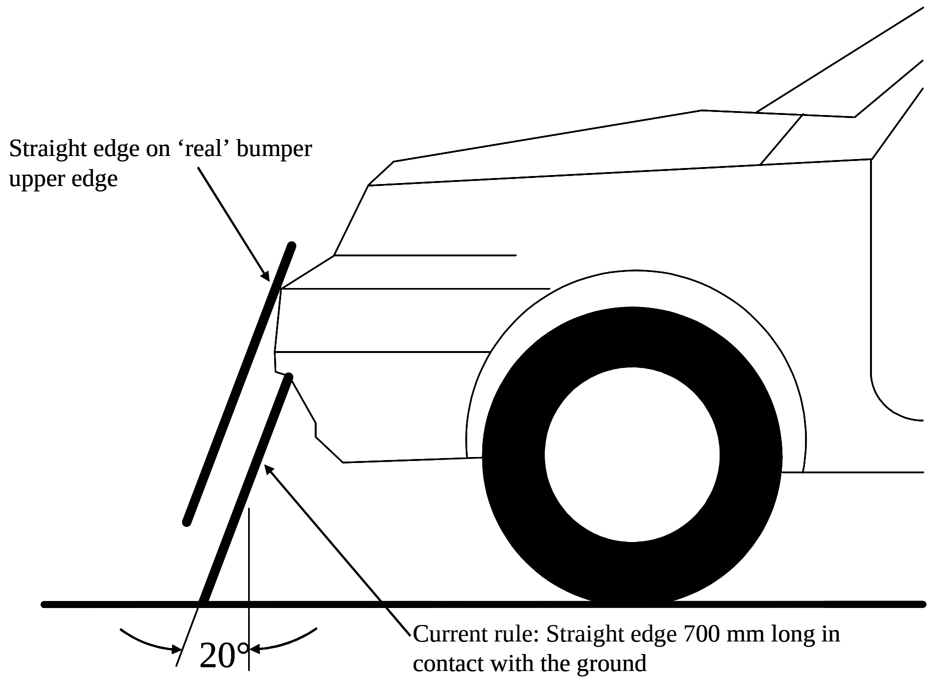


Figure 3.9. Problem marking-up high bumper with regard to centring the upper legform impactor

For a vehicle with an extremely high bumper we could have a lower bumper reference line within 23.5 mm of the upper reference line. This would result in the upper legform to bumper test not being centred about the 'real' bumper front face. To overcome this problem the following change can be made to the test methods:

"The Upper Bumper Reference Line identifies the upper limit to significant points of pedestrian contact with the bumper. For vehicles with an identifiable bumper structure it is defined as the geometric trace of the uppermost points of contact between a straight edge and the bumper, when the straight edge, held parallel to the vertical longitudinal plane of the car and inclined rearwards by 20 degrees, is traversed across the front of the car whilst maintaining contact with the upper edge of the bumper.

For a vehicle with no identifiable bumper structure it is defined as the geometric trace of the upper most points of contact between a straight edge 700 mm long and the

> bumper, when the straight edge, held parallel to the vertical longitudinal plane of the car and inclined rearwards by 20 degrees, is traversed across the front of the car, whilst maintaining contact with the ground and the surface of the bumper. See Figure 1a."
>
> *Note that the second paragraph of 2.2.1 (in the EEVC WG17 test methods), about shortening the straight edge, is no longer necessary. We suggest that Figure 1a is changed to show the more common case of a stick not in contact with the ground.*

When examining off-road vehicles it was observed that some had a permanent rigid towing eye or loop fixed below the bumper front face, in such a position that it would not be directly involved in an upper legform to bumper test, yet where it could be injurious to a pedestrian. It is recommended that where towing eyes are positioned beneath a high bumper, in such a position that they are not contacted by the upper legform impactor, that they be set back a minimum distance behind the front face. In an impact with a pedestrian at about 40 km/h it can be estimated that the femur might penetrate approximately 100 to 150 mm into a bumper that passed the upper legform tests. Therefore it is recommended that permanent towing eyes be set back by at least 150 mm.

3.3.3 Upper legform test

3.3.3.1 Upper legform tool

No alternative upper legform test tools are available and no modifications to the EEVC impactor have been suggested. Therefore, no changes to the test tool are proposed for the second phase of the EC Directive.

3.3.3.2 Upper legform certification

The effects of humidity on the performance of Confor™ foam has been discussed in Section 3.3.1.3. The study by Matsui (Matsui and Takabayashi, 2004) includes drop tests onto samples of Confor™ and these results show that is the Confor™ foam itself that is affected by humidity. The upper legform certification test is thought to be less sensitive than the legform dynamic certification test to acceptable changes in the performance of Confor™ foam, because the foam is not crushed to the same extent as in the legform certification test. Therefore, it may not be necessary to introduce a humidity tolerance. Nevertheless, car manufacturers give a high priority to minimising test variability, so the extra cost of controlling humidity in the upper legform certification and vehicle tests may be considered cost-effective. Therefore, consideration should be given to introducing a similar humidity tolerance to that proposed for the legform test.

3.3.3.3 Upper legform test method

For the upper legform there is nothing available to borrow from other test methods, as there are none. However, recommendations have been produced to revise the current test energy curves based on a more biofidelic pedestrian model and improved vehicle model (Neale *et al.*, 2001) than that used by EEVC WG17 to specify the current energy look-up curves. The new energy curves proposed were 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 (see Figure 3.10) were far less sensitive to these marking-up errors and were therefore more robust.

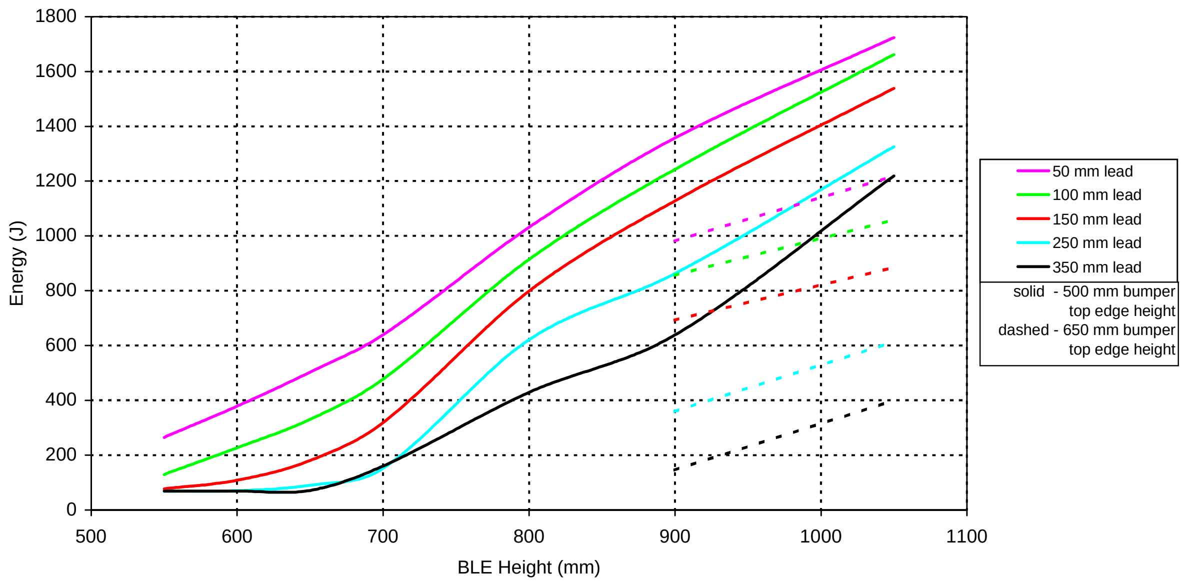


Figure 3.10. Upper legform impact energy curves, for use with a straight edge at 40° to the vertical, proposed by Neale *et al.* (2001)

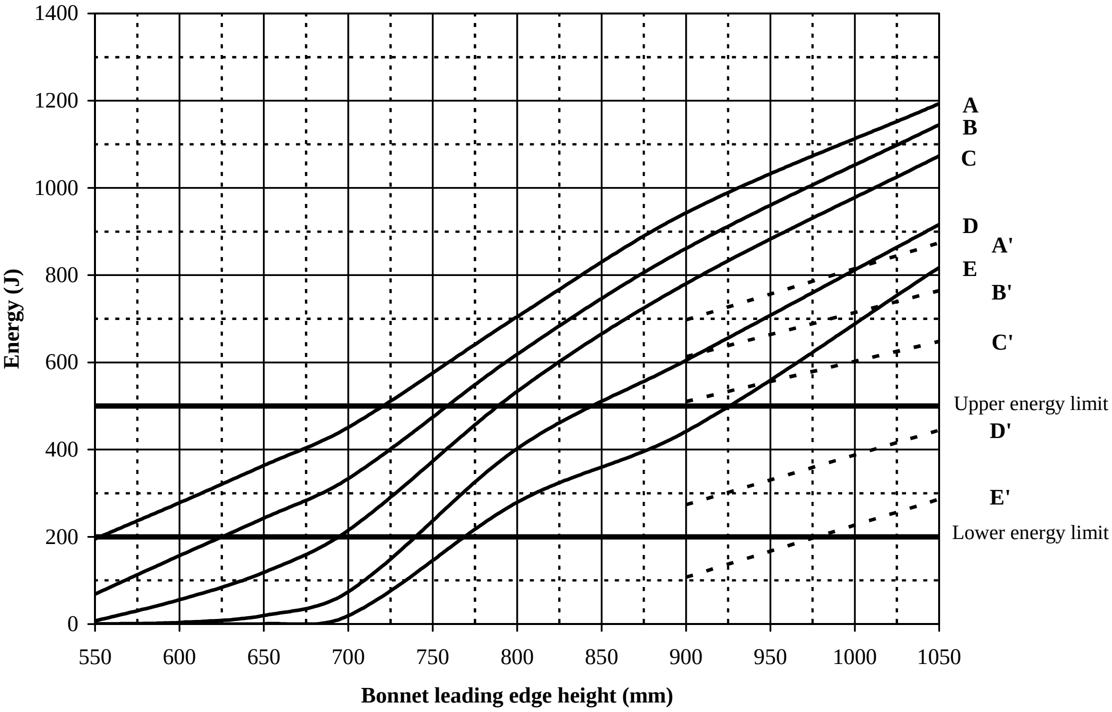
However, it was also noted that these energy curves required higher energies for many car shapes than the previous ones. The working group discuss the appropriateness of the test energies when compared with the comparatively low injury rates for bonnet leading edge impacts found in accident studies and the high failure rates seen when current cars are tested. One reason why older cars fail the upper legform test, yet relatively few femur and pelvis injuries are seen in real world accidents, compared with lower leg and head injuries, is that the upper legform test energies were found in conjunction with a theoretical pedestrian friendly bumper. With a pedestrian friendly bumper, due to the low stiffness and allowable crush depth, the pedestrian's leg will be propelled up towards car speed gently and as it penetrates into the bumper, therefore the bonnet leading edge contact with the upper leg will be comparatively severe. However, most current vehicles have a comparatively hard bumper due to the presence of a strong bumper beam. Therefore, in many current real world accidents, a hard bumper contact, typically just below the knee, will start to sweep the pedestrian's upper leg up to vehicle speed before the bonnet leading edge makes contact. Also the bumper is likely to cause fractures of the bones below the knee or knee ligament failure. The effect of this additional hinge is to reduce the effective mass of the upper leg when the bonnet leading edge strikes it. As a lower force is required to propel a reduced mass up to vehicle speed, the risk of upper leg injury is reduced if the bumper causes fracture or knee joint failure. Because of these two effects of hard bumpers on bonnet leading edge impact severity, the upper leg test can be said to represent more of a 'worse case' than occurs with most current cars, but it would be more appropriate for cars with a pedestrian friendly bumper. As the intention of the EU Directive is to save injuries to the knee and lower leg by requiring softer, safer bumpers, then the test energy for the upper legform should be appropriate for a pedestrian friendly bumper. Although the working group accepted this argument they concluded that the current gap between test severity and injury rates for the bonnet leading edge was too large to be caused by the effects of hard current bumpers. 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 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 would seem reasonable 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 is proposed that the new test energies, shown in Figure 3.10, be adjusted, as agreed in principle by WG17, by introducing a 30 percent reduction. Some additional minor adjustments have also been 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 has been progressively reduced for the more streamlined car shapes, where the test energy is too low to fully crush the impactor flesh.

The new energy curves include an upper energy limit that has been reduced from 700 to 500 J; the need for this is discussed in Section 10.2.3.4. A further conclusion made by Neale *et al.*, (2001) was that the angle of the straight edge used to determine the bonnet leading edge reference line should be changed from 50 degrees to the vertical to 40 degrees, in order to identify more accurately the centre of the upper leg impact. It is recommended that this could be considered for phase two of the EC Directive; therefore energy curves are provided in Figures 3.11a and 3.11b to take account of both straight edge angles (these figures also include a set of interpolation rules). When typical cars with rounded profiles in the region of the bonnet leading edge are measured, the bonnet leading edge height and bumper lead obtained will depend on the straight edge angle that is used. The differences between Figures 3.11a and 3.11b are such that the energy obtained for a typical car, with a radius at the bonnet leading edge similar to that used in the simulations by Neale *et al.*, should be approximately the same for both straight edge angles.

With the current WG17 curves, the points with the high bumper at a bonnet leading edge height of 1050 mm happened to be consistent with the trend for low bumpers at BLE heights up to 900 mm. Since most cars with a 900 mm BLE height have a low bumper and most with a 1050 mm BLE height have a high bumper it was possible to combine the low and high bumper data into a single set of curves, in order to simplify the look-up method. However, with the currently proposed curves the low and high bumper data give quite dissimilar impact energies, so it is now necessary to keep the low bumper and high bumper energies as separate curves and lines. This will also allow appropriate test energies to be obtained for vehicles with a high BLE and a low bumper; this combination would arise if a bumper is designed to be automatically or manually moved between a high off-road position for a higher ramp angle and a low on-road position for greater pedestrian safety and compatibility with other cars.

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.



Key:

A & A′ = 50 mm bumper lead

B & B′ = 100 mm bumper lead

C & C′ = 150 mm bumper lead

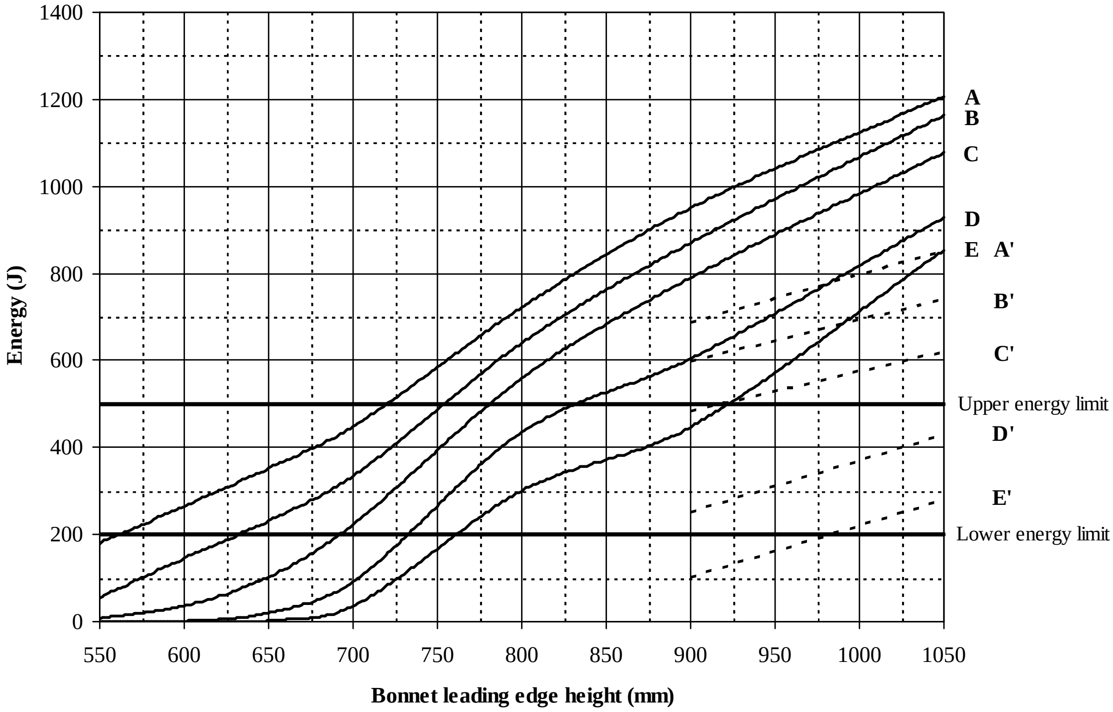
D & D′ = 250 mm bumper lead

E & E′ = 350 mm bumper lead

Notes:

- For vehicles with a bumper top edge height of less than 575 mm:
  - Interpolate vertically between the solid curves.
  - With bumper leads below 50 mm - test as for 50 mm.
  - With bumper leads above 350 mm - test as for 350 mm.
  - With bonnet leading edge heights above 1050 mm - test as for 1050 mm.
- For vehicles with a bumper top edge height of 575 mm or greater:
  - Interpolate vertically between the dashed lines.
  - With bumper leads below 50 mm - test as for 50 mm.
  - With bumper leads above 350 mm - test as for 350 mm.
  - With bonnet leading edge heights above 1050 mm - test as for 1050 mm.
  - With bonnet leading edge heights below 900 mm - test as for 900 mm. However, if the energy thereby obtained is greater than for a vehicle with a bumper top edge height of less than 575 mm, test as for a bumper top edge height of less than 575 mm.
- With a required kinetic energy above 500 J - test at 500 J.
- With a required kinetic energy below 200 J - no test is required.

Figure 3.11a. Upper legform impact energy curves for use with a straight edge at 50° to the vertical (proposed as an option for use in phase two of the EC Directive)



Key:

A & A′ = 50 mm bumper lead

B & B′ = 100 mm bumper lead

C & C′ = 150 mm bumper lead

D & D′ = 250 mm bumper lead

E & E′ = 350 mm bumper lead

Notes:

- For vehicles with a bumper top edge height of less than 575 mm:
  - Interpolate vertically between the solid curves.
  - With bumper leads below 50 mm - test as for 50 mm.
  - With bumper leads above 350 mm - test as for 350 mm.
  - With bonnet leading edge heights above 1050 mm - test as for 1050 mm.
- For vehicles with a bumper top edge height of 575 mm or greater:
  - Interpolate vertically between the dashed lines.
  - With bumper leads below 50 mm - test as for 50 mm.
  - With bumper leads above 350 mm - test as for 350 mm.
  - With bonnet leading edge heights above 1050 mm - test as for 1050 mm.
  - With bonnet leading edge heights below 900 mm - test as for 900 mm. However, if the energy thereby obtained is greater than for a vehicle with a bumper top edge height of less than 575 mm, test as for a bumper top edge height of less than 575 mm.
- With a required kinetic energy above 500 J - test at 500 J.
- With a required kinetic energy below 200 J - no test is required.

Figure 3.11b. Upper legform impact energy curves for use with a straight edge at 40° to the vertical (proposed as an option for use in phase two of the EC Directive)

There is a minimum practical mass that can be achieved with a robust upper legform impactor and guidance system. EEVC WG10 selected a mass of 9.5 kg. The test method requires the mass to be derived from the test energy and the test velocity. To prevent an impractically low mass being required for some shapes of car, WG10 adjusted some of the points on the velocity curves, where necessary, to reduce the test velocity, so that when the adjusted velocity was used with the test energy for a car of that shape a mass of at least 9.5 kg would be required. It was again found that the new energy curves proposed above, for some vehicle shapes, require a mass lower than this practical minimum, when used with the current velocity look-up curves. Therefore the velocity curves were reviewed in conjunction with the new energy curves. The intention was to follow past practice for the EEVC WG10 velocity curves and adjust them so that the calculated impactor mass was never less than 9.5 kg. The latter are the parameter curves used in EC Decision 2004/90/EC. Past practice was also to make further minor changes to maintain the smooth shape of the curves and the 'family relationship' of the set of curves.

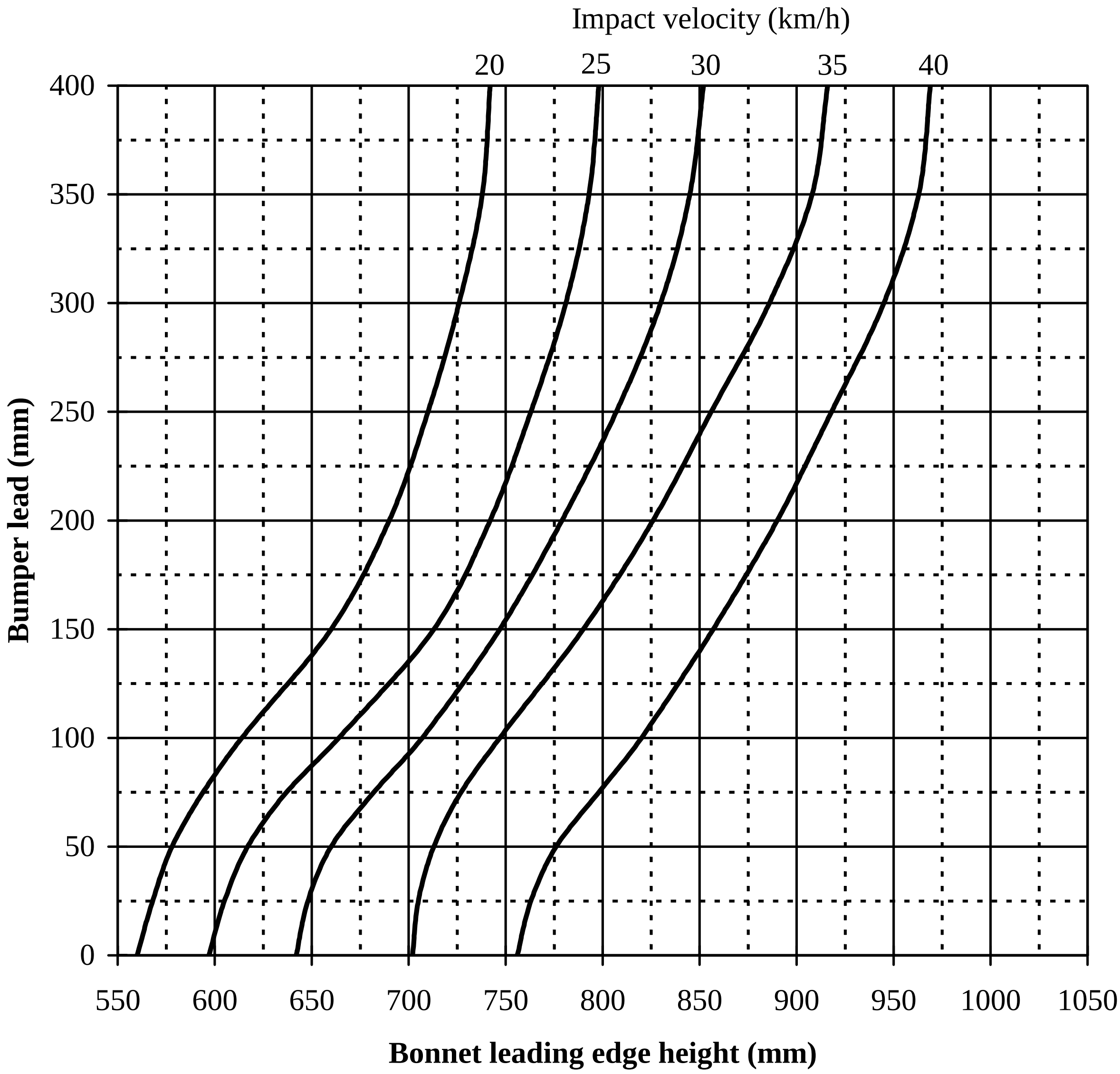
The exercise of adjusting previous velocity curves was repeated, separately for each of the energy curve options (Figures 3.11a and 3.11b). To reduce the cumulative effect of successive adjustments, the starting point was the velocity curves proposed in 1991.

This exercise revealed two problems. Firstly, the proposal for energy includes a 500 J energy cap. Many car shapes, where the energy would be capped, are those tested at the highest speed of 40 km/h, which would give an impactor mass of only 8.1 kg. Secondly, the proposed graph for impact energy includes separate lines for vehicles with high bumpers, as the simulations that were used predicted lower impact energies for these vehicles. Some of these shapes would give impactor masses as low as 3.2 or 3.6 kg at the velocity obtained from the velocity graph (for energies from Figures 3.11a and 3.11b respectively). It was therefore decided that neither of these cases could be managed by making minor adjustments to the velocity curves. Therefore, it is proposed that an additional rule be introduced, that if the calculated impactor mass is less than 9.5 kg then it should be set to 9.5 kg, and the test velocity should be changed to maintain the impact energy. This is an extension of what is already provided to permit the impactor mass to be changed by up to 10 percent for the operator's convenience. It is suggested that the first paragraph below be added in the appropriate place and that the second replace the current wording:

> "If the upper legform impactor mass thus obtained is less than 9.5 kg then the required upper legform mass shall be 9.5 kg and the required impact velocity shall be changed using the above formula to maintain the same impactor kinetic energy."
>
> "The upper legform mass may be adjusted from the value obtained above by up to ±10%, provided the required impact velocity is also changed using the above formula to maintain the same impactor kinetic energy."

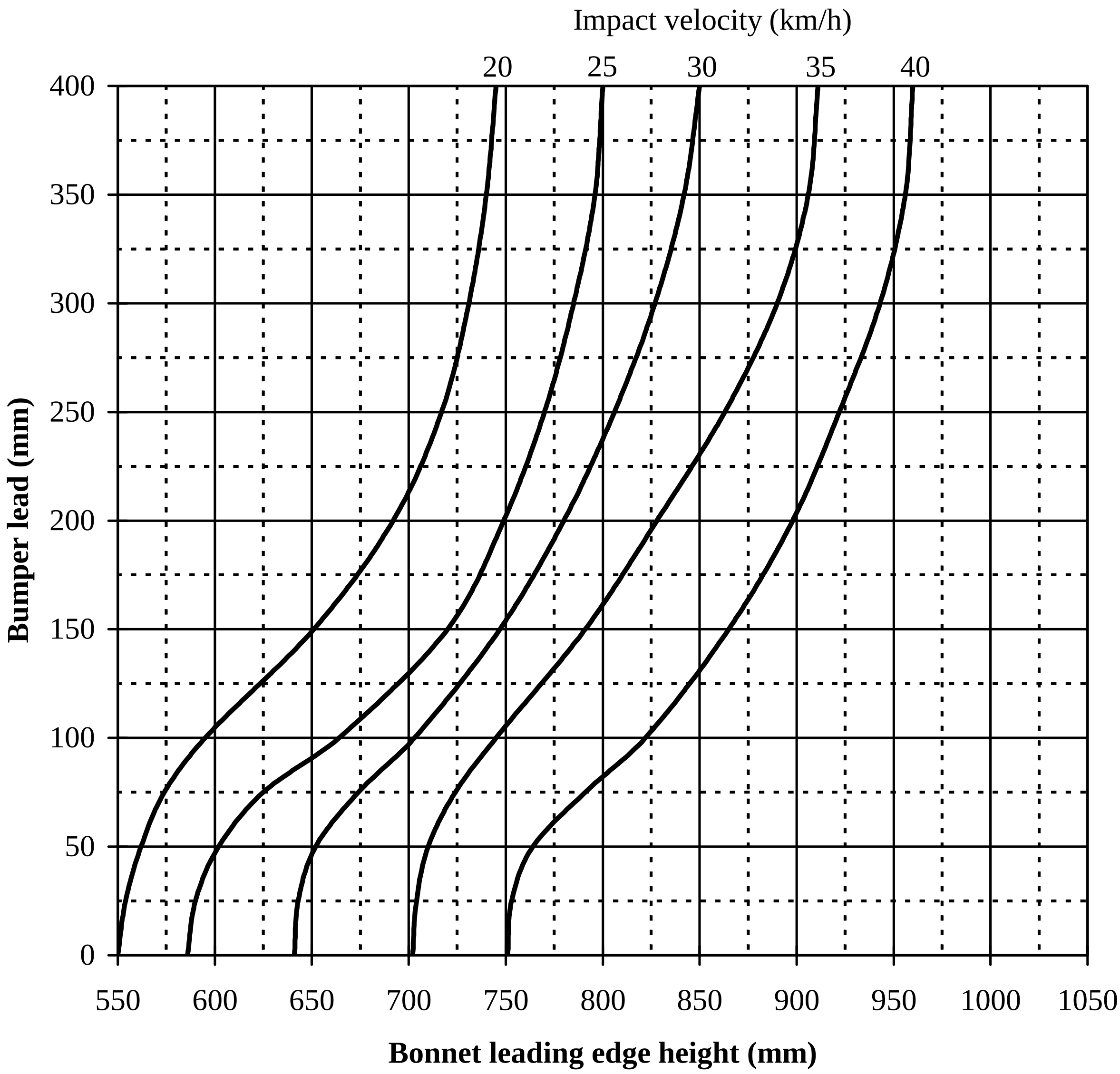
The intention is that these paragraphs act in turn, so that if the mass is changed from less than 9.5 kg to 9.5 kg it would then be permitted to change it to a mass within the range 9.5 kg ±10 percent. If these changes are made to affect only phase two of the test procedures it would mean that the energy and velocity graphs would be different for phase one and phase two, and therefore the redrafting would be more complex. The text changes above would not conflict with phase one and could therefore be made to text that was common to both phases.

The velocity curves were adjusted as described above, so that when using them most cars will be tested at or over 9.5 kg without invoking the proposed new rule. This includes all cars with standard height bumpers that are not energy capped. These velocity graphs are presented in Figures 3.12a and 3.12b, for use with Figure 3.11a (50° straight edge) or Figure 3.11b (40° straight edge) respectively. However, with the proposed new rule in place it would alternatively be possible to use velocity curves with all the adjustments for minimum mass removed. This would have the advantage that some shapes of car would be tested at impactor velocities and masses slightly closer to those derived from the dummy test and simulation results.



Notes:
1. Interpolate horizontally between curves.
2. With configurations below 20 km/h - test at 20 km/h.
3. With configurations above 40 km/h - test at 20 km/h.
4. With negative bumper leads - test as for zero bumper lead.
5. With bumper leads above 400 mm - test as for 400 mm.

Figure 3.12a. Upper legform impact velocity curves for use with a straight edge at 50° to the vertical (proposed as an option for use in phase two of the EC Directive)



Notes:
1. Interpolate horizontally between curves.
2. With configurations below 20 km/h - test at 20 km/h.
3. With configurations above 40 km/h - test at 20 km/h.
4. With negative bumper leads - test as for zero bumper lead.
5. With bumper leads above 400 mm - test as for 400 mm.

Figure 3.12b. Upper legform impact velocity curves for use with a straight edge at 40° to the vertical (proposed as an option for use in phase two of the EC Directive)

As discussed in Section 3.3.3.2, it may be beneficial to introduce a humidity tolerance in the upper legform vehicle test in order to reduce the variability. Therefore it is recommended that some consideration should be given to introducing a tolerance of 35 ±15% of relative humidity to the upper legform certification requirements in the second phase of the EC Directive.

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. It is also considered that, as a result of the vehicle modifications necessary, the need for this test may not be justified on the basis of injury numbers. More information, with respect to modern vehicle design, is required to ensure the development of a properly agreed test.

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.

3.3.3.4 Upper legform criteria

Matsui *et al.* (1998) 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.

3.3.4 Headform test

The differences between the EEVC headform test methods (included in the second phase of the EC Directive) and the alternative test methods and tools have already been discussed in Sections 3.1.3 and 3.2.3.

3.3.4.1 *Headform tools*

Based on the discussion on effective mass in Sections 3.1.3 and 3.2.3 it is recommended that a 3.5 kg headform should be used to test the child area in the second phase of the EC Directive.

The possible use of the alternative 4.5 kg mass is discussed in Section 10 under feasibility issues.

3.3.4.2 *Headform test method*

As discussed in Section 3.2.3 no changes to the child and adult test methods are suggested apart from the change in child headform mass and the possible change in the adult headform mass.

3.3.4.3 *Headform criterion*

All three alternative head test methods have the same Head Injury Criterion (HPC) 1000 performance criterion. 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 used in the EC Directive.

4 Global Technical Regulation (pedestrians and other vulnerable road users)

As noted in Section 1.1, a draft proposal for a global technical regulation for pedestrians and other vulnerable road users has been produced recently. This proposal is based on the latest available research and test tools and made use of data provided by international participants including the EC. Because the draft pedestrian GTR represents the latest thinking on combining test methods, tools and feasibility issues, it is likely to make a significant contribution to the debate on what should be included in phase two of the Directive or any Regulation which replaces it. A further advantage of the draft GTR is that it could reduce manufacturing, and therefore consumer, costs by standardisation of safety requirements worldwide.

The authors understand that, in the light of the draft GTR and the forgoing examination of work relating to issues arising, the Commission may want to harmonise between the passive requirements of the draft GTR and any amendments proposed for phase II combined with options such as the fitting of brake assist to all vehicles (within the scope of the legislation) and extending the scope of the legislation (phase two pedestrian protection) to include larger vehicles.

In order to understand the consequences of replacing the second phase of the current Directive with requirements based on the draft GTR it is first important to identify the significant differences along with some key similarities. Table 4.1 below shows the main differences identified by the authors.

4.1 'Normal' Bumpers

The GTR group have noted the potential of the Flex-PLI legform for this test because of its high biofidelity and recommend that it should be considered for future use in a GTR. They have established a Technical Evaluation Group (TEG) to evaluate the reliability and suitability of the tool for regulatory use. This evaluation and development programme has not yet been completed. Therefore, currently the draft GTR specifies the WG17 lower legform test tool. Until the evaluation and development programme is completed and the impactor is shown to be suitable, the Flex-PLI cannot be considered for regulatory use. The TEG group intend to complete their development and assessment, and report by the end of 2007.

4.1.1 Protection criteria

The difference between the draft GTR, and phase two of the current Directive, is the introduction a small lower protection zone. In addition for the remaining part of the bumper the draft GTR requires slightly less protection against broken tibias (limit of 170 g) than in phase two of the current Directive (150 g). This is a slight improvement over an earlier suggestion to take account of feasibility issues, to use 190 g made in the 2004 EC feasibility study (Lawrence *et al.*, 2004a). In practice, taking into account the additional safety allowance that manufacturers will apply, typically car bumpers would be slightly better than the current Directive phase two minimum requirement.

4.1.2 Lower legform parameters

The difference between the draft GTR, and in phase two of the current Directive, is the introduction of an allowance for the thickness of a shoe. Again this follows the recommendations made in the 2004 EC feasibility study (Lawrence *et al.*, 2004a). The authors understand that this was an oversight by EEVC WG17; therefore this should be regarded as an improvement to the test method.

Tighter tolerances on legform position at first contact, which have been suggested by Lawrence *et al.* (2004a), would have reduced test to test variability, but would have made carrying out the tests more difficult.

Table 4.1: Main differences between phase two of the current pedestrian Directive and the GTR

	Directive, current, phase two	Draft GTR
Bumper test - protection criteria	Whole of test area: 15°, 6 mm, 150 g	Higher protection zone: 19°, 6 mm, 170 g *Lower protection zone: 19°, 6 mm, 250 g *(*applied to maximum width of 264 mm)*
Bumper tests - lower legform parameters	Foot end at ground reference level	Foot end 25 mm above ground reference level
Bumper test - speed	11.1 ±0.2 m/s	11.1 ±0.2 m/s
High bumper test - application	>500 mm manufacturer's option LL or UL	≥500 mm UL only, ≥425 <500 mm manufacturer's option LL or UL.
High bumper - protection criteria	5.0 kN & 300 Nm	7.5 kN & 510 Nm
High bumper - test speed	11.1 ±0.2 m/s	11.1 ±0.2 m/s
Bonnet leading edge (BLE) test	Tested with hard protection criteria	No BLE test at this time; intend to develop test with better impactor
Headforms used	2.5 kg child & 4.8 kg adult	3.5 kg child/small adult & 4.5 kg adult with minor specification improvements
Headform area - front limit	1000 mm WAD or 130 mm behind the tested BLERL #	1000 mm WAD or 82.5 mm from BLERL #
Headform areas child / adult transition	Split @ 1500 mm WAD #	Split @ 1700 mm WAD #
Headform test speed	40 km/h nominal (11.1 ±0.2 m/s)	35 km/h nominal (9.7 ±0.2 m/s)
Headform protection criteria	HPC 1000	2/3 HPC 1000, 1/3 HPC 1700 (on combined area but child area at least ½ HPC 1000)
Headform certification	Certified with impactor at high speed	Drop test *(Authors' suggest could be used for phase 1 of the Directive)*
Humidity tolerances – (principle for upper and lower legform flesh)	n/a	Tolerances of for test laboratory and conditioning of flesh
Speed measurement accuracy – all tests	No measurement tolerance (tolerance on test velocity only)	Measurement tolerance ±0.01 m/s

WAD = **W**rap **A**round **D**istance BLERL = **B**onnet **L**eading **E**dge **R**eference **L**ine

4.2 'High' bumpers

4.2.1 High bumper application

Of the two draft GTR changes here the change to the high bumper definition is the most significant, effectively lowering the transition point for high bumpers by 75 mm. EEVC WG17 based their high bumper definition on the most critical dimension, in terms of impactor suitability, the lower bumper reference line. This is the part that the lower legform will rotate about when the bumper is too high for this type of impactor because it lacks an upper body mass. It is recommended that a definitive study be carried out to determine what range of bumper heights the lower legform impactor (one without an upper body mass) is appropriate for, and the bumper height at which it becomes inappropriate. Until this is done a well justified high bumper definition cannot be produced. Nevertheless, it is clear that a legform impactor without an upper body mass will be unsuitable for bumpers of such a height that the main impact is above the knee.

However, when discussing the current EEVC WG17 high bumper definition the main arguments should probably be concentrated on what is feasible for 'high' bumper type vehicles. Most vehicles with 'high' bumpers are so equipped in order to give them off-road capability in terms of ground clearance and ramp angle. Testing such a vehicle with the lower legform impactor is likely to result in the need to add a low bumper or spoiler to prevent failure due to lateral knee bending. This would have an adverse affect on the vehicle's ability to go off-road. One solution would be to have a movable or bolt-on spoiler design with on and off-road options, but there are recognised problems in the use of this solution. Thus, the use of a transition zone, in the manner proposed in the draft GTR, could be acceptable.

As previously noted some vehicles with high bumpers are provided with permanent towing eyes which project forward, with radiuses but a narrow edge, and are very strong. As such features could result in serious injuries if they make contact with a pedestrian's leg consideration should be given to requiring them to be set back at least 150 mm behind the front face of the bumper, see Section 3.3.2.

4.2.2 High bumper protection criteria

It can be seen from Table 4.1 that the draft GTR protection criteria are different (offer less protection) than required in the current phase two of the Directive.

The draft GTR proposes force and bending limits to be set at 7.5 kN and 510 Nm respectively, which compares with 5 kN and 300 Nm in phase two of the current Directive. The current Directive criteria were selected by EEVC WG17 based on an injury risk of 20 percent. In the GTR preamble it is suggested that the EEVC WG17 criteria overestimated the risk of injury because it was based on PMHS tests which would not include the contribution from muscles in a live human. In fact WG17 used data from reconstructions of real accidents and therefore the WG 17 values relate to the live victims (European Enhanced Vehicle-safety Committee, 2002a). The draft GTR limits are equivalent to an injury risk of about 68 percent, using the WG17 injury risk graphs and method. Lawrence *et al.*(2004a) had suggest that a lower protection zone would be needed to improve feasibility with the current Directives phase two high bumper protection criteria, as the GTR criteria are less demanding a lower protection zone is not needed with these criteria.

4.3 Bonnet leading edge (BLE) test

The statement rationale and justification in the draft GTR points out that European in-depth accident data shows few or no cases with femur or pelvis injuries caused by the bonnet leading edge for 'cars' in accidents at speeds up to 40 km/h. However, they point out that:

> 'In contrast, data from the United States of America indicate a high incidence of above-the-knee injuries due to the prevalence of light trucks and vans in the United States fleet, and that consideration should be given to evaluating thigh, hip, and pelvis injuries in future test procedures.

> 'Despite the desire to address any potential injuries in the upper leg or pelvic area, the group was also concerned that there was a serious lack of biofidelity for the existing test device and the respective test procedure to assess injury caused by the bonnet leading edge of high profile vehicles. Therefore, the group recommended excluding the upper legform impactor to bonnet leading edge test at this stage.'

Proposals have been made 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.

When the bonnet leading edge test method was first proposed a significant number of serious injuries were attributed to the bonnet leading edge in accidents at speeds of up to 40 km/h. More recently European accident studies show a marked decline in such injuries. However, both car design and styling are not fixed but evolve over time and sometimes reverse for a 'retro' look. On this basis it would be unfortunate to have a potentially dangerous area of the car un-tested as proposed by the draft GTR. Even so, it must be acknowledged that the overwhelming majority of experts are of the opinion that there is a serious lack of biofidelity in this test method. The IHRA Pedestrian Safety Working Group is intending to develop a new impactor and test method for this area of the car. It's clear that there is a need for more research. The potential options are to identify the deficiencies of the current sub-systems test and rectify them or to develop an impactor that represents more completely a whole pedestrian within a test where the shape of the car directly influences the impact conditions.

Given the current climate of expert opinion it may be reasonable for legislators to take the view of the majority and not make compliance mandatory for conventional European cars shapes, for the revised phase two. However, for these vehicle shapes it is recommended that the bonnet leading edge test be retained as a monitoring only test, preferably using the proposal for revised test energies and the revised protection criteria as target values. The use of this test as a monitoring test will thus be useful in determining its' appropriateness and a possible specification for its use in the future. For example the results from the monitoring test could be used to identify specific types of vehicle and the accident statistics for these vehicles could then be examined.

The GTR group considered an American accident study which showed that high profile shaped vehicles cause a higher incidence of femur and pelvis injuries (Informal Working Group on Pedestrian Safety, 2006). Therefore, it would be more appropriate to consider the use of the bonnet leading edge test for these types of vehicles. Currently there are comparatively few models of this type of vehicle in Europe. Although many of these vehicles would be heavier than average, vehicle shape, rather than vehicle mass, would be more important in deciding if a vehicle has a bonnet leading edge of such a height that a bonnet leading edge test would be more appropriate.

4.4 The bonnet top headform test

4.4.1 Headforms used

The change in the draft GTR is to replace the EEVC WG17 2.5 kg and 4.8 kg child and adult headforms with 3.5 kg child / small adult headform and a 4.5 kg adult headform. This follows the recommendations made in the 2004 EC feasibility study (Lawrence *et al.*, 2004a). The draft GTR includes a first natural resonance frequency requirement (>5,000 Hz), which will minimise errors in transducer outputs if a test excites the headforms to vibrate naturally.

4.4.2 Headform area - front limit

For most normal car shapes both phase two of the Directive and the draft GTR will use the same limit of a Wrap Around Distance (WAD) of 1,000 mm. For taller vehicles the bonnet leading edge may be close to the 1000 mm WAD. In this case, if a bonnet leading edge test is included, then without an additional exception the same area of the vehicle would have to meet both the headform and bonnet leading edge protection requirements. The feasibility of making one structure meet two different requirements was discussed by EEVC WG17 as their procedures include a bonnet leading test. It was agreed that making one structure to meet two different protection requirements would be difficult and would require a larger crush depth than meeting just one or the other. The working group therefore decided to introduce a one headform diameter back from the bonnet leading edge rule for these taller vehicles (European Experimental Vehicle-safety Committee, 2002a). This rule would mean that for a small area of the bonnet leading edge, some priority is given to protection for the adult femur or pelvis over protection for the head of certain statures of child. This is because it is thought that only a small proportion of children involved in accidents will be of such a stature that their head aligns with bonnet leading edge of the vehicle concerned. Also protection intended for the adult femur or pelvis will probably be of more benefit (than protection for the child head) in accidents where the bonnet leading edge makes contact with the child's upper body (thorax and shoulder). However, if the bonnet leading edge test is for monitoring purposes only, then the argument to give priority to that test no longer applies, and the one headform diameter back rule may not be needed. Currently the draft GTR does not include a bonnet leading edge test. Based on just this it could be argued that the child head zone should start at the 1000 mm WAD as with smaller vehicles. However, for these large vehicles the effect would be that the front part of the head protection area would include the grill and headlamp area whereas for 'normal' car sized vehicles it would start on the bonnet, which is easier to change to provide protection. The GTR group considered these feasibility arguments and decided to retain a WG17 type rule for this but decided to reduce the distance behind the bonnet leading edge reference line from one headform diameter to one radius (note that IHRA, ISO and the draft GTR have proposed a larger more representative child head diameter than that of WG17).

4.4.3 Headform areas child / adult transition

Options for the transition between the child to adult head test area have been discussed in Section 3.2.3.1 and the main points are briefly summarised here.

Analysis of accident data with measured head impact locations has shown that the transition from child to adult starts at the Wrap Around Distance (WAD) of 1400 mm and ends at 1700 mm. Therefore, ideally the protection within that transition zone should be suitable for the comparatively lightweight heads of children through to the heavyweight male adult head. There are two ways of achieving this.

The first is simply to have an overlapping child and adult zone. This option has the advantage of reproducing the accident situation where there is an area which is more likely to be struck by heads of different mass. It assumes, reasonably, that if it is safe for the two headforms masses used then it will also be safe for any masses in between.

The second is to have a sudden transition between the adult and child zones. This second method works for most cases because in practice a step change in stiffness within the same vehicle structure is not feasible. Therefore to pass each side of the (sudden) transition line with the different headform masses will result in complying vehicle designs having a 'safe' overlapping zone about that line (of approximately the required width). The second method is used in both the draft GTR and in the second phase of the EC Directive. 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.

The difference between phase two of the Directive and the draft GTR is the WAD value used for the transition line. As already noted, accident data indicates that protection for a range of head masses is required between 1400 and 1700 mm. The EEVC approach of placing the transition line at approximately the middle of this zone seems reasonable as a 'safe-for-any-realistic-head-mass' zone should extend each side of the transition line (they selected 1500 mm on older data so it is not precisely in the middle). The draft GTR decision is based on arguments that protection tuned for a child head will be less inappropriate for an adult head than the other way around. If this argument is accepted then biasing the transition line towards a WAD of 1700 mm would seem more sensible noting that 1700 mm is already used in the Japanese pedestrian regulation. However, as already mentioned, the sudden transition line method will not provide a safe zone for both child and adult heads when the 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. This is far more likely to be the case if 1700 mm is used instead of 1500 mm as the back of the bonnet or fresh air intake at the base of the windscreen falls around the 1700 mm WAD for many smaller European cars. In many cases the use of a 1700 mm line will help feasibility by only requiring the bonnet top to protect for one headform mass; however, for some cars it may be disadvantageous because the heavier adult mass requires proportionately higher protection stiffness which may be easier to achieve in the base of the windscreen area. Overall, the authors do not have strong views on this matter and recognise that the 1700 mm proposal does have feasibility advantages and provides harmonisation with other regulation.

4.4.4 Headform test speed and protection criteria

It was previously concluded that a number of changes were necessary to take account of feasibility issues for the bonnet top area (Lawrence *et al*., 2004a). The key changes for feasibility proposed by Lawrence *et al.* (2004a) were:

- a continuation of the lower protection zones of phase one;
- adjustment of the protection criteria in order to take account of manufacturers' allowances.

With regard to the lower protection zones the draft GTR has a similar approach to that proposed but with larger zones. In the draft GTR the protection criteria are more demanding than those proposed by Lawrence *et al*. (2004a) but the reduction in test speed from 40 to 35 km/h is significantly less demanding reducing energy by a square law. However, the equation used to calculate the Head Performance Criterion (HPC or HIC) is also non-linear so the improved protection criteria will compensate to some extent for the reduction in velocity. The net effect of the two differences is that the head protection offered by the draft GTR is less when compared with phase two of the current Directive.

4.4.5 Headform certification

The heads of car occupant test dummies are normally certified by dropping the head (detached) a specified distance onto a steel plate. This method was originally used by EEVC for their headform certification test method. Because the drop height is small, the impact velocity when the headform strikes the plate is very low. EEVC WG17 became concerned that the certification test was not ideal for pedestrian testing because tests for car occupants generated or used lower velocities than those used in the pedestrian tests. They therefore developed a new high speed certification test. However, the new WG17 test appears to have a problem, which has not yet been resolved. It appears that the method is sensitive to small differences in the equipment used, such that when the same headform is tested at different laboratories there is significant scatter in the results, this problem was discussed by Lawrence (2005). Lawrence compared a certification time history with that of a test to a 'safe' car and showed that the impact duration of the certification test was less than a tenth of the duration of the 'safe' car test (HIC 728). Given the scatter and the unrealistically short impact duration of the WG17 certification test method, then reverting to drop test certification method, as in the draft GTR, seems reasonable.

There is also a concern, that variation in the shear modulus of the headform skin might influence test results, where the headform impact is not normal to the bonnet surface. The shear modulus is not controlled by the WG17 certification method or by a drop test procedure. Ideally a study should be carried out to see if an additional shear modulus test is necessary but in the absence of such a study it is suggested that the headform skin (flesh) material be described as 'PVC or similar' in the regulation.

4.5 General differences

4.5.1 Humidity tolerances

The draft GTR has a humidity requirement for the upper and lower legform flesh (Confor foam); the dynamic performance of this material has been shown to be sensitive to humidity, see Section 3.3.1.2. The humidity tolerances in the GTR follow the proposal made in the original feasibility study (Lawrence *et al*., 2004a) which was supported by a later study by Lawrence *et al.* (2005). The only concern with the draft GTR proposal is the time allowed between humidity conditioning and use, of up to two hours, which is thought to be sufficient time for foam's humidity to change significantly. It is suggested that consideration should be given to the time allowed between conditioning and use and whether it would be practical to carry out a certification or vehicle test in about 5 to 10 minutes.

4.5.2 Speed measurement accuracy – all tests

The draft GTR includes a speed measurement accuracy requirement, which has a tolerance of ± 0.01 m/s. It may be technically difficult to achieve such accuracy (particularly if this tolerance is applied to the whole measurement process and not just the timing gate itself). However, if it proves to be possible then a higher accuracy would be beneficial because it would help reduce test variability. It is recommended that a study is carried out to determine what measurement accuracy is feasible.

5 Scope

As noted in Section 4, the EC are proposing that the scope of the draft GTR be extended to apply to all category 1-1 vehicles over 0.5 tonnes mass (with up to 5 years lead-in for vehicles over 2.5 tonnes; Informal Working Group on Pedestrian Safety, 2006). The change will mean that the current limit of up to 2.5 tonnes will be removed. They are also proposing to add to the scope larger goods vehicles of a similar frontal shape to category 1-1 vehicles with a mass up to 2.5 tonnes.

It is possible that similar changes to scope could be considered for Europe. Obviously any increase in the scope will increase the benefits and estimates of improved benefits which are made in Section 13. However, as well as providing extra benefits, a change in scope could have other implications in terms of feasibility and cost, and the suitability of the test methods and tools for testing larger vehicles. The situation is complicated by the fact that the vehicle classification methods used in the draft GTR, although broadly similar, may prove to have some differences to those used in the European Directive. To explore the possibilities for extending the scope of the Directive the options were identified first. Then the consequences of using the test methods for larger vehicles than was originally intended are considered and discussed.

Currently the Directive applies to M1 and N1 derived from M1 up to 2.5 tonnes (gross vehicle weight as defined by the manufacturer).

Options to extend the scope are:

- Change M1 mass limit to 2.5 tonnes unladen or kerb weight (instead of current gross)
- Increase M1 mass limit from 2.5 to 3.5 tonnes gross
- Remove M1 mass limit completely
- Add N1 not derived from cars but of car shape
    - suitable definition needed, see below
- Include all N1 vehicles

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 of the options suggested above is to include NI vehicles not derived from cars, but only those of car shape. 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 of those of cars shape so they can be included. Consideration could be given to a rule based around 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 windshield 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.

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.

For example, additional abdomen and thorax tools and methods may be needed for larger vehicles (especially for smaller statures of pedestrian). Different head impact conditions may be needed for high or flat-fronted large vehicles. The real head impact area (or parts of it) would be excluded by the current test area definition if it is not behind the bonnet leading edge reference line.

As discussed in Section 4.3, vehicles with high bonnet leading edges are more likely to cause more femur and pelvic injuries for adults. For children and small females, injuries to the upper body (abdomen, chest) neck and head may be more likely and for very large vehicles, adult injuries above the pelvis could also result from bonnet leading edge contacts.

Although increasing vehicle mass will reduce the slowing of the vehicle due to transfer of energy to the pedestrian, this is a very small effect. Therefore mass is not as important as size and shape in deciding what vehicles should be included in the scope or which vehicles might need different treatment. Current vehicle definitions are a mixture of use and mass and so do not necessarily comply with the size and shape definition needed for pedestrian protection. New marking rules, test conditions and vehicle definition (e.g. for flat fronted vehicles (see above) or those with a high bonnet leading edge) may be needed for an expanded scope.

In general, it is considered that the application of the EEVC or draft GTR type tests to larger vehicles will result in an improvement in their pedestrian safety and would be very unlikely to make protection worse. However, for large vehicles the EEVC or draft GTR test methods and therefore the protection they require will not necessarily be so appropriate. This is because the pedestrian body part represented by the test and the impact conditions prescribed were principally developed for ‘normal sized’ car-type vehicles. In some cases a test method and tool representing one part of the pedestrian’s body may, in practice, be used to test a vehicle area which will be predominantly involved in impacts with a different pedestrian body region in real accidents. The test methods rely on simplified marking up rules that were developed for and validated for normal car shapes. Problems in using these rules are almost certain to be found when they are used on larger vehicles, in terms of application and appropriateness, particularly if they are applied to all N1 vehicles and not just those of car shape. It would, therefore, be essential to carry out a mark up and mock test to a representative range of large vehicles to develop workable new rules for the current tests applied to large vehicles. Ideally, new test methods and rules should also be developed.

6 Assessment of the development and availability of new technologies

There are a number of technologies that could be regarded as new and which could contribute to reducing the number of pedestrian and other vulnerable road user casualties (for brevity these are collectively referred to as 'pedestrians' in the list below). In the specification for this study these were referred to as alternative active and passive technologies. However, these names are often used in a different context so it would be of help to define them here.

Passive systems are considered as:

- Those that provide improved protection after contact with a pedestrian. These would include systems that:
    - Absorb energy by controlled deformation (as this is a normal method of providing protection for pedestrians, 'new' might be defined as systems that absorb energy more efficiently than current designs / materials allow).
    - Those that provide more crush space by changing the vehicle shape after first contact (e.g. pop-up bonnets triggered by leg to bumper contact).

Active systems are considered as:

- Those that change the outcome of a potential pedestrian accident by recognising and responding in some way before contact with the pedestrian occurs. These would include systems that:
    - recognise an emergency and apply the brakes more effectively (brake assist)
    - recognise that an accident is about to occur and provide additional energy absorption on the vehicle (e.g. bumper, bonnet top and A-pillar air bags)
    - assist the driver to recognise or alert the driver to potential accidents so the driver may avoid them (e.g. smart lights that provide wider or shaped beams at potential danger points or that adapt to steering wheel inputs to illuminate around bends, and infrared systems to detect pedestrians in the dark combined with display screen or head-up displays)

6.1 Technology already in use

6.1.1 Passive protection

From discussions with car manufacturers it appears that most are intending to use a variation of the current methods used to absorb parking and accident energy. The energy in parking and crash accidents is absorbed in boxes, channels, double skinned and single skinned panels, etc. by deformation of the metal or plastic that they are made from, through crumpling, collapsing or stretching. In addition, energy can be absorbed by the crushing of plastic foams which can be fitted between the inner and outer surfaces. These methods are being adapted to provide the required stiffness and crush depth for pedestrian protection but, in addition, a more uniform stiffness profile of the structure is needed as each pedestrian test only involves a small area of the car.

6.1.2 Active protection

6.1.2.1 Brake assist

Although not designed solely for the protection of pedestrians and other vulnerable road users, brake assist is a technology that comes as standard on some new cars. Studies have shown that frequently the maximum possible deceleration is not achieved by the driver alone because they are reluctant to apply sufficient pressure (ACEA, 2004). Brake assist is a function that interprets the manner in which a driver presses the brake pedal and if it is computed to be in a manner typical of responding to an emergency situation, the vehicle will apply more braking than the force on the brake pedal would dictate alone. Through this assistance the available braking of the vehicle, including Anti-lock Braking System (ABS) engagement, can be used to a greater extent than perhaps the driver was aware was possible. These systems support the driver and lead to reduced collision speed, or help to avoid the potential accident altogether since evasive driving manoeuvres can be performed more easily once the speed is reduced more effectively.

The efficiency of Brake Assist Systems (BAS) is related to the hesitant braking performance of many drivers in real world situations. The brake assist leads to braking at the level to give the shortest possible stopping distance, even though only limited effort is provided by the driver. The brake assist efficiency is therefore the difference between typical real world drivers' braking and the greatest possible braking.

The Directive requires, in its Article 5, that alternative measures shall be "at least equivalent in terms of actual effectiveness" to the requirements of the second phase of the Directive. The European Commission are considering including a requirement for compulsory fitting of brake assist systems to all new vehicles in order to augment the savings of secondary pedestrian protection. Brake assist along with other measures, such as a wider scope, could be used to obtain the 'at least equivalent effectiveness' required. The cost-benefit study, which can be found in Section 13, includes estimates of the effectiveness of the proposed alternative measures relative to the current phase two requirements. This includes estimates for the benefits of BAS. Therefore it is important to understand how BAS works and its limitations. It is also important to understand the methods used to estimate the benefits of BAS and the limitations and reliability of these estimates. This is covered in Section 9 of this report.

6.1.2.2 Head-up displays

Currently, Head-Up Display (HUD) systems are available on relatively few American passenger vehicles. The concept of HUDs is to move the important information that a driver needs to see up into their line of sight, so they don't have to take their eyes of the road. To do this, HUD systems project an image so that it appears to float in mid air, just past the front end of the vehicle. With the image at this range, the eyes of the driver do not have to refocus to see gauges and indicators, and then refocus again to see the road ahead. Studies made at the University of Berkeley, California, have found the timing between looking at dash mounted instruments and looking back on the traffic is about two seconds, whereas with a HUD in this configuration it takes only half a second. In the time it takes the driver's eyes to refocus, when travelling in free moving traffic, their vehicle may have travelled several car lengths further down the road. Wildlife, another vehicle or a pedestrian could suddenly pop out in front of their vehicle and keeping their eyes on the road may expedite the driver's reaction.

Not all information is shown on the projected display. Usually vehicle speed, indicator use and main-beam indicators and sometimes audio selection are all that are displayed. Warning indicators will also light up if a vehicle problem develops. By keeping only commonly used and important information displayed, the driver's attention stays on the road (Kerr, 2002).

As an extension of the HUD systems currently used in America, the HUD systems are advancing to project Infra-Red (IR) images of the road onto military-style see-through displays in front of the driver (Stevens *et al.*, 1998).

These HUDs were originally developed to speed up the reactions of fighter pilots in combat. With one civilian version, the apparatus works by flipping a clear screen into the field of view of the driver when night falls. An IR camera takes images of the road ahead that are projected onto the screen. This moving image is superimposed onto that which the driver can see, making it possible to see warm objects, such as people, vehicles and animals, with greater contrast and outside the range of the headlamps, improving perception and accident avoidance when the light is poor.

The system uses a second set of filtered car headlights to illuminate the scene ahead of the vehicle with Near Infra-Red (NIR) radiation. A NIR sensitive digital CCD camera, mounted at the front of the vehicle, captures an image of the scene and exports the data to a digital signal processor which calculates the right exposure level for the camera and protects it from being saturated by oncoming headlights or street lights. The processed image is then sent to the HUD display module, which projects the image onto a partially reflective element in the windscreen. By this means, the driver sees a life-sized image of the warm objects superimposed on the real view through the windscreen. The HUD image is focused at a suitable distance in front of the vehicle so that, when the driver looks through the windscreen, both the NIR and normal forward view are at the same focal length. This system architecture will allow the inclusion of many other features in the future if desired, such as automatic hazard identification, navigational information, and instrumentation display, in an appropriate position.

The Cadillac DeVille, DHS and DTS were the first cars in the world to offer the technology of “Night Vision,” the Cadillac name for the HUD projected IR viewing system.

The following description is a summary of the Cadillac "Night Vision" system. It uses an IR camera, which is mounted on the centre of the vehicle's grill, to intercept the thermal radiation (or heat) given off by all objects. The energy is focused on and absorbed by an array of detector elements. The resulting image travels by cable and is projected in front of the driver's windshield onto an aspheric mirror that is part of the HUD mechanism on the dash of the car. Each detector element thus becomes a pixel in the video image, producing a monochromatic image that appears in far-off focus on the lower part of the windshield, showing hot objects as white while cooler objects appear black. As a result of the aspheric shape of the mirror, the curve of the windshield does not distort the image. The result is a windshield display of the road ahead that looks like a photographic negative. With the new technology, a driver can see about 450 metres in front of him, instead of 90 metres as with regular headlights (Simon, 1998).

6.2 Technology designed for use on new vehicles

Pop-up bonnet systems triggered by bumper contact are being developed by first tier suppliers and vehicle manufacturers. These systems will provide additional crush space by pushing the rear of the bonnet up before the pedestrian’s head strikes it. Ideally such systems would be reversible so that after activation they can be reset and be made operational once more at little or no cost. Both reversible and non-reversible actuators have already been developed to achieve the operational speeds necessary for them to be used with contact sensors. The systems currently being developed for near-term application are likely to use irreversible pyrotechnic activation to push the bonnet up. With these devices, although it may be possible to simply reset the pop-up mechanism, the activating components will need to be replaced and the costs could be significant.

One use for pop-up bonnet systems is to integrate them into an existing vehicle model design to minimise the amount of redesign and re-engineering work needed to achieve compliance. However, due to the high cost of such systems it is thought more likely that they will be reserved for vehicles where conventional energy absorption by deformation is more difficult, such as sports cars and model variants with large engines.

Such systems need time to trigger, push-up and arrest the bonnet and this must be completed before the pedestrian’s head makes contact. Both mathematical simulations and full-scale dummy tests can be used to show the time available for the system to operate. The time of head impact depends on both the impact speeds and dummy sizes.

Non-reversible actuators may be less costly and require less packaging space than some reversible systems. On the negative side, inadvertent deployment associated with non-reversible systems requires parts to be replaced; the reversible systems would only require resetting.

Future systems with pre-crash sensing will enable pre-impact triggering, so that slower reversible actuators can be used. It is thought that slower systems might be easier (less expensive) to reset and it is possible that they could reset themselves automatically minimising the consequence of inadvertent deployment.

In an impact with a pedestrian, a contact trigger system would detect the pedestrian by means of sensors mounted in the bumper. Intelligent systems can determine whether the impact is with a leg-type object and take actions on that decision. Those actions might be to raise the bonnet, should it be a pedestrian impact, or lock it shut to increase rigidity of the vehicle front end, should it be a vehicle to vehicle impact. Should the bonnet be deployed, then the bonnet would be raised rapidly at the rear, typically pivoting about the bonnet catch at the front. The principal benefit to pedestrians is that this creates space underneath the bonnet, so that when hit by the pedestrian's head the bonnet can deflect into this space without hindrance from hard under-bonnet components. As most cars would not be headform tested at the very front of the bonnet (the headform test area starts at 1000 mm wrap around distance) much of the test area would have large increases in crush space due to the pop-up action. The areas at the front with the smallest increases tend to be those that are less difficult to engineer with non-deploying systems.

Many methods for lifting the bonnet have already undergone review. One consideration for selection of a lifting system is that the vehicle needs to be restored to a driveable state after the firing of the active bonnet, particularly when the triggering may have been inappropriate or completely false. Springs and motors are attractive lifting mechanisms because of the relative ease of resetting them after an accident or false trigger incident. However, if they are relatively slow to deploy they could only be viable as part of an 'active' system (i.e. with pre-impact triggering). Therefore, most current development has been of systems that extend due to rapidly expanding gas.

Replacement costs may be significant if the bonnet must be replaced as well as the lifters after each triggering. To solve this, the bonnet needs to be rigid enough to perform as intended, be stable when activated - ready for impact, not fail under impact from a pedestrian torso and not deform unless contacted. Unfortunately, these requirements may conflict with the head impact protection of the bonnet when not 'popped up,' where to be less aggressive for pedestrian impacts it should deform and absorb the energy of the impact.

The effectiveness of active bonnet systems was documented by Fredriksson *et al.* (2001). In that study, a large European car was equipped with the head protection system. This car had been tested by Euro NCAP and had passed three out of six of the child headform test points and two out of six of the adult headform test points. An active bonnet was fitted to the vehicle, comprising two lifting elements which lifted the rear corners of the bonnet, which in turn consisted of compressed metal bellows that were filled with gas from micro gas generators in the event of an accident. When the adult headform test points were re-tested with the active bonnet in its raised position, all of the tests passed the performance criterion of having a HPC value of less than 1000. The highest active bonnet HPC was 778, compared with the standard bonnet values ranging from 877 to 7056. An additional test was performed on top of one of the lifters to investigate whether the mechanism had introduced any potentially injurious stiffness and resulted in a HPC value of 774.

Further tests were performed with a complete pedestrian dummy. The bonnet lifting devices were activated at approximately 30 ms after the impact and the bonnet was fully raised at 70 ms. The bonnet remained in a raised position until the head impacted the bonnet. This confirmed that the lifting mechanism could support the torso of a pedestrian for the required period as opposed to sinking before the head impact occurred. Headform tests alone would not have been able to provide this reassurance.

Depending on the size and shape of the bonnet it might also prevent or reduce the severity of contacts with the wing edge and windscreen base areas making the protection requirements less onerous in these areas. As a pop-up system lifts the bonnet clear of the support of wing edges and rear firewall a stronger bonnet can be used than in a non-deploying system.

A deployable protection system must be designed to work in all real-life accident situations and it is also important that it works reliably, throughout the life of the vehicle. Obviously a system that fails to detect a pedestrian accident, one that is still deploying when the pedestrian makes contact or one that fails to operate due to a malfunction will not be effective or will be less effective and, in some situations, it could exacerbate a pedestrian's injuries. These issues are discussed in Sections 7 and 8.

6.3 Technology under development

One of the fundamental issues with bumper trigger systems is fitting the time required for sensing that an impact is with a pedestrian, for triggering and then for deploying additional protection, into the limited time from first contact with the pedestrian to a potential head or torso impact. One solution to this issue would be to increase the time from the first detection of the (impending) impact to the time where the protection is required. A further benefit of pre-impact triggering is that extra protection could be provided before impact at the bumper and bonnet leading edge, by the use of airbags, as well as pop-up bonnets or airbags for the head. Therefore, further developments of deployable protection systems have led to consideration of pre-crash sensing.

For all of these systems, there would be a concern about their behaviour when an impact with a pedestrian is close to the corner of the vehicle. These concerns focus on failure to trigger or contact with the pedestrian during deployment, due to pedestrian kinematics not planned for in the contact sensors and algorithms.

6.3.1 Active protection

Pre-crash sensing will enable energy absorbing systems to be deployed before contact with the vehicle. Potentially these would enable deploying pedestrian protection to be provided at all the most dangerous pedestrian contact points on the car (bumper, bonnet leading edge, windscreen base, A-pillars, etc). These systems will be able to sample over a longer time than contact sensors and should therefore be better at discriminating real pedestrians and potential accident situations. Early warning of a potential accident contact would provide sufficient time for slower reversible deploying systems to be used. Reversible systems would reduce or eliminate repair costs if they are triggered unnecessarily; this would mean that systems that err on the side of always deploying in cases of doubt would be more acceptable.

Should the pre-crash sensing time be extended further, the possibility would then be realised for a system that can deploy in case of an accident but retract automatically should the deployment be incorrect or disadvantageous. This might also be the case for moveable bumpers and spoilers and possibly for the bonnet leading edge.

The potential protection for a pedestrian that could be offered by external airbags on the bumper and bonnet was evaluated in a preliminary investigation by Holding *et al.* (2001). They found that head injuries could be reduced by a factor of five, chest deceleration could be halved and lower limbs could also be protected by suitably designed, externally mounted airbags, as long as they are correctly damped. The advantages of using airbags for the vehicle manufacturer are also significant as they would not restrict styling to the same extent as body modifications. However, to fire such airbags effectively, the sensor system must be able to determine the size of a pedestrian and the likely points of contact throughout the trajectory.

One negative aspect of activating externally mounted airbags would be the cost of deployment. Following deployment of the airbags, the vehicle owner would need to replace the airbag modules and any burst-open covers. Additionally, they would also have to replace any vehicle panels that may have been deformed by the deployment. The vehicle will need to be repaired after activation necessitating the replacement of parts such as the airbags, bumper and bonnet. External airbag systems may be difficult to justify from a cost-benefit viewpoint unless false triggering rates and / or repair costs are very low.

Also, vehicle manufacturers may be reluctant to use such systems if the potential litigation makes them responsible for any injuries from deployment whether incorrect or correct. If an airbag could be deployed in such a way as to cause the driver to crash or if the airbag could be deployed and proven to have increased the injuries a pedestrian or vulnerable road user sustained, then the benefits of such systems may be negated. In effect, it will be extremely difficult to condone any protection system that could give rise to such issues, without developing for it a very reliable triggering system that could accurately discriminate the types of impact sufficiently well to avoid injurious deployments. However, pedestrian protection will be more difficult in some styles of vehicles such as sports cars; in this case use of these high-tech systems may be justified.

6.3.1.1 Pre-crash sensors

For a pre-crash sensor to be effective and able to avoid frequent false triggering, it needs to be able to recognise objects, separate the pedestrians and vulnerable road users from others and decide if they are going to be hit. This decision would need to cope with many factors including the vectors of the object under consideration and the car, changes in direction of the car and pedestrian and also where on the car the object will make contact.

7 Comparison of deploying and non-deploying passive protection

Car manufacturers and component suppliers were contacted requesting information on the methods proposed for use as passive and active measures for protection of vulnerable road users. A number of visits were also carried out in order to learn about the current technologies and to discuss problems encountered. Of the technologies discussed in the preceding section most came under the heading of active safety and worked by helping to prevent or reduce the severity of an accident. The only new passive protection measures found were pop-up bonnets.

7.1 Non-deploying passive systems

Designing a non-deploying passive safety system in a vehicle involves introducing pedestrian friendly design features. However, it is often difficult to incorporate such safety measures within the design parameters of the vehicle. It has been found that the current baseline for non-deploying systems is more or less the requirement of phase one of the Directive and one of the best available examples of passive non-deploying designs is the Honda Civic. This has already been extensively tested by Lawrence *et al.* as part of a previous project for the UK Department for Transport (Lawrence *et al.*, 2002). These tests have included headform tests using the 2.5 kg child headform at 40 km/h and headform tests using a 3.5 kg headform at 35 km/h. Possible alternative test methods for phase two were discussed in Section 3 and these included using a 3.5 kg headform. However, no results of tests to the Civic with a 3.5 kg headform at an impact speed of 40 km/h were available to the authors.. One of the more difficult design areas for manufacturers is the line between the bonnet and wing edge, and this is one of the main features of the pedestrian protection provided by the Civic. As part of this study three impact tests were therefore carried out to this area on the Honda Civic and these will serve to provide an estimate of the protection that could be provided and how feasible it may be to meet a HPC <1000 requirement in this area. To negate the influence of collateral damage a new bonnet, wing and wing supports were fitted before each test.

The tests were carried out using a child / small adult headform (3.5 kg) at 40 km/h (11.1 m/s). This headform was made by modifying an EEVC WG17 (1998) adult headform, but it complies with all of the requirements for the 3.5 kg headform as specified in phase one of the Directive, with the exception of the position of the accelerometer seismic masses. Although the positions of these masses were slightly outside the positional tolerances of phase one, the headform was aligned such that this caused no significant error.

In addition to these tests on the Civic, knowledge from Euro NCAP tests and manufacturers will be used to assess the potential level of passive non-deploying protection.

7.1.1 Results for the Honda Civic

The bonnet was impacted in three positions with the 3.5 kg headform at an impact speed of 40 km/h; the target locations were recorded relative to the rear and side of the bonnet and are given in Table 7.1. The points were chosen to be close to the points tested on the Civic by Lawrence *et al*. (2002).

The HPC values and impact velocities are also shown in Table 7.1. The acceleration time histories for the three impacts are shown in Figure 7.1.

The tests to the wing edge of the Honda Civic with the 3.5 kg child / small adult headform at 40 km/h provided a benchmark for what is feasible in this difficult area.

Table 7.1: Results from testing the Honda Civic with a 3.5 kg child / small adult headform at 40 km/h

Impact location	Position of target impact point: From rear corner of bonnet (mm)	Position of target impact point: From side of bonnet (mm)	HPC	Impact velocity (m/s)
Front	416	11	1523	11.17
Middle	270	20	1215	11.07
Back	51	23	1510	11.14

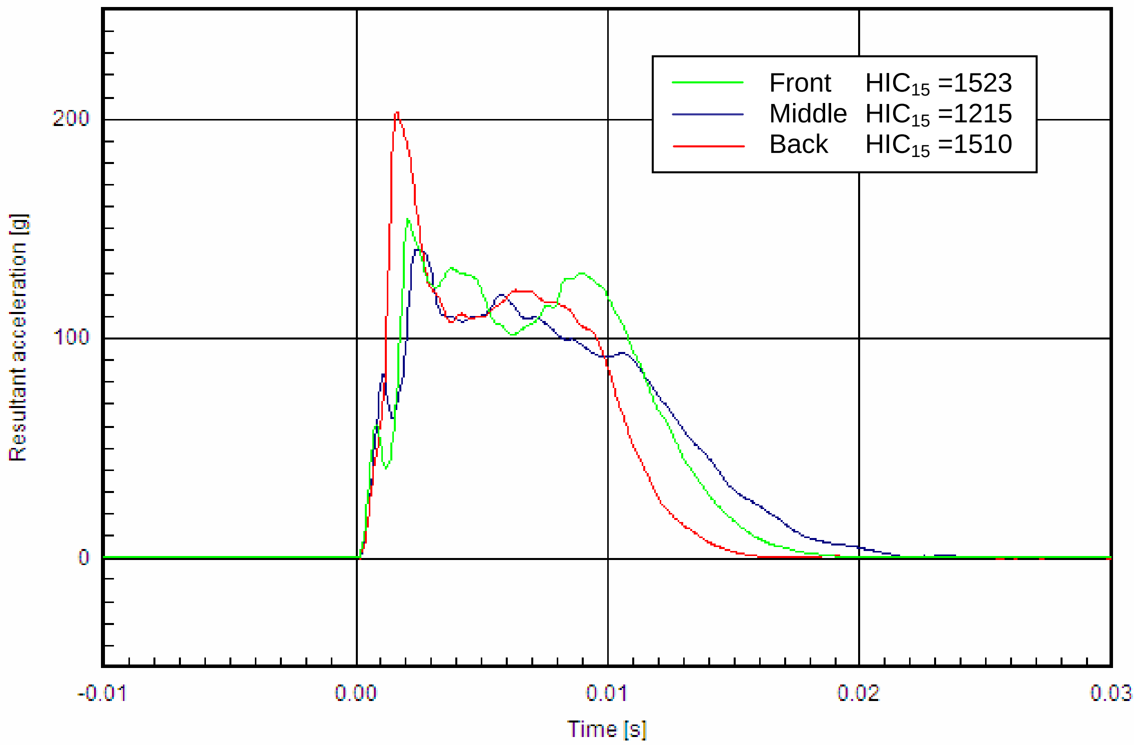


Figure 7.1. Resultant acceleration time histories for 3.5 kg child / small adult headform impacts to the front, middle and back of the bonnet / wing edge of the Honda Civic at 40 km/h

7.2 Deploying systems

Deploying systems are designed to detect an impact and trigger a protection system that moves into a different position before the pedestrian impacts that part of a car. This movement could be the inflation of an airbag or the upward movement of a bonnet. Initially it was intended to test a number of different deploying systems, provided by industry or their suppliers. However, in the event, only one pop-up bonnet system was provided for testing. The assessment of the system was conducted in four main areas:

- The trigger mechanism
- Examination and testing of the deployment for reliability
- The real-life fitness of the active device
- Impact testing of the device using the phase two test method and possible alternatives to it

Due to confidentiality restrictions, placed on the authors by the supplier, some of these areas are not discussed further in this report.

7.2.1 The trigger mechanism

The trigger mechanism should be assessed using a test that simulates the human property or properties to which the trigger system is sensitive. The first tier supplier has developed a sensor integrated into a bumper that will detect impacts to the bumper. An electronic control unit (ECU) would then process the signal from the bumper and other inputs (vehicle acceleration, vehicle speed), using a defined algorithm to determine whether the bonnet should be deployed. The sensor has been tested by the first tier supplier under a number of scenarios, including using the EEVC legform. However, this has a large diameter, heavy core with less weight in the simulated flesh (compared with a human).

7.2.1.1 TRL sensor legform

The sensor system used by the manufacturer concerned had a number of measures that together were used to detect a pedestrian contact. From examination of this system the authors concluded that to test this system thoroughly it was necessary to use a purpose made sensor legform and not just the Directive's legform impactor. At first it might appear that the Directive legform must be suitable for testing any trigger system, but in fact the test device must be adapted to match the properties measured by sensor technology, e.g. it would have to be the correct temperature for a heat sensor. In this case it was critical to produce a human-like force-time and force-distribution on the bumper face, throughout the contact. Therefore the authors decided to make a simple sensor legform to test the bumper sensor, with the aim of producing an input to the sensor system that was human-like.

The concept was to simply replicate the human leg in terms of mass distribution between flesh and bone, bone bending, knee deformation, flesh properties and flesh distribution. Drawings of the legform without the flesh are shown in Figures 7.2 and 7.3.

Particular attention was given to make the tibia human-like; however, due to time constraints within this study, it was not possible to match all human properties accurately. Two possible tibia options were considered, one using a nylon bar and the other using an aluminium tube; the final choice was the nylon bar. Simplified knee ligaments were made and the waist shape was adjusted iteratively to produce a bending moment of around 300 Nm at an angle of 15°. This stiffness is somewhat weaker than the requirement for the WG17 legform and was chosen because it is important for a sensor test device to represent a wider range of accident situations than the regulatory tool. This is because a worst case regulatory tool (heavy bumper impact) will require effective protection for better cases, but a trigger system must always trigger to protect the head even if the accident situation produces a light bumper impact e.g. a pedestrian hit from behind on the back of the knee.

The WG17 legform was designed with the metal skeletal structure all aligned along the axis of symmetry; however, this is not the case in a human as shown in Figure 7.4. Table 7.2 shows the leg geometry dimensions for the top, middle and bottom of the tibia. The flesh dimensions were supplied from data being used by a leg computer-modelling project at TRL. The tibia dimensions were obtained by direct measurement of a model skeleton. The tibia shaft at the top and middle is roughly kite shaped and it is more circular towards the bottom, but the sensor legform has a simple circular tibia of 30 mm diameter. The total tibia length is around 405 mm and the calf is fattest approximately a third of the way down from the top of the tibia. However, the sensor legform tibia copies the WG17 legform in being longer to include the foot (without a shoe) in the length of the lower leg. In the sensor legform, layers of Sorbothane have been used to replicate the flesh distribution around the tibia.

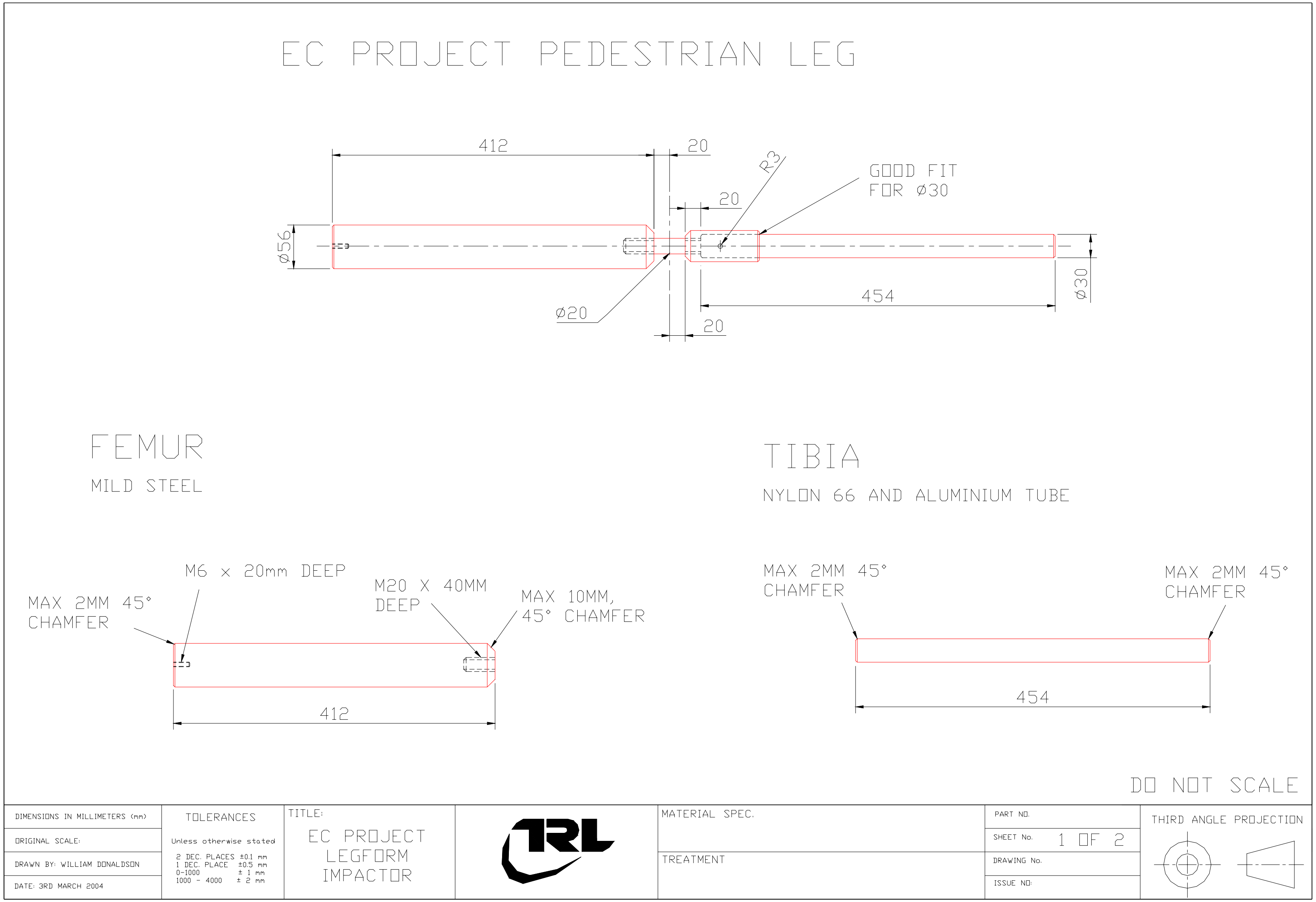


Figure 7.2. Sensor legform drawings – femur, tibia and assembly drawing of skeletal parts

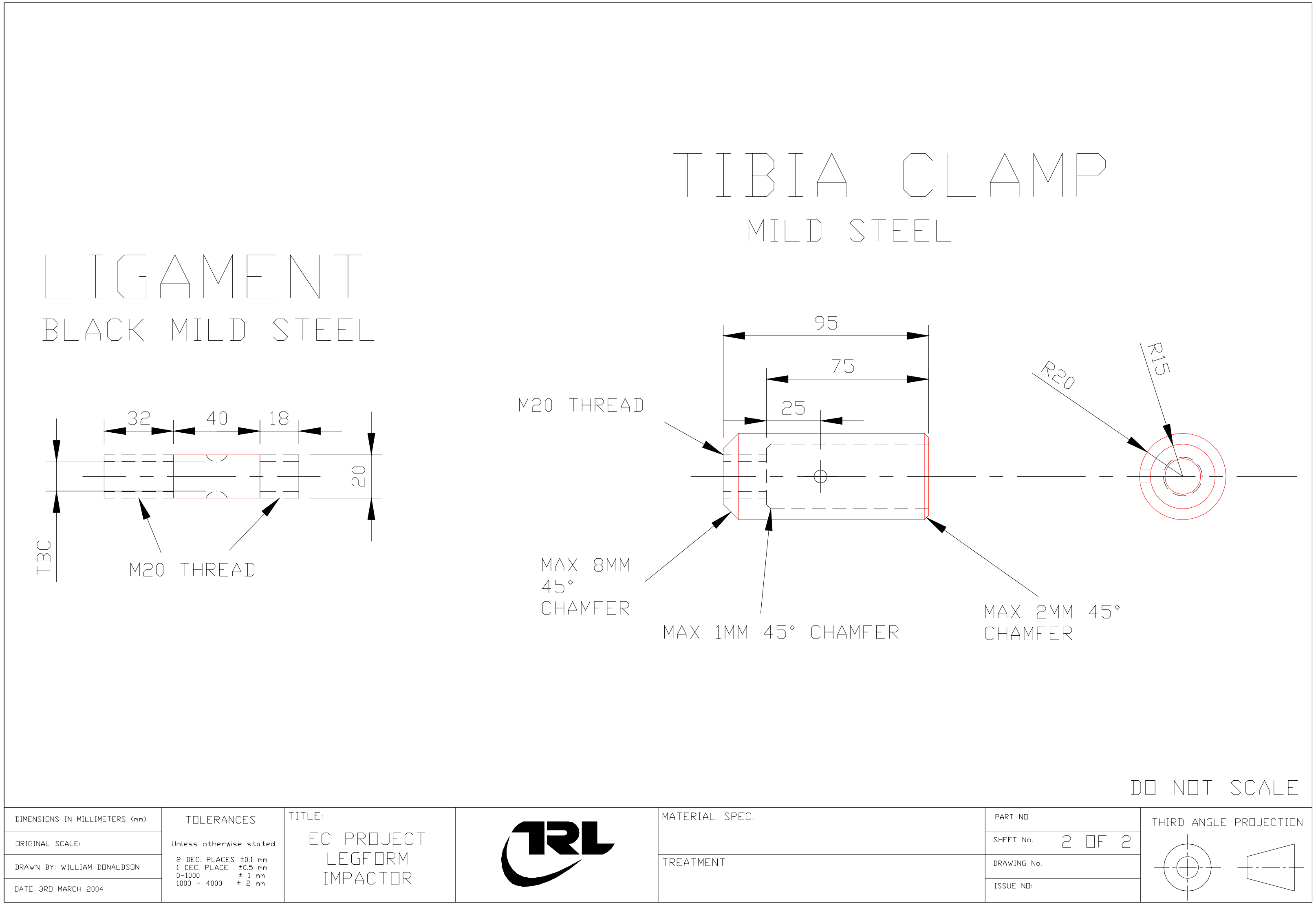


Figure 7.3. Sensor legform drawings – ligament and tibia clamp

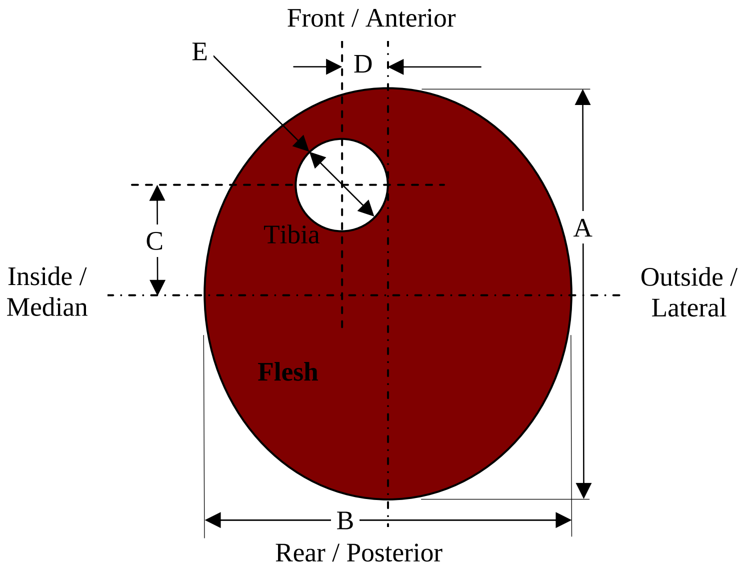


Figure 7.4. Typical cross-section of a human lower leg

Table 7.2: Typical (adult male 50th percentile) human lower leg dimensions

Dimension (see Figure 7.4)	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)#
Towards the of the tibia shaft	132	116	36	15	33½ x 22½
Middle of the tibia - where calf is fattest	134	121	35	15	28 x 17
Bottom of the tibia just above the ankle	82	67	21	11	21½ x 17½

The dimensions are fore / aft by lateral.

Sorbothane was chosen as it is of roughly similar density to flesh (it's denser than flesh but is much closer to flesh than the foam 'flesh' of the WG17 legform). A lower leg made using this has a much higher proportion of the mass in the 'flesh' and correspondingly less in the 'bone', compared with the WG17 legform. Sorbothane is a heavily damped material, as is human flesh, so it is preferable to alternatives with less damping. In this respect it is similar to the Confor foam of the WG17 legform, but the Confor foam has a low density. The sensor legform was placed inside a WG17 legform impactor skin, to secure the 'flesh' in place.

The nylon tibia has not been tapered to try to account for the variation in the tibia dimensions along its length, but was thought (using simplified calculations and material properties) to be roughly representative of the tibia in terms of bending. This means that the exact geometry of the leg described in Table 7.2 was not copied, but the mass distribution should be better than the WG17 legform impactor.

Figure 7.5 shows the design of the prototype sensor legform lower leg flesh. This shape was made using several layers of ¼ inch (6.35 mm) thick Sorbothane sheet, glued together using heavy-duty double-sided adhesive tape. For a production sensor legform it would be possible to have the Sorbothane moulded to the required shape, in one piece. This layout simulates a pedestrian's right leg; the top of the diagram would be a pedestrian's front. The sensor legform was used with the impact on the right side in the diagram.

The 'target outer' in Figure 7.5 was the desired outer profile based on the top and middle dimensions in Table 7.2. As the legform was to be finally clad in a WG17 impactor skin, the 'target inner' was the resulting inner surface of the skin, which would then roughly be the outer profile of the flesh in

Table 7.2. However, as the Sorbothane flesh is slightly heavier than human flesh, a revised ‘reduced inner’ profile was calculated to give the correct mass. The outer layers were gradually made shorter to approximately mimic the tapering of the lower leg flesh; only Layers 1 to 4 extend to the foot end. The equivalent inner profile for the ankle end dimensions in Table 7.2 is also shown in Figure 7.5, and this can be compared with the Layer 4 profile. Although the shape at this height doesn’t match particularly well, this was adequate in an area that shouldn’t be directly impacted and it also avoids unnecessary complication by keeping each layer rectangular. This arrangement was still too heavy so the outer and inner profiles were reduced slightly and the layers shaped to fit.

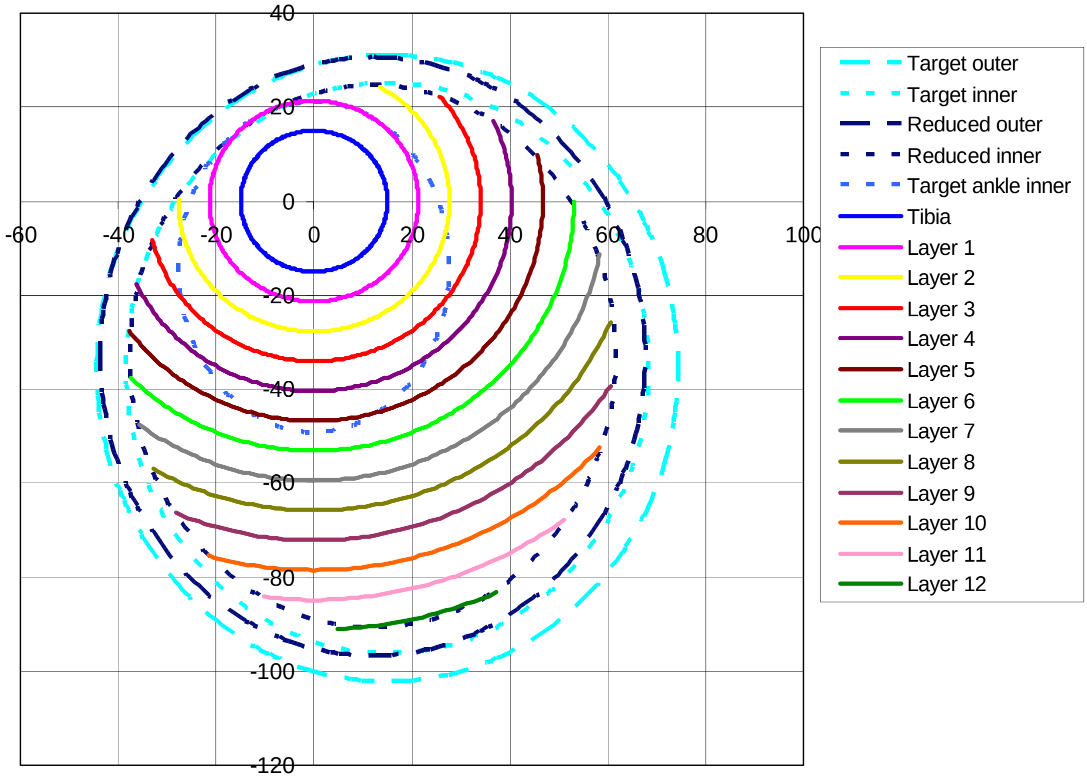


Figure 7.5. Lower leg flesh layout

As the femur section would not contact the bumper, much of the weight was concentrated in a simplified heavy steel femur section and three layers of lightweight Confor™ foam were used to roughly represent the femur flesh as shown in Figure 7.6. The strip of Sorbothane shown in the figure was used to adjust the assembled mass.

The flesh was finally secured in place using cable ties, as shown below in Figure 7.7. Figure 7.8 also shows how the legform (shown without the skin layer) compares to a human leg and it is easy to see that the shape and mass distribution are much better than that of the WG17 legform.

The two halves of the sensor legform are assembled by screwing the ligaments in place.

The aim of producing the prototype sensor legform was to test the bumper sensor with a more human-like device so that the results could be compared with tests using the Directive legform impactor. However, there was insufficient time within this project to develop the impactor to be a good representation of a human. Therefore, any difference seen in the results of tests with the legform impactors and the more human-like sensor legform only show the need for such a device and are not necessarily typical of results that would be ultimately found with a well-developed sensor legform.

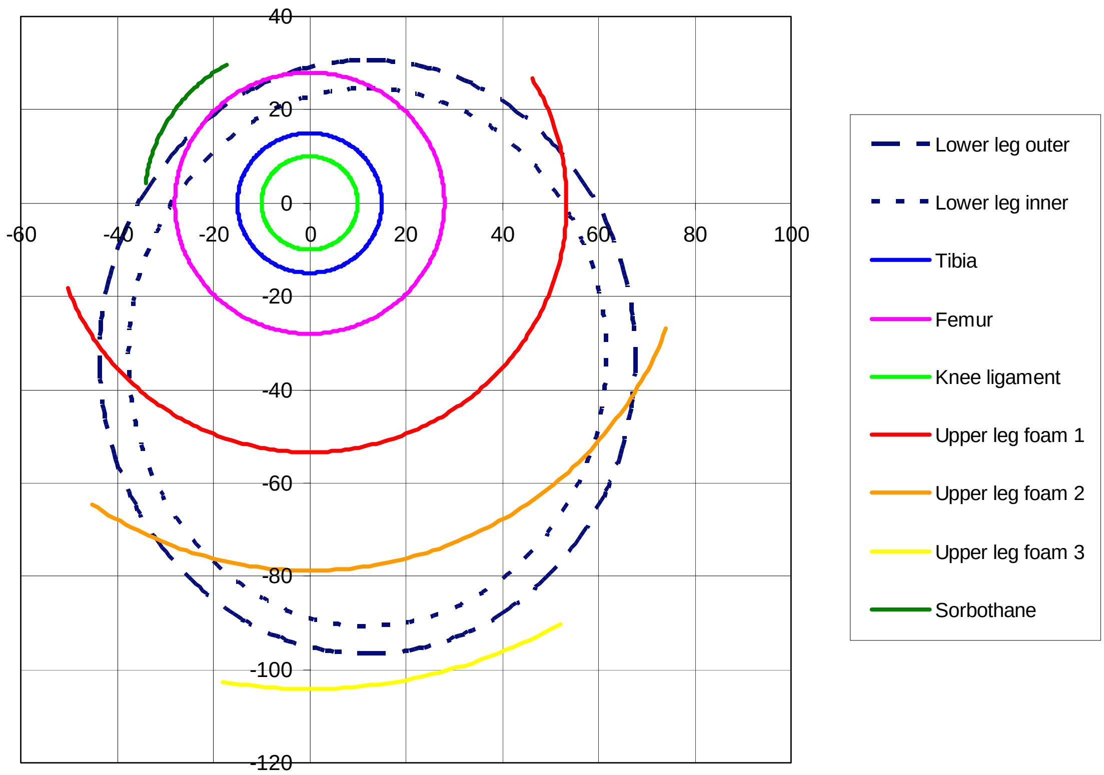


Figure 7.6. Upper leg flesh layout

Figure 7.7. Construction of the lower leg (skin removed)

Figure 7.8. Comparison of sensor legform (skin removed) with a human leg

7.2.1.2 Results of testing with the sensor legform

Due to the shape of the sensor leg it was feared that there might be problems with its release and that it might rotate during free flight. However, with padding positioned on the launcher to stabilise the leg during acceleration, it was found that a clean release and flight was achieved. The high-speed video showed that there was in fact very little rotation of the legform during flight and it impacted at the required height. Due to the flexible tibia, the lower leg deflected around the lower spoiler causing the femur to rotate into the bonnet, producing approximately 15° of bending to the knee ligament. Due to the 'soft' impact caused by the tibia and the resulting rotation, a significantly lower force was detected in the bumper sensor than with the WG17 legform.

This lower output could be significant in setting the trigger threshold. However it should be noted that the TRL sensor legform test device is a first prototype and needs further development and validation. Nevertheless even in its current state of development it may be better for evaluating contact type trigger systems than using current pedestrian dummies or the EEVC legform impactor. These results do suggest that the bumper trigger output from a human contact might be lower than those from the WG17 legform. A child version of the sensor legform might appear to be a worst case; however, to be realistic it would need to be closer to a complete dummy because the femur and upper body of a small child may also be involved in the impact, resulting in a greater force on the bumper sensor. It is not clear what the worst case is, so it will be necessary for the worst-case pedestrian stature and build situation to be found. In this case the loads detected in the bumper may be similar to those for small objects such as dogs or chickens and thus a 'no fire' situation may occur for a human, unless an appropriately low trigger threshold was used.

Figures 7.9 and 7.10 show pictures taken from the digital video of tests using the WG17 legform and the sensor legform. The pictures clearly show the sensor leg and flesh deflecting around the lower spoiler, unlike the WG17 legform.

Figure 7.9. Bumper test using WG17 legform

Figure 7.10. Bumper test using TRL sensor legform

The signals recorded by the bumper sensor in these tests with the sensor legform were processed by the manufacturer's algorithm, which showed that it would have deployed the pop-up bonnet. The purpose of the algorithm is ultimately to determine whether the contact is a pedestrian-like impact and if so to initiate deployment of the pop-up bonnet, provided the vehicle is travelling within the speed range for deployment. The algorithm has been tested by applying modified inputs to get extreme cases and provisional deployment limits have been set. However, it's not clear from the data provided to the authors that the sensor / trigger system will work as intended in all cases including pedal cyclists. The manufacturer's assumption is that failure to fire when needed is not acceptable but some unnecessary deployments will be acceptable provided the repair or re-setting cost can be kept relatively low.

The lower outputs seen with the sensor legform show that it is very important that any trigger system be tested with a test device that is appropriate for the sensor technology used. It is also clear that the trigger should be tested over a wide range of pedestrian statures and accident situations although this has not been explored in any detail here. Because of the need to develop suitable test devices in response to the sensor technology used, it is not thought possible to produce a suitable regulation to cover this issue. Instead a more general protocol could be produced and followed, with the results for each trigger system independently assessed. The sensor legform reported here is considered to be a good starting point for developing an impactor for a bumper contact switch / force type sensor system; however, it would need far more development before it could be used to approve such a trigger system.

Obviously a trigger system that fails to detect a pedestrian accident will result in the protection system not being effective. The tests reported above show that it is important to use an appropriate trigger test tool. It is also clear that any malfunction in the chain of components, connectors, etc. from the bumper face to the pop-up bonnet, could result in a failure to deploy or a deployment that takes too long. Therefore, the whole system must be very reliable over the whole life of the vehicle. System reliability is discussed in Section 8.

7.2.2 Examination and testing of the deployment mechanism

A first tier supplier supplied a mule vehicle fitted with a prototype pop-up bonnet system, to allow an evaluation of the deployment mechanism and its reliability. Five deployment tests were carried out.

The results for the five tests are shown below, in Table 7.3. There were three types of test carried out with the deploying system. Two tests were carried out with the lifters in the hinge, two more with the lifters under the bonnet reinforcement and one test with only one lifter under the bonnet reinforcement. A fully developed system for a rear-hinged bonnet would have the lifters in the hinge system, but with these prototype parts it was useful to test the lifter without restriction by the hinge. Each test was recorded on high-speed video and the approximate lift times were found by counting the frames from trigger to the bonnet being fully lifted.

Table 7.3 shows the lift time and the peak displacements for three different lift scenarios. The tests under the hinges do not reach 120 mm due to the hinges only having a total travel of around 110 mm. The hinges had a release system which when locked allowed the bonnet to open in the normal way but when released allowed the bonnet to pop-up. The hinges were still in the prototype stage but the release mechanism for the hinge was found to perform well and proved that the concept works.

Although only five tests were carried out, two lifters were used for each except the last test making a total of nine actuator firings. No failures to fire or problems during activation where found despite using prototype parts, which gives some indication of reliability.

Overall, it was concluded that the lifter deployed the bonnet as intended on the mule vehicle. However, to work in practice it would need further development and tailoring of the complete vehicle system including the bonnet, hinges and catch. This development would need to be carried out, in collaboration with the vehicle manufacturer, model by model. It is known that this type of collaboration is now taking place but the results are currently confidential.

7.2.3 Impact testing of the deployable system

A series of headform tests were also carried out on the same pop-up bonnet system and mule vehicle as used for the deployment tests. The test matrix was selected to provide information on the potential of the system in both the current phase two headform test and in a revised phase two test. Although the actuator was in the adult test area on the vehicle concerned, it was also tested with the 3.5 kg child headform to see how the system would perform if used in a smaller car where it would be within the child test area. The WG17 4.8 kg impactor was used instead of the proposed 4.5 kg impactor with the test velocity reduced to match the energy of a 4.5 kg impactor at 40 km/h.

Table 7.3: Lift times and peak displacements in pop-up deployment tests of bonnet

Test	Time to 120 mm displacement #			Peak displacement			Comments
	LH rear (ms)	CL rear (ms)	RH rear (ms)	LH rear (mm)	CL rear (mm)	RH rear (mm)	
ECP 08	25	28	25	111	127	110	Lifters under hinges
ECP 09	25	29	26	110	125	110	Lifters under hinges
ECP 15	28	33	28	123	135	122	Lifters under bonnet
ECP 16	28	32	27	124	136	124	Lifters under bonnet
ECP 17	n/a	n/a	n/a	109	101	102*	One lifter under bonnet (LH)

The maximum displacement for the hinge was approximately 110 mm and it then prevented further lifting, so the time for tests ECP08 and ECP09 are time to 110 mm displacement.

* Difficult to measure due to the twisting of the bonnet.

The tests were split into comparative tests of the pop-up bonnet in the two positions, deployed and closed (not deployed). The results provide comparison levels for the sub-assembly with and without deployable passive protection. The test buck had no engine, so results in the centre of the bonnet may represent the best case. Table 7.4 shows the test matrix and results.

Test results are also shown in Table 7.4 and clearly show the benefits of the deploying system. If the results for the non-deployed and the deployed tests are compared, the resulting HPC is reduced by over 50 percent by the pop-up bonnet. The tests were concentrated around the lifter as this is seen to be a problem area, however, overall improvement to the performance where there is insufficient clearance over the engine, suspension, wing edge and scuttle can also be expected.

Some resultant acceleration time histories are shown in Figures 7.11 and 7.12. In these two tests there was approximately 40 mm more deflection with the 4.8 kg headform compared to that of the 3.5 kg child / small adult headform. The size and mass of the impactor made a difference in the amount of deflection and thereby the HPC value obtained. The worst test with the deployed bonnet was with the 2.5 kg WG17 child headform (HPC 1576).

As the test buck was mounted on a frame with no wheels or suspension, the position for the most forward child headform test at a WAD of 1000 mm had to be estimated from a photograph of a similar car marked up for a Euro NCAP test. It is interesting to note that the point gave almost identical HPC results with the system deployed or not deployed. This may have been due to the fact that the impact point was directly over a reinforcement in the bonnet. Figure 7.13 below is a comparison of the time histories for the two impacts and it clearly shows that the impacts were nearly identical.

In many vehicles HPC values that exceed by a large margin the pass criterion of HPC 1000 are often due to the headform bottoming out on underlying objects. The lifted bonnet allows deformation of the bonnet to occur without the head impacting an underlying structure.

Table 7.4: Test matrix and results for deployable bonnet tests

Test	Position of bonnet	Headform type	Impact point	Impact velocity (m/s)	HPC
ECP11	Not deployed	Adult (4.8 kg at 4.5 kg impact energy)#	Above lifter	10.64	1517
ECP05	Not deployed	Child / small adult (3.5 kg)	Centre of bonnet close to WAD 1000	11.04	1164
ECP06	Not deployed	Child / small adult (3.5 kg)	Above Lifter	11.19	2125
ECP14	Deployed	Small child (2.5 kg)	Above lifter	11.06	1576
ECP02	Deployed	Child / small adult (3.5 kg)	Above lifter	11.04	926
ECP10	Deployed	Adult (4.8 kg at 4.5 kg impact energy #)	Above lifter	10.80	449
ECP03	Deployed	Adult (4.8 kg)	Above lifter	10.98	428
ECP04	Deployed	Child / small adult (3.5 kg)	Centre of bonnet close to WAD 1000	11.13	1163

Target velocity 10.7 m/s

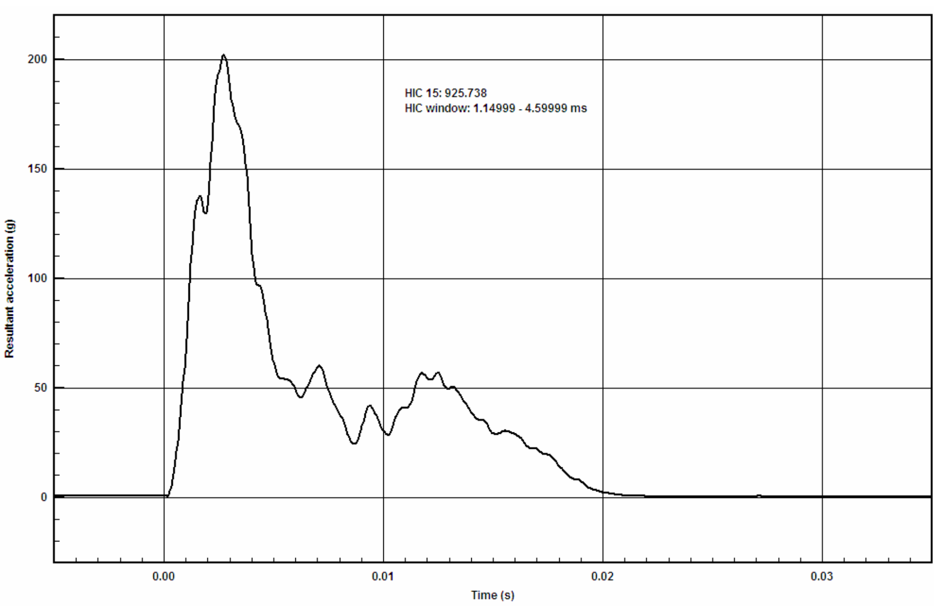


Figure 7.11. Test ECP02 - 3.5 kg child/small adult headform to bonnet above lifter

7.2.4 The real-life fitness of the deployable device

For any deployable system it is important that the device deploys as intended. At low speeds the deployable systems should not deploy even if it hits a pedestrian because there would be no significant benefit to the pedestrian in activating the system and the false triggering and repair costs would be unacceptable. In high-speed impacts there would be a risk that the bonnet would be still moving up at head contact, potentially increasing the risk of injury so in this case it again might be better not to deploy the system. However, testing may show that in high-speed impacts it is on balance safer to be hit by a still deploying bonnet rather than by one that has not been deployed, particularly when the bonnet is in the stabilisation phase rather than the main lift phase. Therefore the manufacturer will need to select a range of impact speeds where he wants the system to deploy. Below this speed he will have to build in sufficient crush depth in the non-deployed vehicle that the pedestrian's energy can be safely absorbed by conventional deformation. Therefore, the trigger system will need to be able to detect the impact velocity and determine whether deployment is necessary. In addition to responding to accident speed, both the trigger and the pop-up bonnet system will have to be shown to work safely over a wide range of accident situations including different pedestrian statures, postures and relative motion.

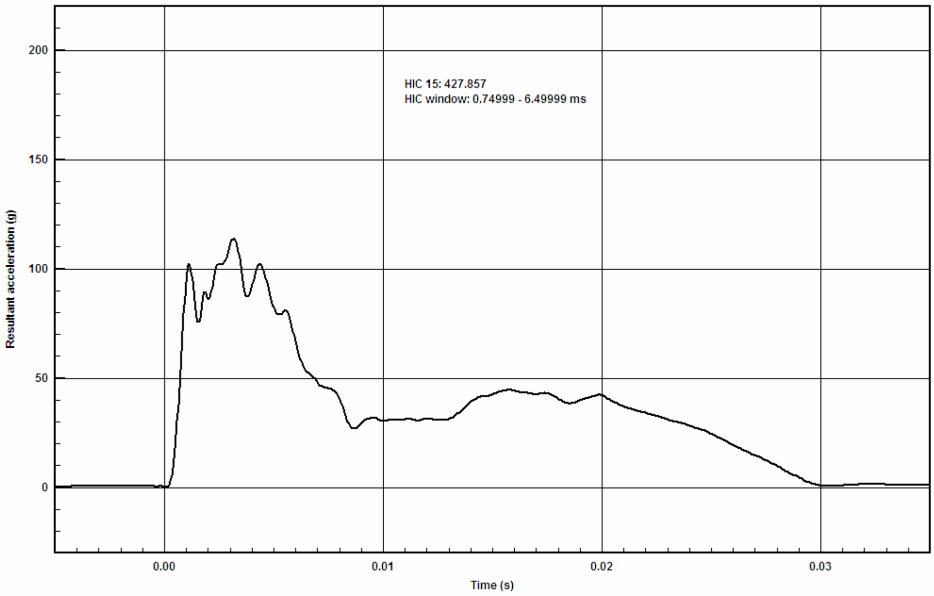


Figure 7.12. Test ECP03 – 4.8 kg adult headform to bonnet above lifter

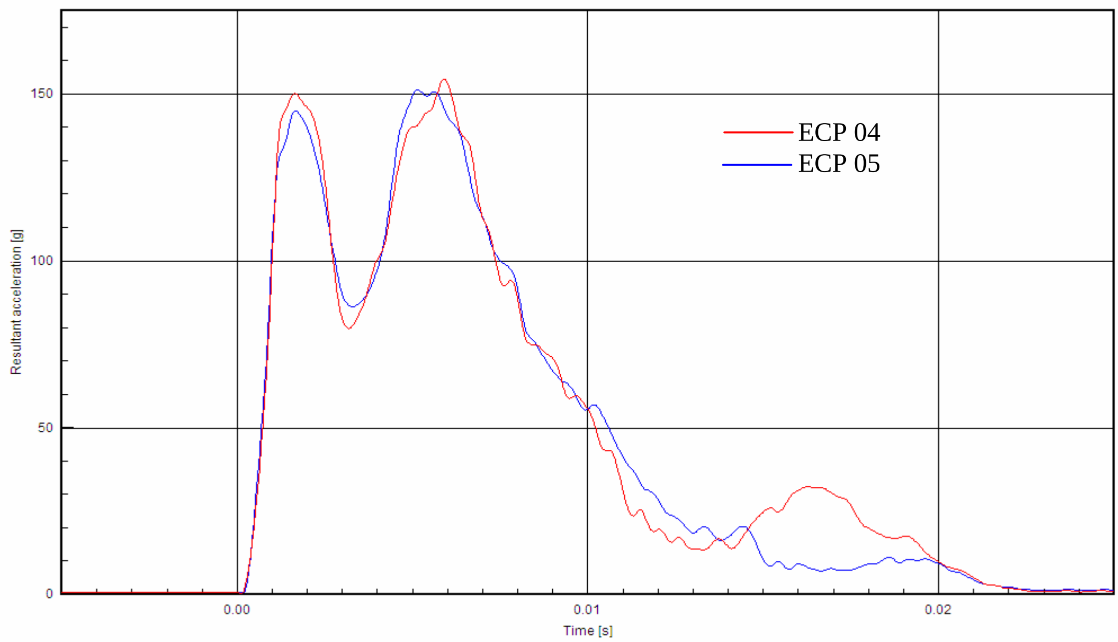


Figure 7.13. Tests ECP04 and ECP05 – 3.5 kg child / small adult headform to bonnet at same WAD distance with the bonnet not deployed and deployed

The manufacturer of a pop-up bonnet system under consideration, in addition to considering reliability and suitability of the trigger, has also carried out a combination of tests with pedestrian dummies, both real and by using mathematical simulation. There are a number of concerns for the heads of very tall adults or very small children due to pedestrians of these statures applying only a small force to the bumper in an impact. Further development is still required.

8 Review of reliability of new technologies (pop-up bonnets)

When struck by a car, pedestrians risk serious or fatal head injury. Research shows that the bonnet is a major source of these head injuries. This is because there are many stiff engine components beneath the bonnet, but very little space for the bonnet to deform and absorb energy. Traditional pedestrian protection in cars has comprised various means to increase the space beneath the bonnet and absorb some of the energy. However, this approach often leads to a conflict between protecting pedestrians and achieving desirable aerodynamics and styling at the front of the car.

In Section 6, a new approach was introduced, the deployable (pop-up) bonnet. This system provides additional space between the bonnet and the stiff components beneath by raising the rear of the bonnet before contact with the pedestrian's head.

The aim of this section is to provide a review of the reliability to be expected from this new technology. The popular definition of a reliable system is that it works as intended and remains trouble free for a long time. There are many techniques employed by reliability engineers to investigate a system or product. Typically, these techniques require detailed knowledge of the system, including in-service reliability data. In the case of the deployable bonnet system, this information was unavailable and hence to some extent a generic system has been described rather than a specific product. Nevertheless, in order to have a sufficiently detailed description one solution may be described whereas other solutions might use alternative technologies. Whilst any conclusions may therefore be tentative, the review was intended to uncover potential problems with the deployable bonnet.

The approach used to examine the reliability of generic deployable bonnet systems was:

- Define a general description of the system under consideration with a breakdown of the significant assemblies and components
- Analyse the operation of the system
- Identify the potential failure modes for the system and complete a fault tree analysis to examine the potential causes of the failure modes
- Complete a Failure Mode and Effects Analysis (FMEA) using engineering judgement to assign a risk priority number to each potential cause of failure
- Summarise the potential failure modes and their causes and make recommendations as appropriate

8.1 System functional description

8.1.1 General system definition

The deployable bonnet system considered here has three main features: a sensor assembly in the front bumper to detect the impact, a processing unit to decide whether to deploy and actuators to lift the bonnet. The bumper sensors feed information about the impacting object into an Electronic Control Unit (ECU), which uses a safety algorithm to decide whether or not to deploy the bonnet. The ECU also receives information from the car's speedometer and from an accelerometer. An overview of the complete system is shown in Figure 8.1.

8.1.2 Brief component functional description

8.1.2.1 Bumper sensor assembly

The assembly comprises different components. One component is a sensor used to determine the force applied to the bumper. An optional switch-type contact sensor, across the width of the bumper, provides the ECU with the first indication that an impact is taking place as well as the location of this impact. This sensor is divided into elements, each with a number of switches that give a signal when closed. The ECU can use these pieces of information to confirm the impact (reliability) and to adjust the decision according to the impact location.

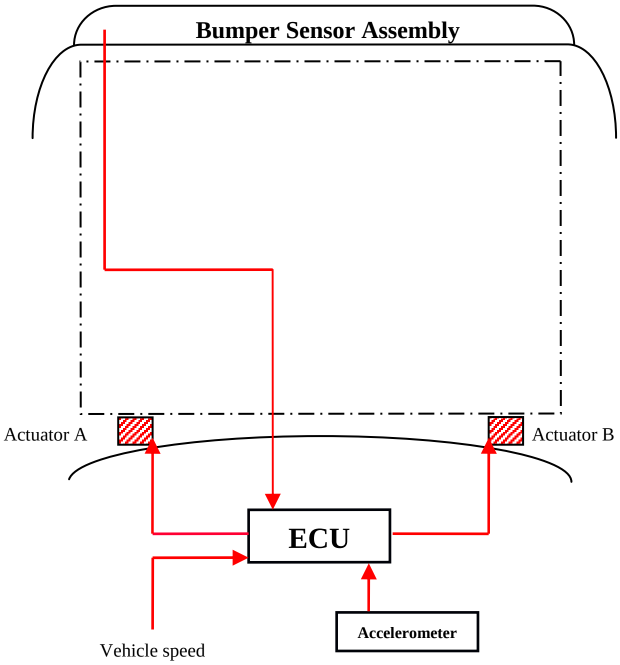


Figure 8.1. Deployable bonnet system overview

8.1.2.2 Electronic control unit (ECU)

The main function of the ECU is to control the deployable bonnet actuators but there may also be a performance-monitoring element. The safety algorithm takes data from the bumper sensor assembly, the car's speedometer and from an accelerometer, to decide whether to deploy the actuators. The ECU contains a number of electronic components, but for the purposes of this study it will be considered a single component. The term ECU system fault will be used to characterise the various failures possible within the ECU itself. It is very likely that the ECU will be a wider 'Crash ECU', managing all safety- related features such as air bags, anti-lock brakes, electric power-assisted steering and others.

8.1.2.3 Deployable bonnet actuator

There are two pyrotechnic actuators that raise the rear part of the bonnet in the event of a pedestrian accident. These devices function in a similar way to current pyrotechnic air bag inflators; when the car hits a pedestrian, a propellant is ignited producing a gas as it burns. In the system considered, the gas fills bellows that expand to raise the bonnet in time to provide a crush zone between the bonnet and the engine block. The bonnet is intended to be deployed before head contact occurs and remain in the raised position. Energy is absorbed by deflection of the bonnet and by deformation of the bellows. The actuators are tuned to resist deformation by upper torso loading in order to absorb maximum energy when head contact occurs. It is recognised that several other methods of raising the bonnet have been developed (see Section 6). However, for simplicity, this part of the study is focused on pyrotechnic bellows only.

8.1.2.4 Bonnet hinge release mechanism

The deployable bonnet system calls for dedicated bonnet hinges (in the case of front opening bonnets), which must allow the bonnet to open and close as normal, yet deploy in a pedestrian impact. These dedicated hinges would typically be developed in collaboration with the car manufacturer and may therefore vary from car to car. However, the component is likely to be based on conventional hinges with an extra hinge point that can be released by the action of the actuators and hence allow the bonnet to be raised.

8.1.2.5 Electrical connection

This refers to communication between the ECU and the actuators. Sensor cables from sensor to ECU were considered integral to the sensor.

8.2 Mode of operation

When the car strikes an object, sensors in the front bumper indicate that an impact has taken place. The operation of the deployable bonnet system can then be characterised by two distinct phases.

The first phase comprises the signal processing within the ECU where a safety algorithm decides whether or not to deploy the bonnet on the basis of a number of sensor inputs. For instance, the speed of the car must fall within a defined range. The low threshold prevents unnecessary deployments where the pedestrian is unlikely to receive serious injury. The high-speed threshold prevents deployments where the bonnet may still be rising when contact occurs. Secondly, the accelerometer measures the car’s deceleration and compares it with a deployment threshold. This serves to prevent deployment during impacts with solid objects and other vehicles. Thirdly, the bumper sensor assembly measures the extent of the force applied to the bumper. The ECU uses all these data to determine whether the object hit is a pedestrian. If all the conditions are met, the second phase of the operation begins (i.e. the ECU deploys the bonnet).

In the second phase, the propellant within each actuator is ignited by a signal from the ECU. The gas produced as the propellant burns fills the bellows, which start to expand. The action of the actuators releases a latch within the bonnet hinges and the bonnet is then raised. It is intended that a stable deployment is achieved before contact with the head of the pedestrian occurs.

8.3 Failure modes

A potential failure mode describes the way in which a product or process could fail to perform its desired function. In the case of the deployable bonnet system there are two functions. First, it is intended to raise (and hold) the bonnet when the car strikes a pedestrian. Secondly, it must absorb some of the energy from the impact between the pedestrian’s head and the bonnet, particularly when the head impact is above or close to the actuator. With these functions in mind, three potential failure modes of the system become apparent immediately:

- Failure to deploy when required (i.e. when the car strikes a pedestrian)
- Failure to absorb energy when deployed
- Deployment when not required

The first of these failures refers to a pedestrian impact in which the bonnet does not deploy, or deploys partially. In these circumstances, it is likely that the pedestrian would receive a more serious head injury, from the stiff engine components beneath the bonnet.

The second failure refers to a situation whereby the bonnet has deployed but it fails to provide adequate protection during the impact between the pedestrian and the car. This failure is also likely to result in a more serious head injury for the pedestrian.

Deployment when not required means that the bonnet has deployed in an impact with something other than a pedestrian, for instance, an animal or a roadside object. This represents a failure of the system to discriminate between a pedestrian and other impacting objects. Deployment when not required could also mean an inadvertent deployment when no impact has taken place. This could occur when the car is parked or, perhaps more seriously, when it is being driven. The repair costs and added inconvenience from an unnecessary deployment are likely to result in customer dissatisfaction. Furthermore, an inadvertent deployment, whilst the car is being driven, might distract the driver to such an extent that an accident is caused. This could lead to injury, with possible legal implications for the manufacturer.

Having identified failure modes (and their effects) for the deployable bonnet system, potential causes of the failures must be found. A cause is the means by which a particular aspect of the design results in a failure mode. The term ‘potential’ is used to indicate that causes do not automatically result in the failure mode. It is possible to imagine many potential causes for these three failure modes. Good design practice employed in the components of the system should prevent or minimise the frequency of some causes of failure. Nevertheless, it is useful to consider all the potential causes of failure that are possible within a system. A fault tree was therefore constructed to analyse the potential causes of failure for the deployable bonnet system. The fault tree, as shown at the end of Section 8 is in three parts, from Figure 8.2 to Figure 8.5. For each part, the top event is one of the failure modes that are identified above. The objective of the fault tree was to work downward from this undesired top event to determine credible ways in which it could occur, given the operating characteristics and environment of the deployable bonnet system.

The fault tree showed that many of the potential causes of failure were associated with a particular component in the system. These were typically hardware failures or human errors in the design process. The following sections summarise some of the potential causes identified for each of the system components.

8.3.1 Bumper sensor assembly

The potential causes of failure associated with the bumper sensor assembly were erratic sensor performance or a damaged sensor. Erratic performance can have several underlying causes, e.g. Electromagnetic Compatibility (EMC), Electromagnetic Interference (EMI), conditions such as temperature or dirt or a faulty electrical connection. A damaged sensor may be due to vibration, environmental conditions or voltage errors such as over voltage. It should be emphasised that faults in one sensor may not necessarily lead to a failure mode since the decision to deploy is based on a number of conditions that must be met.

8.3.2 Electronic control unit (ECU)

This section refers to the various faults possible within the ECU itself; the effects of external components on the ECU are discussed elsewhere. Faults in the ECU could result in either a failure of the bonnet to deploy when required (i.e. ECU fails to provide an electrical output to the actuators) or an unwanted deployment. The term ECU system fault was used to characterise these potential causes of failure. ECU system faults include ECU component failures, a Single Event Upset (created by radiation or build up of static charge) or a failure due to EMC or EMI.

8.3.3 Deployable bonnet actuator

There are a number of potential causes of failure associated with the bellows used to deploy the bonnet. Three main causes were identified, with a series of underlying causes for each.

- Damage prior to actuation
- Inadequate pyrotechnic output

- Ruptured bellows

The first of these could occur if the location of the actuators is not conducive to routine servicing, if there is a lack of consideration for tamper-proofing, if inadequate or improper mounting has led to damage during its normal life or if there was a lack of consideration for the environmental conditions at the component's location.

Inadequate pyrotechnic output could be a result of an unsuitable material chosen for the pyrotechnic charge, it could occur if the material has been affected by the environmental conditions or if the material has aged during its normal life.

Finally, the bellows might rupture if an unsuitable material was used, if there were flaws in the material, (such as voids which could cause actuation anomalies or failure) or if the material has ‘age-hardened’ during its normal life.

8.3.4 Bonnet hinge release mechanism

This component is fundamentally mechanical with no electrical interface. A fault would inhibit the operation of the actuators and could therefore result in a failure to deploy (or a partial deployment). The part could be physically damaged or jammed due to corrosion or the influence of an undetected foreign body. Alternatively, poor design specification could result in a mechanism that is too stiff to unlatch when the actuators deploy.

8.3.5 Electrical cable connection

Faults identified for cable connections refer to ECU to actuator connections. Sensor to ECU cables were considered integral to the sensor as a unit. There were several causes of failure associated with electrical cable connections. These were electrical faults such as a faulty termination or a short on a cable; alternatively, there could be a lack of consideration for tamper-proofing, inadequate or improper mounting of a cable that could lead to damage during its normal life or finally, the location of the cable may not be conducive to routine servicing.

8.3.6 Deployment algorithm

An additional category of potential causes of failure were identified by the fault tree analysis. These causes were not associated with a particular component of the system but instead, relate to the safety algorithm that decides whether to deploy the bonnet. The decision is based on a number of conditions that must be met for deployment to occur. These conditions are intended to distinguish a pedestrian from other impacting objects. It is therefore essential that the conditions and any thresholds are appropriate.

There are a wide variety of objects each with different geometry, mass and stiffness. A potential cause of failure is an unexpected accident scenario that the algorithm is unable to detect. An example might be a pedal cyclist, an adult with a pushchair or a traffic cone.

Another potential cause of failure is the use of pedestrian dummies and computer models to tune the deployment conditions and characteristics. Dynamic impact tests of the system will therefore depend on the ability of the dummy to reproduce the interaction between human and car. Since it is not possible to experiment with humans in this way, the behaviour of the pedestrian dummy is typically compared to a pedestrian mathematical model. While this model may be validated, it may not correspond exactly to a real person.

Finally, crash test dummies represent a standardised human anthropometry (size and shape). It is possible that an unusually proportioned pedestrian may display different kinematics when struck by a car, particularly in the timing and location of the head to bonnet contact.

8.4 Failure mode assessment

Each potential cause of failure was incorporated within a Failure Mode and Effects Analysis (FMEA) for the deployable bonnet system. The potential effects of each failure mode were rated on a scale of one to ten, where ten was the most severe consequence. This rating was called the Severity. The potential causes of failure were rated in terms of the chance of the cause occurring, also on a scale of one to ten, where ten was the greatest likelihood. This rating was called the Occurrence. The ability to detect the cause of failure prior to it occurring was also rated on a scale of one to ten, where ten was the least likely chance of detecting the failure. This rating was called the Detection. The severity, occurrence and detection ratings were multiplied together to obtain a risk priority number. The FMEA for the deployable bonnet system is shown at the end of Section 8 in Figure 8.6.

A subjective analysis based on engineering judgement was used to complete the FMEA. With this approach, potential causes of failure associated with the sensors and ECU achieved a low risk priority number. This reflects the 10-15 years experience in the automotive industry with advanced electronic systems, which suggests that their reliability is no worse than other well designed components. Hence the reliability of this aspect of the deployable bonnet is likely to be of the same order as existing systems employed in air bags or anti-lock brakes, assuming that proven design characteristics are used.

Areas of greater risk (as indicated by the risk priority number) concerned the actuators used to raise the bonnet and in the safety algorithm which decides whether to deploy or not. There are two critical aspects of the actuators that must be considered, the bellows and the pyrotechnic material. In the case of the bellows, the material requirements must be specified carefully so as to achieve the deployment profile and avoid failures associated with an inappropriate material. There must also be an evaluation of the manufacturing processes used to form the bellows since it follows that these processes could influence their performance. Equal consideration must be given to the pyrotechnic material, which is burnt to produce the gas needed to expand the bellows. An appropriate material and quantity must be found and it is important that its performance is not influenced greatly over time by the environmental conditions under the bonnet.

Regarding the safety algorithm, a number of potential problems were identified. The ECU ‘decides’ whether to deploy the bonnet based on a number of conditions that must be met. These deployment conditions comprise various sensor inputs concerning the impacting object and the car’s dynamics. Thresholds were set using computer modelling and dynamic impact tests. Clearly, the ability of the ECU to make this decision depends on the validity of the deployment conditions and thresholds. Since it is not possible to test the deployable bonnet system on real people, the reliability of the system therefore depends on the biofidelity of pedestrian dummies. It is therefore important that the manufacturers of the system have an understanding of the relationship between a dummy and a real person.

In any FMEA, the risk priority number is used to identify those potential causes of failure that require most attention. In a typical automotive FMEA, engineers may apply an acceptable limit to the risk priority number. For instance, one manufacturer reports that the number should be no greater than 100. With this in mind, the deployable bonnet system FMEA highlighted a number of areas of potential concern. However, it was not the intention to imply that the system displays potentially unacceptable reliability. Instead, since the analysis was subjective in nature, some potential causes of failure were given deliberately high occurrence and detection ratings in order to focus attention on them. These were typically components that reflect a new technology or new application of existing technology from the point of view of the manufacturer. It seems likely that manufacturers of the deployable bonnet system have had similar areas of concern and have already taken preventative or corrective action to ensure that the fully developed system will have acceptable reliability.

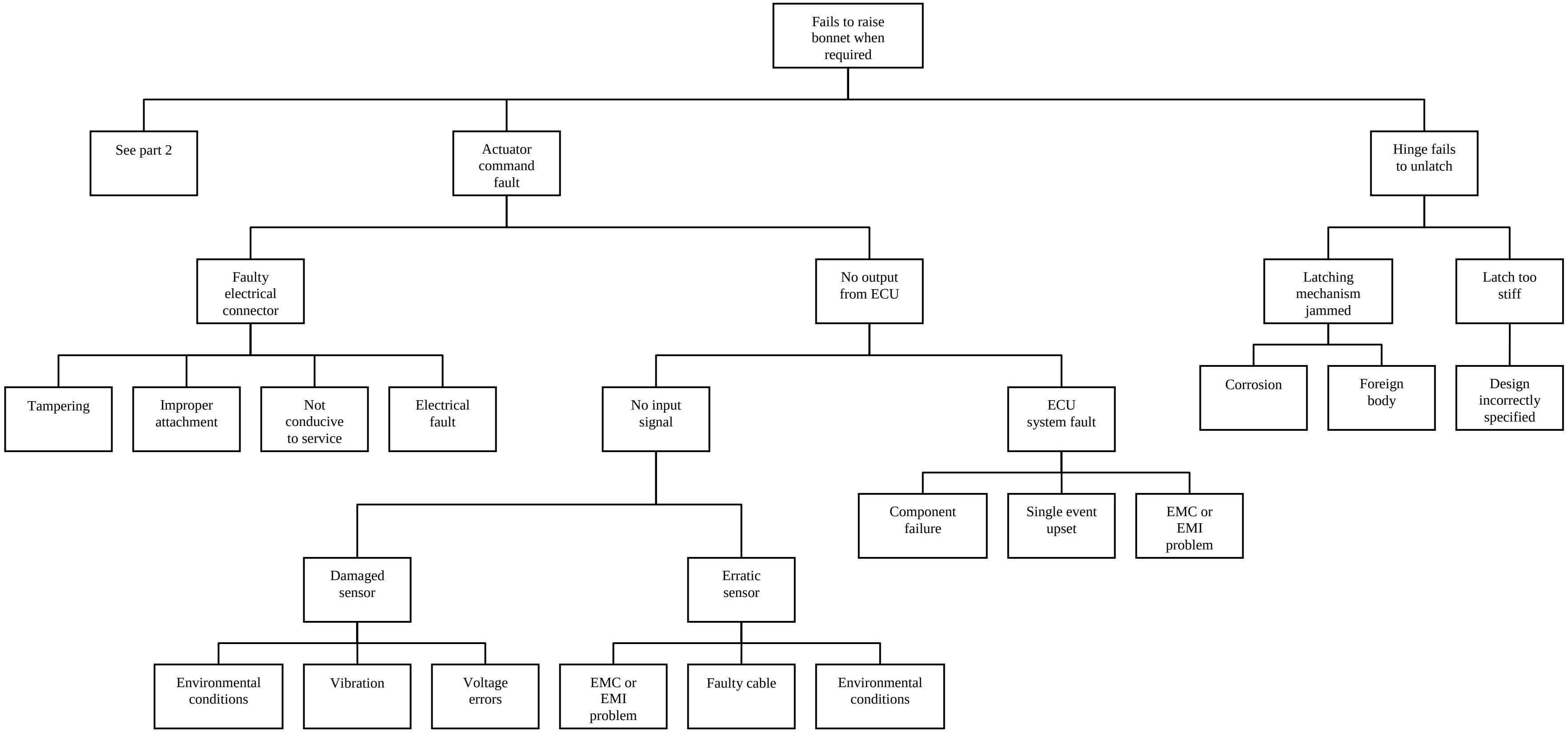


Figure 8.2. Fails to raise bonnet when required fault tree – part 1

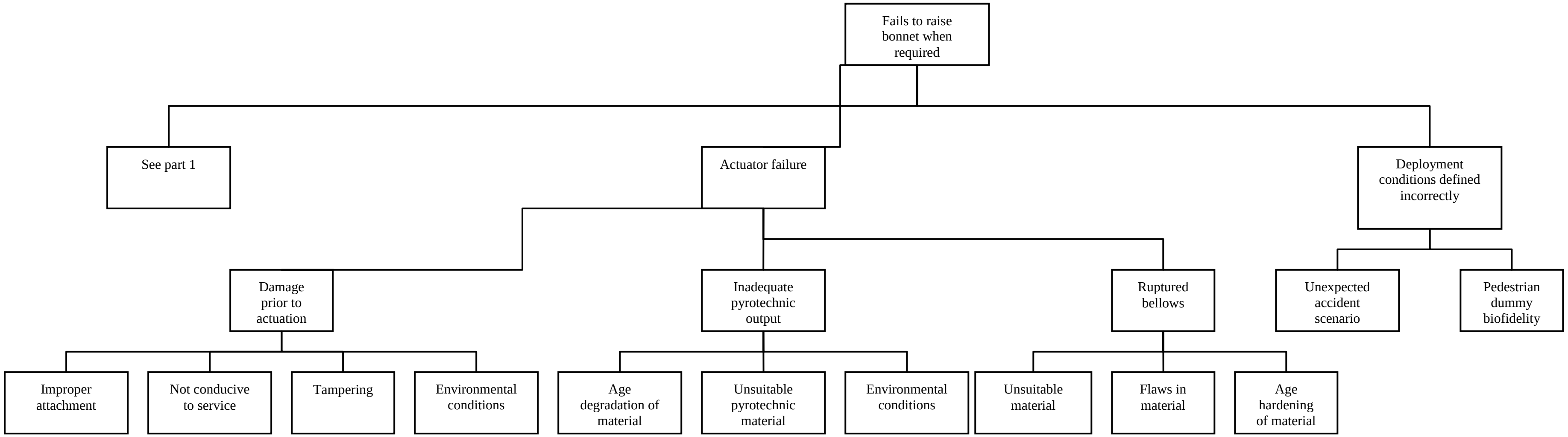


Figure 8.3. Fails to raise bonnet when required fault tree – part 2

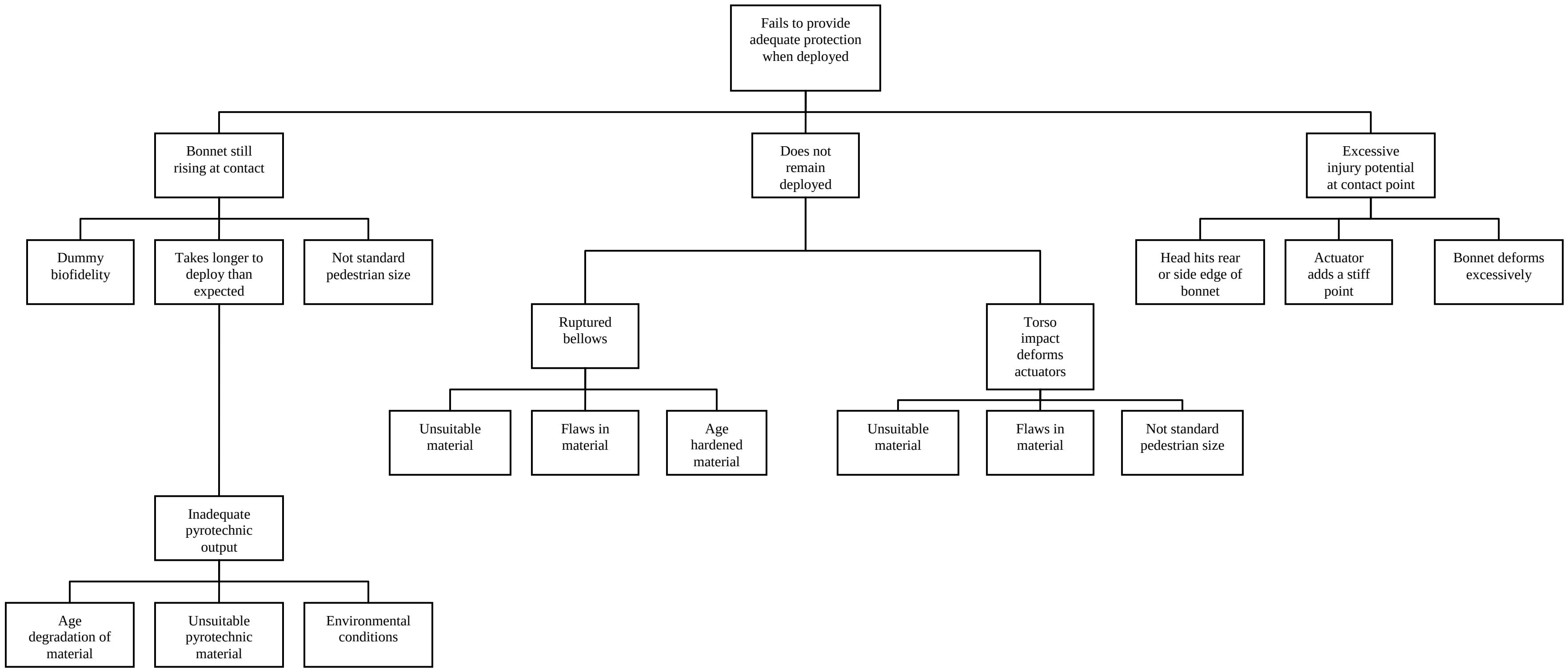


Figure 8.4. Fails to provide adequate protection when deployed fault tree

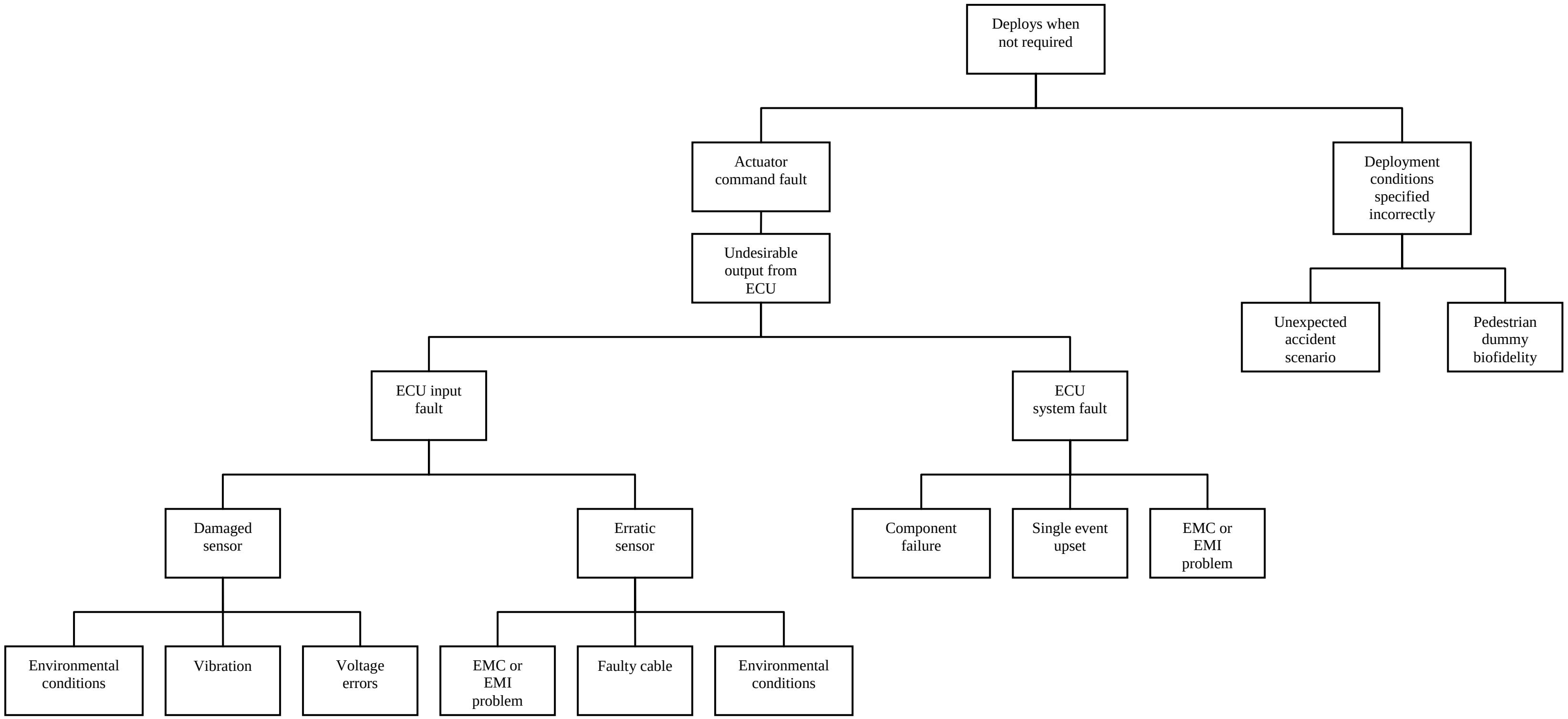


Figure 8.5. Deploys when not required fault tree

Potential Failure Mode	Potential Effect of Failure	Severity	Potential Cause of Failure	Occurrence	Detection	RPN
Fails to raise bonnet	**Increases injury severity to pedestrian**	**10**	**Damaged sensor**			
			Due to environmental conditions	1	1	10
			Due to vibration	1	1	10
			Due to voltage errors	2	1	20
			Erratic sensor			
			Due EMC or EMI problem	2	1	20
			Due to environmental conditions	1	1	10
			Due to faulty cable	2	1	20
			Loose or faulty electrical connection			
			Due to tampering	2	1	20
			Due to improper or inadequate attachment	2	1	20
			Due to location not conducive to routine servicing	2	1	20
			Due to electrical fault	1	1	10
			ECU system fault			
			Due to component failure	1	1	10
			Due to single event upset	1	1	10
			Due to EMC or EMI problem	2	1	20
			Ruptured bellows			
			Due to inappropriate material selection	8	5	400
			Due to flaws in material	6	5	300
			Due to age hardening of material	4	6	240
			Inadequate pyrotechnic output			
			Due to unsuitable propellant selection	3	2	60
			Due to propellant affected by environmental conditions	2	3	60
			Due to age degradation of propellant	2	3	60
			Actuator damage prior to deployment			
			Due to location not conducive to routine servicing	2	1	20
			Due to improper or inadequate attachment	2	2	40
			Due to tampering	2	2	40
			Due to environmental conditions	1	3	30
			Hinge latching mechanism is jammed or damaged			
			Due to corrosion	3	2	60
			Due to foreign body	1	3	30
			Due to inadequate design specification	2	2	40
			Deployment conditions incorrectly defined			
			Due to unexpected accident scenario	3	4	120
			Due to poor pedestrian dummy biofidelity	6	5	300
Fails to provide adequate protection when deployed	**Increases injury severity to pedestrian**	10	**Ruptured bellows**			
			Due to inappropriate material selection	8	5	400
			Due to flaws in material	6	5	300
			Due to age hardening of material	4	6	240
			Torso impact deforms actuators			
			Due to unsuitable material	8	5	400
			Due to flaws in material	6	5	300
			Due to unexpected pedestrian size	7	4	280
			Excessive injury potential at contact point			
			Pedestrian's head hits rear or side edge of the bonnet	4	5	200
			Actuator is a stiff point (i.e. if poorly designed)	2	2	40
			Due to excessive bonnet deformation	2	2	40
			Bonnet still rising at contact			
			Due to poor pedestrian dummy biofidelity	6	5	300
			Due to unexpected pedestrian size	4	5	200
			Inadequate pyrotechnic output			
			Due to unsuitable propellant selection	3	2	60
			Due to propellant affected by environmental conditions	2	3	60
			Due to age degradation of propellant	2	3	60
Deploys when not required	**Dissatisfied customer**	8	**Damaged sensor**			
			Due to environmental conditions	1	1	8
			Due to vibration	1	1	8
			Due to voltage errors	2	1	16
			Erratic sensor			
			Due EMC or EMI problem	2	1	16
			Due to environmental conditions	1	1	8
			Due to faulty cable	2	1	16
			ECU system fault			
			Due to component failure	1	1	8
			Due to single event upset	1	1	8
			Due to EMC or EMI problem	2	1	16
			Deployment conditions incorrectly defined			
			Due to unexpected accident scenario	3	4	96
			Due to poor pedestrian dummy biofidelity	6	5	240

Figure 8.6. Deployable bonnet system FMEA

9 Brake assist systems

9.1 The problem

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. This problem can be broadly divided into two:

- Drivers that never apply sufficient force to reach maximum braking during an emergency
- The time taken to reach maximum braking

Perron *et al.* (2001) carried out experiments where ordinary drivers were asked to follow a vehicle that towed a trailer. To simulate an emergency braking event the trailer was released and braked at 7 m/s^2. It was found that only 20 percent of drivers who braked but did not swerve managed to avoid a collision, 50 percent of all drivers did not brake sufficiently hard to activate the ABS at any point and for 85 percent of drivers there was a substantial delay before maximum braking was achieved. Similar results were noted by Hara *et al.* (1998) in tests where the emergency was simulated by unexpectedly throwing an object in front of the vehicle from the side of the road. It could be argued that this type of test more closely simulates a driver's reaction to a pedestrian stepping into the road. Hara *et al.* (1998) also noted that the pedal force applied by drivers that failed to activate the ABS was less than a third of those that did and that in the case of the latter there was a tendency to reduce the force on the pedal during the course of the braking operation.

McCarthy *et al.* (2004) carried out a study with ordinary drivers in a driving simulator that was specifically investigating pedestrian collisions. They also found that braking was the most common avoidance strategy and that the brake force applied by different drivers was highly variable.

All of the research noted that there was scope for adaptation of the brake system to improve the actual braking performance that real drivers achieved in emergency braking applications.

9.2 The basic solution

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. Again, the performance of the system can be divided into two parts:

- How the intention of an emergency brake application can be detected
- What action is taken when an emergency brake application is detected?

9.2.1 Detection of emergency brake application

The same research that had identified deficiencies in the braking behaviour of typical drivers was also used to determine the factors that characterised emergency braking. Hara *et al.* (1998) found that there was a significant difference in the initial pedal travel speed between 'normal' and 'emergency' situations and also that the initial pedal travel speed was the same for drivers who reached full pedal force and ABS braking and those who did not. This was supported by Perron *et al.* (2001), who produced the graph of driver behaviour shown in Figure 9.1, below.

Fenaux (2003) also used the data shown in Figure 9.1 and reported that only 5 percent of emergency brake applications occurred with a pedal speed less than 300 mm/s and that 95 percent of normal brake applications were at a speed of less than 300 mm/s such that pedal application speed characterised emergency braking very well.

Based on these findings it is possible to say that a BAS triggered on pedal speed with a threshold of 300 mm/s will offer benefits to 95 percent of drivers in emergency situations. However, for 5 percent of drivers it may interfere during normal driving, allowing the possibility that the system could be a contributory cause of collisions to the rear of the equipped car.

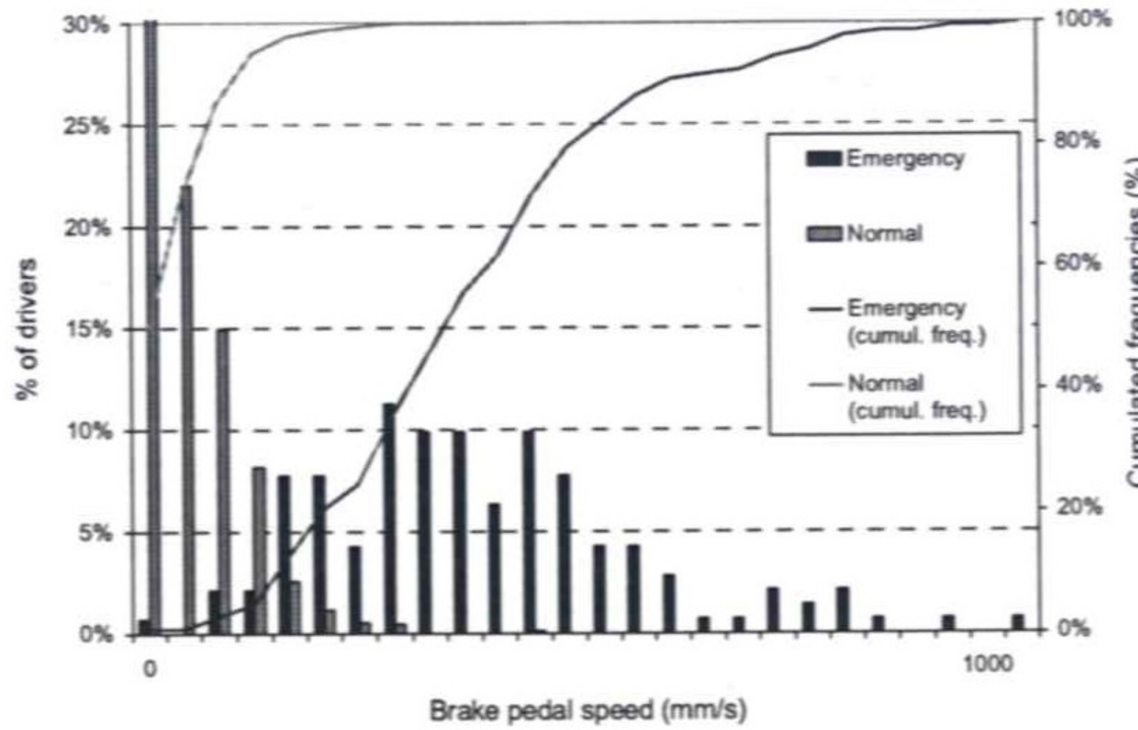


Figure 9.1. Driver braking reaction (copied from Perron *et al.*, 2001)

Hara *et al.* (1998) also noted that despite the significant difference in initial pedal speed between emergency and normal brake applications, there was an overlap where the emergency behaviour of some drivers was similar to the normal behaviour of others. They concluded that emergency braking could not be detected adequately by pedal speed alone but that combining pedal speed and pedal stroke (distance that the pedal is depressed, which is strongly related to pedal force) could provide an adequate detection system. Perron *et al.* (2001) also acknowledged that due to significant overlap between normal and emergency braking behaviour, single parameters could not detect all emergency actions without ever activating assistance unnecessarily in normal driving conditions. They found that combining the data obtained in their track experiments (as shown in Figure 9.1) with measurements of normal behaviour from trials on the public road showed that the combination of different parameters could significantly enhance the detection of emergency braking, but at the time this research was still at an early stage. It should be noted that none of the research papers studied suggested the use of pedal stroke, pedal force, or hydraulic pressure as a solitary detection criterion.

Although the research discussed the driver behaviour that characterised emergency braking and the relative merits of different approaches, none of the papers studied specifically stated what criteria would actually be installed in any particular production car.

In order to try to identify the methods employed in different manufacturers' vehicles an internet search was carried out. Information was reviewed for Bosch, TRW, Continental, Mercedes, BMW, Nissan, Renault, Peugeot, VW, Audi, and Mazda. In some cases the methods used to detect an emergency were not stated but in most of those where it was specifically defined the method used was brake pedal application speed (Bosch, Continental, Jaguar, Mercedes, BMW, Renault). However, there were manufacturers that were using different criteria. Mazda (www.Mazdausa.com) described a system that read *"brake pedal depression speed and force"* to detect an emergency brake application. Mitsubishi (www.mitsubishi-motors.com) stated that their system was activated when a force threshold was exceeded and showed the graph of system characteristics that is reproduced in Figure 9.2.

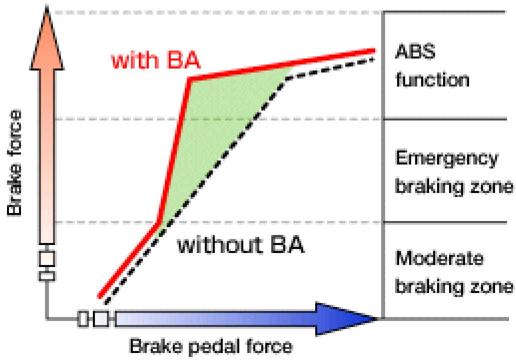


Figure 9.2. Mitsubishi BAS characteristics (www.mitsubishi-motors.com)

Nissan also stated that their system was activated based on a pedal force threshold. It was also noted that Mercedes training material (Mercedes-Benz, 2004) stated that the BAS system was disabled at speeds lower than 5 mile/h.

9.2.2 Brake system action in the event of an emergency

Once an emergency situation is detected the basic premise of improving performance will be to increase the braking over and above what the driver has demanded. However, it is possible to conceive of different ways in which this could be achieved:

- Increase the braking in proportion to the driver demand
- Increase the braking to maximum (invoke ABS)

Once the initial boosting of the brake has been achieved there are then different possibilities for controlling the braking during the stop:

- Modulate the assistance in strict proportion to the drivers input (i.e. if the driver backs off the pedal slightly, the system reduces braking by the same amount)
- Maintain the assisted level of braking throughout the stop or until full pedal release
- Modified modulation, which could fall somewhere between the previous two such that minor unintentional variations are ignored but more significant driver releases are emulated by the system to reflect the fact that the vehicle may be braking too hard

Hara *et al.* (1998) studied two control concepts once an emergency had been detected:

- Application of the maximum braking force whenever an emergency brake application is detected
- After assistance in adding a certain braking force has been provided, the braking force is controlled to reflect the drivers intention

They noted that the full application of brakes would be of most benefit to drivers who did not apply sufficient braking effort but that those who did apply the brakes correctly would dislike the system because control of the level of brake force had been taken away. The report stated that to generate an acceptable system the range for detection of emergency braking would have to be very limited, which would significantly compromise the advantage of the system. However, they considered that in the second concept, the detection of an emergency would not be limited unnecessarily and there would, therefore, be a benefit to a greater number of drivers. The authors concluded that the system should be developed according to the second concept such that assisted braking is in proportion to driver demand rather than a full ABS activation.

The BAS operation described by Hara *et al.* (1998) is shown in Figure 9.3.

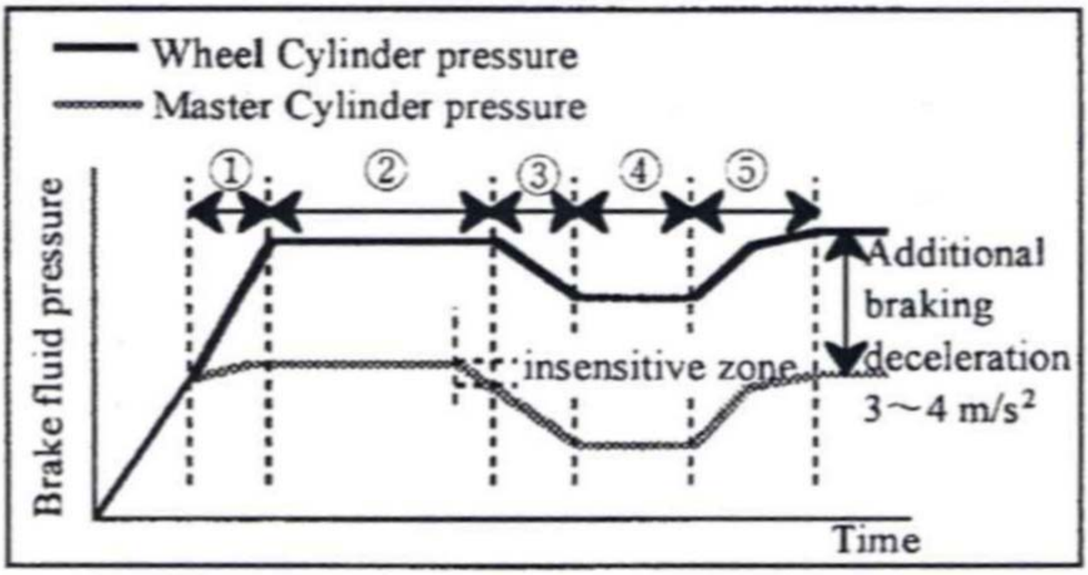


Figure 9.3. BAS pressure control during emergency braking (copied from Hara *et al.*, 1998)

One addition that was made to the concept was that there should be a zone that was insensitive to change. This was because their research had found that some inexperienced drivers slowly reduced pedal force during an emergency brake application. In this way the effect on the actual braking of slow reductions in pedal force is minimised.

This research also highlighted another parameter critical to the effectiveness of this type of BAS, which was the timing of the intervention as shown in Figure 9.4.

It can be seen from Figure 9.4 that in the concept of BAS discussed by Hara *et al*. (1998) if the intervention is triggered too early then the ultimate advantage will be less but if it is triggered too late the driver will brake and then feel an unexpected step increase in braking a short time later.

Perron *et al.* (2001) also considered how a brake assist system should behave in the control phase during the stop. They made no comment with respect to whether the assistance should be a boost in pressure or a full application of ABS braking. However, they noted that in their track trials with ordinary drivers, who were asked to avoid a heavily braked vehicle ahead, that all drivers braked to some extent as part of their collision avoidance strategy. However, 50 percent of the drivers also tried to swerve around the obstacle. Eighty five percent of those drivers who swerved were successful in avoiding a collision compared with only 20 percent of those that braked without swerving. Although it could be argued that swerving may be less successful in a real road environment compared with a test track because of the risk of collision with oncoming traffic or roadside furniture, this research does suggest there are significant benefits to swerving.

The test results (Perron *et al.*, 2001) also showed that all drivers that swerved partially released the brake during the swerve, which, according to the authors, had the effect of increasing the lateral grip available to help steer. Perron *et al.* (2001) concluded that, once activated, an emergency brake assist should keep the driver in the loop such that he can end full braking (ABS) control with only a partial release of the pedal, thus helping in swerving situations.

Again, the research papers studied did not specifically refer to the characteristics of any system fitted to any production cars so a search of manufacturers' promotional literature was carried out to try to identify the characteristics of current systems. Bosch (www.bosch.co.jp) describes two variants of the system:

- A mechanical BAS, termed Emergency valve assist, which increases the effect of the existing brake booster such that the force which the driver must apply to the pedal is reduced
- An electronic-hydraulic BAS, termed pressure boost control, which uses ESP hardware to control braking to the maximum level

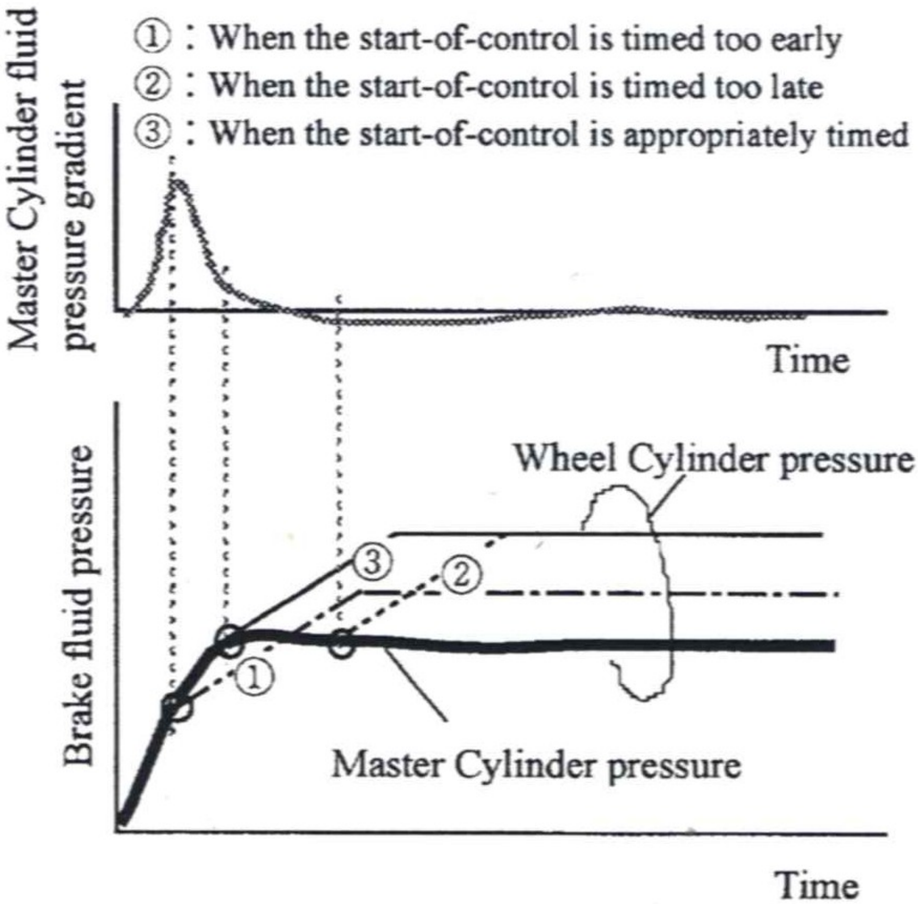


Figure 9.4. Brake pressures in relation to different start of control timing (copied from Hara *et al.*, 1998)

TRW, Continental, Mazda, BMW, Jaguar and Renault web sites all describe systems that apply maximum ABS braking once an emergency is detected. A magazine article (Automotive Engineer, 2005) refers to Mercedes' brake assist system applying full ABS braking in response to an emergency. Mercedes' training literature (Mercedes-Benz, 2004) refers to the system applying maximum boost pressure in the existing brake booster. In this second case it is not clear whether applying maximum boost pressure will be sufficient to invoke ABS braking or whether it will simply amplify the driver's braking by a fixed proportion.

Mitsubishi describe a system that simply boosts the brake pressure proportionally over and above the demand of the driver (see Figure 9.2).

Much of the information on manufacturers' web sites is not technically detailed. For example, Toyota describes the system as supplementing the brake force applied by the driver to slow the vehicle automatically in a controlled fashion. In these cases it is not clear from the published information whether the brake force of the driver is boosted by a fixed proportion or whether full ABS braking is invoked.

Further details of the systems in use on current vehicles were rarely available. However, Renault's safety data sheet nine (www.renault.com) states that BAS applies full ABS braking and that this is maintained until *"the driver has largely slackened pressure on the brake pedal"*. Similarly, Mazda state that full ABS braking is applied and maintained until the pedal is *"decidedly released"*.

9.3 Physical assessment of the benefits of brake assist

Hara *et al.* (1998) carried out tests of the BAS that they had developed. The change in the pedal force deceleration relationship and the change in stopping distance are shown in Figures 9.5 and 9.6.

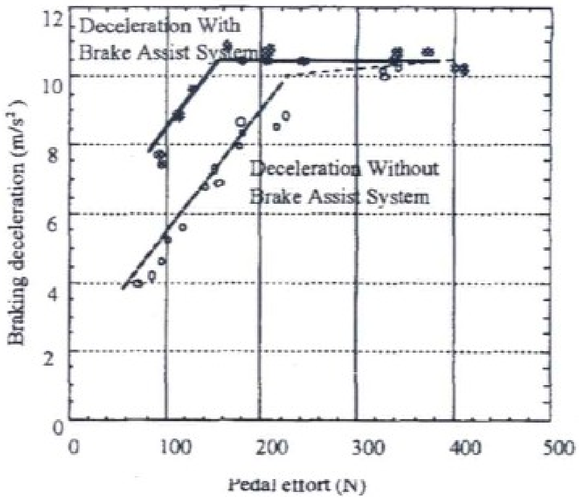


Figure 9.5. Pedal force deceleration characteristics

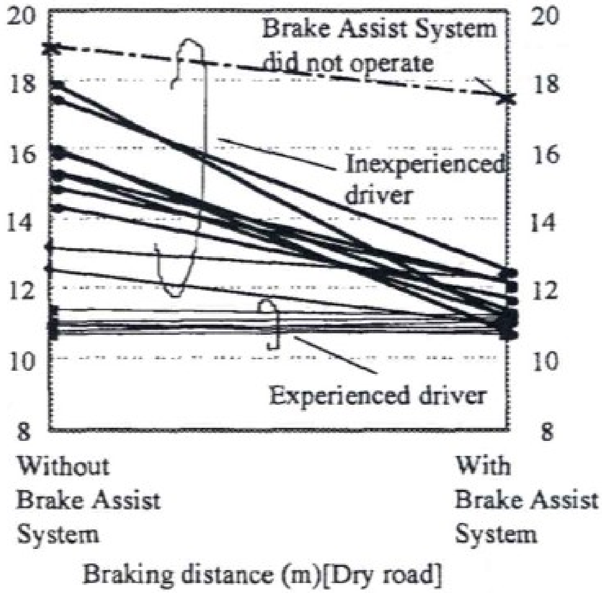


Figure 9.6. Stopping distance with and without BAS

Graphs copied from Hara *et al.*, 1998

Details of the test methods were not specified, but the results suggested there were significant benefits for some drivers. Continental show a graph of stopping distance improvement with their BAS (www.conti-online.com), but again there are no details of the test methods that produced these results or the number of drivers that were used.

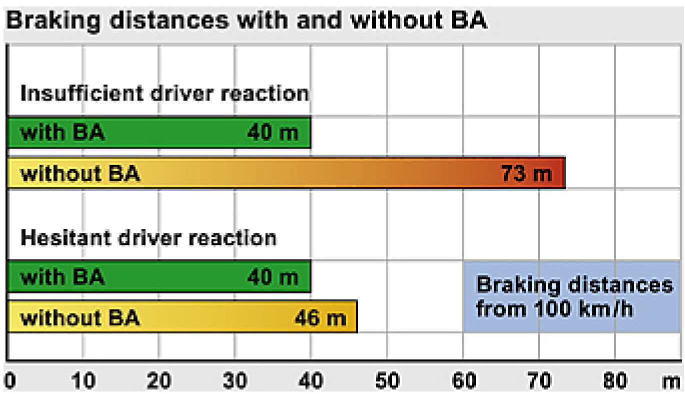


Figure 9.7. Continental-Teves' claims of BAS effectiveness (www.conti-online.com)

Mercedes show a similar comparison chart in their promotional and training material, but again there are no details of how the data were derived.

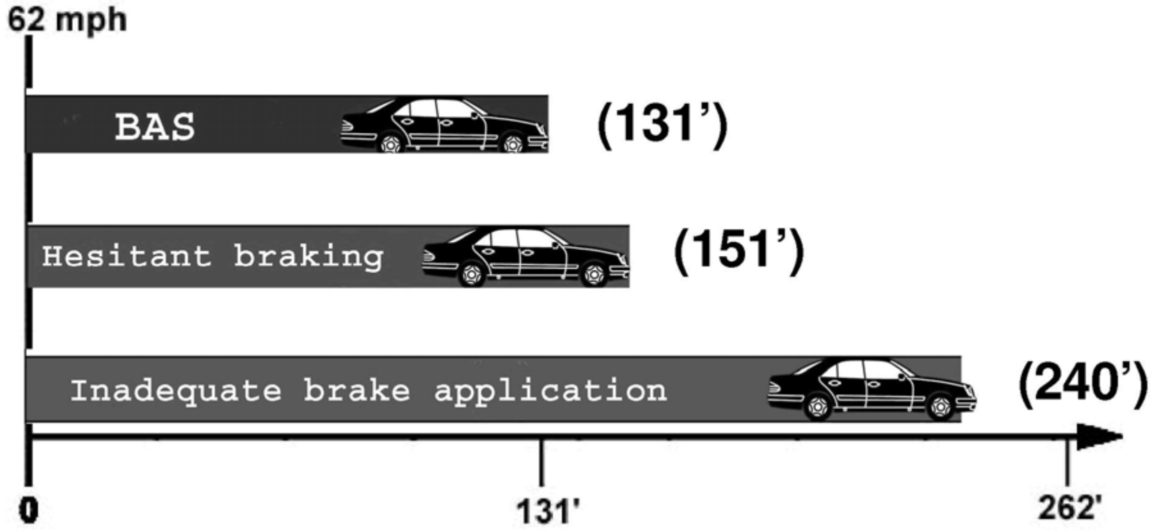


Figure 9.8. Mercedes' BAS effectiveness (Mercedes-Benz, 2004)

The fact that the definitions of braking categories and that the distances achieved are identical (e.g. 240 feet = 73 metres) strongly suggests that the Continental and Mercedes graphs are both based on the same testing, but a detailed technical report could not be found. This means that it is not known whether these results are for a specific driver, the mean result for a group of drivers, or some other representation (e.g. 95th percentile) of a group of drivers.

No published studies were identified that compared the effects of different BAS on the stopping performance of ordinary drivers, the effects of changes in the methods or thresholds for detecting an emergency, or the effects of different control philosophies such as how the system reacts to reductions in pedal force during the stop.

9.4 Assessment of the benefits of brake assist using accident data

It is well documented that using accident data to assess the effectiveness of a primary safety (accident avoidance) feature can be very difficult (e.g. Sandin and Ljung, 2005; Paulsson, 2005). At a simple level this is because when a primary safety feature is fully effective then there is no accident and, thus, no data for comparison. A variety of methods are used to try to overcome this fundamental difficulty and each method has strengths and weaknesses. There are no current methods that are considered perfectly accurate and reliable and all methods have strengths and weaknesses. The discussion of specific analyses carried out for brake assist, that is presented below, must be considered in the context of these fundamental limitations that affect all primary safety accident analyses. Generally, analyses can be broadly divided into two categories:

- Predictive studies – these examine real world accidents where vehicles were not equipped with the feature under consideration, and calculations and/or judgements are made to assess whether the accident would have been avoided or mitigated if the safety feature had been present
- Retrospective studies – these treat the feature under investigation as a risk factor and use statistical methods to compare the relative risk of accidents in real world accident data where vehicles can be identified that both do and do not have the safety feature fitted

Typically, predictive studies have the advantage that they can be used to predict benefits before the measure has been introduced into the vehicle fleet and can be relatively straightforward to carry out. However, in order to be accurate, there must be a detailed knowledge of how each system will perform in every accident within the dataset, including how they interact with driver behaviour. This usually means that a broad range of assumptions is required and the size of the predicted benefit will depend heavily on those assumptions. Analyses can be further limited by the range and quality of data available in the accident data source because there is often insufficient information relating to events immediately prior to impact to make accurate calculations or assessments. It can also be very difficult to take account of unintended consequences of systems, for example, where a feature changes the type of accident from the one it was intended to prevent to some other type of accident such that the net benefit is reduced. Some authors (e.g. Sferco *et al.*, 2001) acknowledge that such methods tend to produce an over-estimate of benefits because of these problems.

Retrospective studies of accident data using statistical methods should produce more reliable estimates of actual benefits because they are directly comparing accident risk with and without the system in the real world with real drivers. However, there are a large number of factors that can contribute to the risk of involvement in an accident for a particular vehicle, such as the:

- Presence of the safety feature under consideration
- Presence of other safety features that may influence accident risk
- Number of that vehicle model registered
- Mileage driven each year
- Use of different classes of road relative to other vehicles
- Age of the vehicle
- Age distribution of the drivers of that model
- Behavioural characteristics of the drivers (e.g. do sportier models attract higher risk drivers?)

The above is far from a definitive list and to provide a perfectly accurate assessment, these and other factors must be eliminated or compensated for in the analysis. In reality, this is not currently possible. It can be very difficult even to identify the presence of safety features on the vehicles in the accident database and the data available in relation to exposure to risk (i.e. distance travelled on what roads, driver age and behaviour, etc.) is very limited. In addition to this, studies that attempt to eliminate as many variables as possible often end up with small sample sizes that are insufficient to provide statistically significant results. A range of assumptions and approximations are usually also applied in these analyses to try to overcome these problems.

Two accident analysis studies (Hannavald and Kauer, 2004a and 2004b; Page *et al*., 2005) have been identified in relation to brake assist and these are discussed in more detail in the following sections. When considering the review of these studies, the fundamental limitations described above must be taken into account.

9.4.1 Predictive studies of brake assist

9.4.1.1 TUD study and use of GIDAS data to estimate benefits of BAS

The Technical University of Dresden (TUD), under contract to ACEA, carried out the equal effectiveness study for pedestrian protection including the effect of Brake Assist (Hannavald and Kauer, 2004a and 2004b). The method used was a predictive study based on accident data from the GIDAS database. TUD are one of the two organisations that investigate the accidents that are included in the GIDAS database.

The comments below are based both on the TUD report itself (Hannavald and Kauer, 2004b) and the meetings and email correspondence between the TRL authors and TUD / ACEA that was described in Section 1.1.

When brake assist detects an emergency situation, from an above average brake pedal force or a fast brake pedal speed, or a combination of these, it can have two benefits. The first is that it can help the driver to apply emergency braking more quickly, and the second is that, for some types of system, it will apply full ABS braking in cases where the driver was only applying brake pedal pressure equivalent to less than the maximum possible braking.

TUD have stressed that their method of calculating brake assist has the advantage of being made on a case-by-case basis based on real accidents, by estimating what would have been the accident outcome had the vehicle been so equipped. However, the data that can be gathered from an accident study, by attending each accident scene shortly after the accident occurred, are limited. The key information required to determine when brake assist would have been of benefit is:

- the vehicle travelling speed just before the accident (or before the driver's first reaction)
- in cases where pre-impact braking occurred, the distance between first brake application and impact (first contact)
- in cases where pre-impact braking occurred, the average deceleration achieved
- the maximum braking deceleration that could potentially have been achieved.

The potential for BAS in each accident case depends on the difference between the assumed maximum braking deceleration that a BAS equipped car could achieve on that road surface and the estimated actual mean braking deceleration. Because the BAS potential depends on the difference of these two estimates it is sensitive to the accuracy of both values. The current study has included a sensitivity analysis to illustrate this, see Section 13.6.

The estimate of the maximum braking deceleration is determined by the road material and surface condition (e.g. wet, dry), and tables of maximum friction values. These three factors are used to estimate the deceleration of the vehicle. In reality it is impossible to determine any of these with any accuracy and it is only possible at all when detectable tyre marks have been left on the road surface. In this case the travel speed can be estimated by the total length of the tyre marks, the estimated braking deceleration and the estimated or measured road surface coefficient of friction. Likewise the impact speed can be estimated by taking the estimated travel speed and deducting an estimate of the pre-impact braking velocity change by using the pre-impact length of the tyre marks, the estimated braking deceleration and the estimated or measured road surface coefficient of friction. At least one additional piece of information (such as position of impact point relative to tyre marks) is required to enable the full calculation to be carried out.

ACEA / TUD were asked how they obtained estimates of actual braking decelerations for cases where brake assist would provide a benefit by providing a higher braking effort than the driver used (because in this case tyres might not leave marks). The question was *"Does obtaining mean braking decelerations from tyre marks rely on there having been fairly large slip angles (approaching those at which ABS works) or can they be obtained at much lower slip angles?"* the reply was**:**

> **"**The mean decelerations which were used are average values over the distance from start of braking till the impact with the pedestrian. Interrupts and single side traces (which are appearing with lower decelerations) are considered too. Tyre marks can also be obtained with lower slip values and are considered. The characteristic of the road surface has a main influence of the appearance of slip marks."

This implies that TUD can detect low braking decelerations from marks left on the road. However, expertise in accident reconstruction has reported that for dry roads at near full braking a dull/cleaned tyre track can sometimes be seen on the road surface, but not often. When braking with a locked wheel, dark to black tyre marks are left. When ABS braking is taking place, tyre marks are rarely seen, but when they are found, they are usually faint and continuous rather than broken. However, for all cases where tyre marks can be detected the level of marking is very dependent on the type of road surface. On wet roads, tyre marks are rarely seen, although they can sometimes be found later when the road has dried out. Therefore, it may only be possible to determine decelerations from tyre marks when a driver was braking at close to the optimum. Research in Japan (Kawakami, 1985; Furumoto *et al.*, 1998) also shows that, although faint tyre marks can be seen at low values of slip, the deceleration during this phase remains close to maximum and can actually be 1.1 – 1.2 times greater than when the wheel is at high slip values and leaving heavy tyre marks. This would mean that there may be no tyre mark evidence in the cases where brake assist would have made its main difference, when there was pre-impact braking at well below the maximum that could have been achieved. In this case it is not possible to estimate from the other available data what the benefits, if any, would have been.

Therefore, it appears that there is some disagreement as to whether it is possible to detect cases where the driver would have benefited from brake assist because he did not use full braking before the impact. If it was possible to identify tyre marks made by a vehicle undergoing a low level of deceleration then one method that might be used to estimate the benefit of harder braking would be to compare the length of pre-impact tyre marks with estimates of the speed and coefficient of friction. However, the estimates of travelling speed, impact speed, pre-impact braking distance and road surface coefficient of friction would all have to be accurate. TUD was asked how the coefficient of friction was estimated for each accident. This was particularly pertinent because the distribution in the GIDAS accident database was not of the form expected (some form of roughly normal distribution would be expected, with a large peak at zero from the no braking cases); see Figure 9.9 for the distribution obtained from the GIDAS data (712 case sample).

The first question on this point was: "*If the decelerations achieved were in many cases limited by the driver's applied pedal force then why did so many drivers achieve 7.5 m/s² (compared with 7.0, 8.0 m/s², etc)?*" (as shown in Figure 9.9).

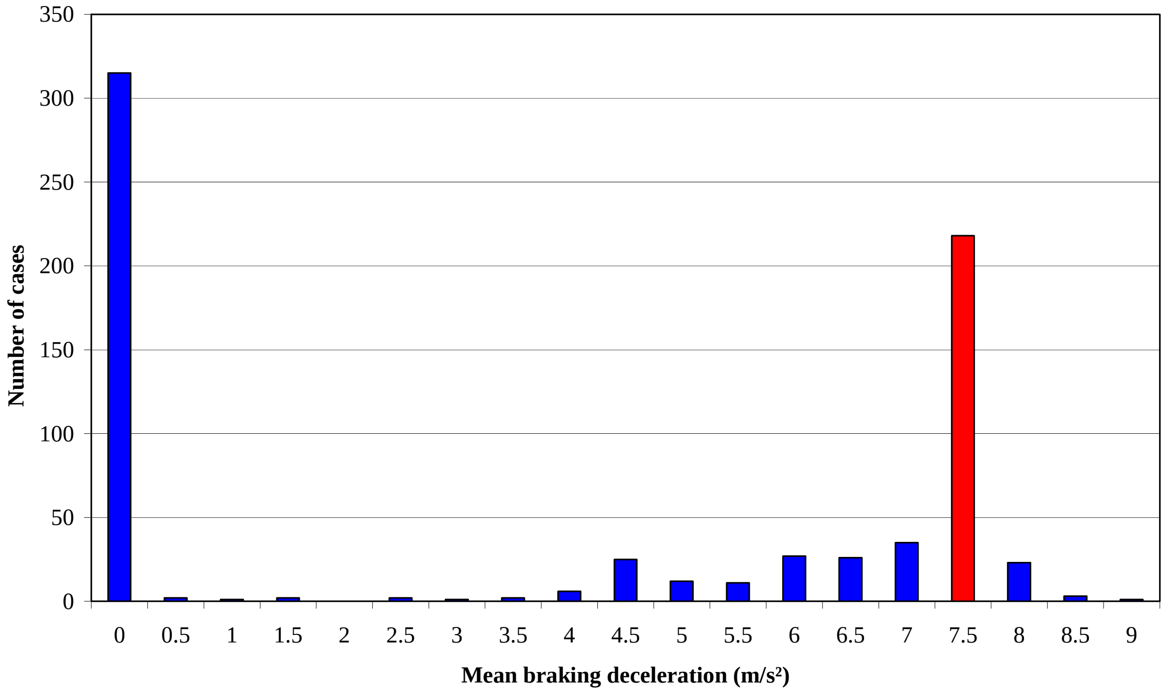


Figure 9.9. Number of pedestrian cases in BAS study database (712 case sample) by mean braking deceleration

ACEA / TUD's answer was: "The values in the database are average values and depend on the results in the investigation on the spot. They vary because e.g. the traces aren't homogeneous over the length. The BAS benefit consists of a constant high deceleration, a better usage of the friction coefficient and of the compensation of insufficient driver pedal application."

The second question was: "*Is there something about the reconstruction method that keeps giving this value, in which case how reliable are the braking deceleration values produced?*"

ACEA / TUD's answer was: "The values used in the accident reconstruction are based on experience of the expert. The braking decelerations in the recalculation are based on objective tests with BAS equipped cars (significantly reduced due to the conservative approach)."

A second, fuller answer to these questions was received later, after the appropriate TUD and MUH experts had been consulted:

> "Determination of the average braking deceleration bv:
>
> The initial traces are subdivided into sequences of different textures of road surface, e.g. change in character from concrete to asphalt surface or driving on tram tracks.
>
> Thereafter, the drawn traces are evaluated within these sequences. Basis of the evaluation are discontinuities or changes in intensity of the traces. Examples are offsets of traces, one-sided traces or full retardation without traces of rear tires.
>
> The roughness of the road surface is evaluated by means of visual impression on scene or pictures of the accident, comparing with praxis oriented measurements of the vehicle fleet. Thereby, a mean deceleration of 7.5 m/s² is assumed on dry and clean asphalt surfaces, for instance. On dry, but worn out and dirty asphalt a mean deceleration of 7.0 m/s² is assumed. Depending on the evaluation, the prior determined sequences are allocated to the probable decelerations and the values for cars equipped with ABS are partly higher. In praxis of a technical reconstruction, the gradation consists of steps of mostly 0.5 m/s².
>
> The range from 7.0 m/s² to 8.0 m/s² is also confirmed by braking tests carried out at the Medical School of Hanover.
>
> The average braking deceleration bv is calculated by covered distance and deceleration considering all sequences.
>
> Accidents involving pedestrians and passenger cars often happen under dry weather conditions on asphalt surfaces with maximum retardation of the vehicle. If only one sequence involving the sector of maximum retardation is examined, the values of the average braking deceleration scatter in a range around 7.5 m/s²."

TRL's accident investigation expert was asked whether it is possible to accurately estimate friction in this way (i.e. by road surface type, observation and experience but not measurement). His opinion was that only a rough estimate could be obtained in dry conditions and only a very rough estimate could be made in wet conditions (UK police make actual measurements of coefficient of friction at the scene of serious or fatal accidents where it is thought relevant, by skidding a car to a halt).

Based on the above, if the current authors' view is accepted then it is only possible to make accurate estimates of the benefits of brake assist in accidents where heavy pre-impact braking took place. In this case the only benefit would be that the transition from no braking to full braking would be achieved faster than the driver's leg can move, once the brake assist has detected the onset of emergency braking.

In general, the authors' view is that TUD's method often over estimates the benefits of BAS when obvious braking marks are left.

The responses reported above from TUD and the 'TRL expert' appear to justify the authors' concerns about the methods used by TUD to calculate the benefits of brake assist. It was therefore decided to see if some validation of the TUD method could be obtained by comparing the proportion of cars fitted with ABS in the whole sample and among those where pre-impact braking was detected. It appears reasonable to assume that these rates should be similar; however, because antilock brakes would leave less distinct tyre marks, this comparison would provide a check on the TUD method. Cars fitted with ABS form 17 percent of the 712 case sample, but are in only 11 percent of the cases where pre-impact braking was detected. This check therefore appears to support the conclusion that the TUD method frequently fails to detect when pre-impact braking has occurred, whether or not ABS was fitted. Therefore the authors' view is that TUD often under estimates the benefits of BAS when faint braking marks or no marks are left.

Because of the above arguments it is considered that the benefits of brake assist estimated by TUD can not be accepted as scientifically rigorous estimates. However, it is clear that brake assist must in many cases offer significant benefits in reducing the injury severity or even avoiding vulnerable road user accidents. It seems that in some cases TUD are over-estimating the potential for improved braking with BAS, yet in other cases they are failing to detect braking and hence are assuming no benefit for BAS. Therefore, although the methods used by TUD may not be scientifically rigorous, it is possible that their estimates may be of about the correct order. Therefore the GIDAS data supplied by TUD have been used in Section 13 to provide indicative estimates of the benefit of brake assist.

9.4.1.2 LAB study

Subsequent to the analysis by TUD (Hannavald and Kauer, 2004a and 2004b), a paper was published by Page *et al.* (2005) from the Laboratoire d'Accidentologie, de Biomechanique et d'etudes du comportement humain (LAB). This also described a predictive analysis of the benefits of brake assist. The method was similar to that employed by TUD but the source data used was police fatal accident reports generated in France in 1991 and the assumptions employed were different.

The LAB analysis was initially restricted to fatal accidents where a car without ABS was involved and skid marks were left at the scene. The starting point was an estimate of the collision speed (speed at the point of first contact with the accident opponent), which was made based on photographs and information from the Police report. It is assumed that this means an estimate based on information such as the circumstances of the accident, the damage to the vehicle and, possibly, reconstruction methods such as pedestrian throw calculations and skid marks present after a known impact point. This type of estimate will inevitably contain a degree of error, but this is largely unavoidable in this type of analysis.

The analysis works backwards from this collision speed such that the length of the pre-impact skid marks are used to derive a speed at the start of the skid marks. In order to achieve this it was assumed that the deceleration achieved during skidding was always 7 m/s^2. This was based on the typical deceleration achieved by non-ABS cars of the time on dry roads. The next assumption was that in these events drivers took on average 0.7 seconds to reach the point of wheel lock from first touching the brake pedal and this was defined as the activation time. This was based on other LAB research into the typical braking behaviour of drivers. It was further assumed that the rate of increase of deceleration during this time was linear such that the average deceleration during the period was half that of full braking, that is 3.5 m/s^2. A speed at the start of the brake application was then calculated.

In order to estimate the benefit of BAS the paper assumes that BAS will halve the brake activation time to 0.35 seconds. Starting with the previously calculated speed at the start of the brake application, the revised activation time is used to generate a revised speed at the point where wheel locking and tyre marks begin. The reduced activation time means that the distance travelled during activation is smaller, such that the distance over which full braking can take place before impact is increased. The revised speed at the start of full braking and the revised distance over which full braking can occur are then used to re-calculate the collision speed, assuming the same deceleration during full braking (7 m/s^2). This set of assumptions is considered to be more robust than the equivalent assumptions used in the TUD analysis because it works on the theory that once a vehicle is leaving skid marks, the presence of brake assist cannot further improve the deceleration but can affect how quickly a driver can get to maximum braking. The current study also includes a sensitivity analysis looking at potential benefits from reducing the rise time; see Section 13.6.

As in the TUD analysis the calculation was repeated for each valid case and a revised speed distribution was compared with injury risk curves for the relevant accident situations in order to derive overall estimates of BAS benefits. The paper described the process of applying the injury risk curves and showed some specific results for collisions between cars or between a car and a fixed obstacle. The effect of brake assist was found to vary for these different crash types. Bearing in mind that only cases where tyre marks were found were studied, brake assist was predicted to save between 19 and 38 percent of the fatalities, dependant on impact type. The lower estimate related to car front to car side collisions that were not at a junction and the upper estimate related to collisions with a fixed obstacle.

These estimates were combined with the proportion of accidents of each type recorded and what proportion of all fatal accidents each specific accident type represented. This was found to correspond to a brake assist benefit of between 4 and 5 percent of all fatal accidents, based on the findings for the four specifically analysed car to car or car to fixed object accident types.

At this point, the paper acknowledged that brake assist could also be of benefit where braking occurred but never reached a level sufficient to cause wheel lock or tyre marks. In order to account for these cases a new set of assumptions was introduced. It was assumed that in cases where no skid marks were found, the drivers who braked only reached 4 or 5 m/s^2 deceleration rather than the 7 m/s^2 that was technically possible. The report did not state how, in cases where no skid marks were left, the proportion of drivers that did brake was identified. It should be noted that if it was assumed that in all cases where no skid marks were left the drivers braked at 4 or 5 m/s^2 then this could result in a significant over estimate because it ignores the possibility that some drivers did not brake at all.

The next assumption was that the distribution of braking distances was the same whether or not the braking action was sufficient to leave skid marks. In effect this assumes that drivers that applied insufficient brake force in an emergency reacted at the same instant as those that did apply sufficient force. The current authors could find no data to quantify how valid this assumption was.

It is considered that this second set of assumptions, regarding the benefit in cases where no skid marks were left, would be less robust than those regarding cases where there were skid marks. This is simply because in the cases with no skid marks there are many more unknowns in each accident and a much larger degree of the findings are dependent on pure estimation. However, based on these assumptions, the paper stated that the benefits were increased such that, in total, brake assist could reduce the number of car occupant fatalities by between 6.5 and 9 percent.

All of the above analyses were predominantly related to the benefits of brake assist for car occupants. The paper in fact only contained a very short section relating to pedestrians. This stated that a similar analysis had been carried out on collisions between cars and pedestrians and that brake assist could reduce pedestrian fatalities by between 10 and 12 percent. It was not clearly stated how much of this benefit arose from reducing the brake activation time in cases where skid marks were present or how much was from increasing deceleration in cases where skid marks were not present.

9.4.2 Retrospective studies of brake assist

Page *et al.* (2005) also carried out a statistical analysis of the accident risk for cars with and without brake assist. This was the only retrospective study identified. The first step in this study was to identify vehicles in the French national accident data where the fitment of brake assist could be identified. This proved difficult and in fact only two vehicles (Renault Laguna and Peugeot 406) were identified, which resulted in a total sample of 2,061 vehicles involved in accidents. For each of these it was known that brake assist was fitted from a certain date and the make, model and date of first registration. The status of ABS fitment could also be identified and non-ABS cars were excluded from the analysis. However, the status of other safety features that may have changed at the same time as brake assist was not specifically stated in the report. It is possible that electronic brake force distributions could have been introduced on some models during the time considered or that crashworthiness or occupant protection measures could also have been improved, which might be expected to influence the results.

The second step was to define a group of accidents where brake assist could potentially be of influence and a second group where it is considered that brake assist would be of no influence. Accident types where it was considered that electronic stability controls (ESC) might have been of influence were excluded from both groups in order to exclude its effect. This resulted in a reduction of the sample size from 2,061 cars to 917 cars. These remaining accidents were split into 4 groups divided by whether or not brake assist was fitted and whether or not the accident mechanism was one which could have been influenced by brake assist.

The analysis method was, therefore, intended to quantify the relative risk of a car with brake assist being involved in an accident that brake assist was intended to influence. This type of analysis is designed to circumvent the problems with exposure data (number of vehicles registered, annual mileage driven, population of drivers, etc.) that are encountered when trying to define the overall risk of a vehicle becoming involved in a certain type of accident. The method has been used in a number of other studies aiming to quantify the benefits of ABS and ESC.

An assessment of relative risk based only on the four groups defined would ignore a range of other factors which may have also influenced the distribution. The report specifically mentioned confounding factors such as location of accidents, driver gender, driver age, vehicle age and year of accident occurrence. The relative risk factor was, therefore, adjusted to compensate where brake assist equipped and non-equipped cars had different distributions of the confounding factors. This was estimated using logistic regression. The results of the logistic regression were not statistically significant but indicated a relative risk of 0.81 which suggested that the risk of being involved in a brake assist relevant accident was 19 percent lower if the vehicle was equipped with brake assist. It was suggested that accidents pertinent to brake assist constituted 60 percent of all French accidents such that the overall effectiveness was expected to be an 11 percent reduction of all accidents. However, the confidence limits for the relative risk were [0.48, 1.38], or from a 38 percent increase in the risk of involvement in brake assist relevant accidents to a 52 percent decrease.

The fact that when considering the risk of involvement in all accidents the sample was not sufficiently large to show statistically significant results meant that it was not possible to divide the sample further to identify the specific effects of brake assist on pedestrian accidents. Although these are serious limitations of the study with respect to the role of brake assist in pedestrian protection it must also be acknowledged that this problem is common to many statistical analyses of the influence of primary safety features on accident involvement. This is because of severe limitations in the data available with respect to vehicle equipment and exposure to risk. It does not necessarily imply that there is no benefit for brake assist.

9.5 Test procedures for identifying brake assist and assessing its performance

The only test procedure relating to BAS that could be found was the one that was provided by ACEA to the EC. This standard considers two types of BAS: those that detect an emergency based on pedal speed and apply full ABS braking and those that boost braking by a fixed proportion when a certain force level is exceeded. Based on the literature and internet searches carried out by the authors, the scope of the standard would cover most BAS on the market. However, systems such as that described by Mazda that use multiple criteria to detect an emergency may not be adequately covered by the standard.

The test procedures described by the standard mainly assess the presence of a functioning BAS. One aspect of performance is inherent in the test procedures for each system. For pedal speed activated BAS, the system must be capable of achieving 85 percent of the deceleration found in full ABS braking when between 50 and 70 percent of the pedal force that would be required to activate ABS (in the absence of BAS) is applied. This does, therefore, prescribe a minimum performance in terms of how much the brake pressure is boosted. Similarly, for the force activated systems, the maximum force over and above the activation threshold that must be applied to reach ABS braking has to be less than 60 percent of the force that would have been required in the absence of BAS. Again, this represents a minimum performance in terms of the amount the system boosts the brake pressure.

However, the human factors research that led to the development of BAS suggested that the method used to activate BAS would be critical to its performance. The test procedures treat both systems that are within its scope equally but it is possible that one principle is more effective than the other and no published research could be found to quantify this. In addition to this the BAS test procedure is written relative to activation thresholds to be specified by the manufacturer for pedal speed sensitive devices. For pedal force sensitive devices there is an indication that the activation threshold "should" lie within a certain range.

This standard would, in theory, permit a pedal speed activated BAS that activated at 750 mm/s or one that activated at 100 mm/s. Research by Perron *et al.* (2001) would suggest that the first system would only offer benefits to very few drivers and the second would substantially interfere with normal driving, possibly causing increased risk of equipped vehicles suffering collisions from the rear.

If this procedure were implemented, it is likely that manufacturers would continue to produce systems with appropriate trigger thresholds because of the desire to produce systems that were acceptable to their customers and concerns over product liability. However, the proposed BAS test procedure would be considerably more robust if it included requirements relating to the trigger threshold as well as the amount of boost applied. This could potentially be achieved relatively simply by amending the procedure such that it continues to specify requirements against an activation threshold specified by the manufacturer but states that the threshold must lie within a certain range. In the case of pedal speed activated systems, Perron *et al*.'s research (2001) would suggest that an activation threshold of between approximately 150 mm/s and 350 mm/s might be appropriate. For pedal force activated systems this would simply involve re-wording such that instead of indicating that the activation threshold "should" lie within a certain range it became a requirement that it "must" lie within that range. However, no published research was identified that informed what the values in that range should actually be.

9.6 Potential enhancements to current brake assist systems

The research has shown that human behaviour during braking is quite variable and that there are a variety of methods of implementing brake assist systems. This suggests that there may be further scope for the optimisation of brake assist systems in order to further refine the compromise between offering benefits to the greatest number of drivers in emergency situations while minimising the intrusion on normal driving. This may involve modifying the criteria for detection of emergencies and/or using multiple detection criteria as well as identifying which control strategies (e.g. full braking until full pedal release or control of assistance in proportion to driver input) are most effective. If optimum criteria and control strategies are identified there is clear potential for standardising across the vehicle fleet such that all systems perform to an equal level of effectiveness and the benefits of the system are maximised. Such standardisation may also help drivers who regularly drive different cars. Rigorous scientific research is likely to be required in order to accurately identify these optimum conditions.

Brake assist systems could also be substantially enhanced by incorporating forward looking sensors that can predict when emergency situations arise, in time to take evasive action. Such sensors offer a wide range of possibilities such as:

- warning the driver of impending collisions
- using the data to enhance the emergency braking detection of the brake assist system and enabling more appropriate control of the braking once activated
- automatically braking once a collision has become unavoidable
- automatically braking sufficiently early to completely avoid a collision

The first two of these enhancements are already in production, for example brake assist plus and predictive brake assist on the Mercedes 'S' class and the Audi A6. Bosch (www.bosch.com.cn) describe their predictive brake assist system, which uses radar to sense emergency situations likely to require emergency braking and prepares the brake system by pre-filling the fluid such that the linings are just in contact with the discs and lowering the tripping threshold of the brake assist system. In this way Bosch claim that full brake performance will be applied within 30 milliseconds of the driver first pressing the brake pedal. Bosch suggest that this will offer substantial safety benefits because only one-third of drivers react to an emergency braking situation with a full brake application and also state that *"most drivers are so hesitant that hydraulic brake assist is not activated"*.

Brake assist plus is fitted to the Mercedes ‘S’ class (www.daimlerchrysler.com) and also uses two radar sensors to detect emergency collisions. The system then transmits an audible and visual warning to the driver and calculates the deceleration necessary to avert a collision. The appropriate deceleration, which may not necessarily imply full ABS braking, will then be automatically applied as soon as the driver presses the brake. The fact that the system only provides the deceleration necessary to avoid a collision, rather than full ABS braking that might have been activated by a standard BAS, is claimed to give drivers behind the vehicle more time to react.

Daimler Chrysler have carried out research in driving simulators to assess the effects of brake assist plus. This research involved 100 ordinary drivers driving around simulated highways and secondary roads and being presented with a range of critical situations such as approaching the end of a highway traffic jam at high speed and a vehicle ahead suddenly braking. In a vehicle with conventional brakes 44 percent of drivers suffered a collision but with brake assist plus fitted this was reduced to 11 percent, suggesting a substantial benefit for front to rear end collisions between cars.

No research was identified that discussed the effectiveness of these systems in terms of pedestrian accidents. A representative of ACEA, contacted by the authors, has stated that the radars used in brake assist plus cannot recognise pedestrians, which would mean that there are currently no benefits of the system for pedestrians. However, McCarthy *et al.* (2004) carried out research that successfully developed a proof of concept sensor system that was capable of detecting pedestrians in front of a vehicle. This project found that such a system could potentially be used to brake the vehicle and/or to implement active secondary safety features such as a pop-up bonnet and that this could offer substantial benefits in pedestrian accidents. The prototype system was developed by fusing a high resolution 24 GHz short range radar with a passive infra-red sensor. The basic functions were that the radar was used to identify distance and relative velocity accurately and the infra-red sensor was used to decide whether or not the object detected by the radar was a pedestrian.

This shows that radar can be used to detect the presence of a pedestrian, but that it will only see it as another object and cannot treat it differently from a vehicle. However, it is unlikely that this distinction would be necessary for an advanced brake assist system. This suggests that even if brake assist plus and predictive brake assist are not a benefit for pedestrians now they could potentially be in the future, with further development of the system. Such systems, and future developments of them (collision mitigation and collision avoidance), are likely to have considerable casualty saving benefits. However, such systems are still very new to the market. A great deal of research (e.g. Prevent, Response, APROSYS) is currently investigating the potential of such systems and how they can be incorporated within legal frameworks. As yet, there is no agreed approach regarding the best way to test or regulate systems and this would make it very difficult to incorporate radar braking systems into a package of regulatory requirements for pedestrian protection for some time to come.

In addition to this, the nature of pedestrian accidents, where pedestrians sometimes step into the road immediately in front of a vehicle such that there is almost no time even for an advanced system to react, means that secondary safety is always likely to have a significant role to play in pedestrian protection.

9.7 Discussion

When all of the research described above is considered, there is considerable evidence to suggest that brake assist systems have a beneficial effect in terms of accident reduction. Accident analysis shows that in many cases drivers brake prior to a collision but fail to stop in time. Driver behaviour research has shown that ordinary drivers often do not use the brakes to their full potential even in emergency situations. A solution has been designed, based on the human factors research, that aims to counter this deficiency in driver behaviour and tests have shown that stopping distance is typically shorter in cars equipped with the system. In addition to this, three analyses of accident data have suggested that this will result in fewer accidents.

However, in terms of accurately quantifying the magnitude of that benefit specifically for accidents involving cars that collide with pedestrians, there is still considerable uncertainty. The TUD accident analysis involved a range of assumptions of questionable validity. The LAB study involved more robust assumptions for the main part of the benefit but also included benefits derived from some more speculative assumptions and did not describe in detail how these related to the estimates of benefits specifically for pedestrians. A retrospective statistical analysis also suggested that cars equipped with BAS had a reduced risk of involvement in accidents but this suggestion was not statistically significant and the sample size was not sufficient to permit a specific study of pedestrian accidents.

The data showing that BAS did result in typically much shorter stopping distances for ordinary drivers did not contain any technical detail allowing a scientific review of the methods used or the meaning of the results. In particular, there was no reference to the detailed characteristics of the BAS studied, while a review of the market showed that there were substantial differences between some of the systems on offer. In the main, there were two types:

- pedal speed sensitive systems that applied full braking in an emergency
- pedal force sensitive systems that boosted the brake pressure proportionally.

However, there were other principles identified, such as using both pedal force and speed as detection criteria. In theory at least, you could also get systems that detected emergencies based on pedal speed but only boosted the braking proportionally rather than fully applying ABS braking. The human factors research reviewed suggested that the benefits of the two main types of system may well have been different but no research was identified that directly compared the performance of the two systems in terms of stopping distance achieved by ordinary drivers.

The predictive accident studies carried out have not taken the different systems into account and assume equal effectiveness for all systems. The assumptions made by TUD are closest to a system that detects an emergency based on pedal force (equivalent to a threshold deceleration of 6 m/s^2) and then applies full ABS braking. The current study uses similar assumptions with a threshold deceleration of 4 m/s^2, see Section 13.4.7. However, no systems were identified that act in this way. Those systems that applied full ABS braking were typically based on pedal activation speed but pedal speed cannot be identified in any known accident database. Those systems that are based on pedal force typically only boost the pressure proportionally and may not be sufficient to boost braking from 4 or 6 m/s^2 to maximum.

Based on the evidence available, it is possible to state confidently that BAS will be beneficial. A range of benefits have been predicted by the two predictive studies and the largest benefit was that BAS would reduce pedestrian fatalities by 12 percent. Given that other estimates of benefits were lower, that predictive studies typically produce over-estimates, and that it is generally assumed that all systems will result in full ABS braking and will work for all drivers with no adverse consequences, it can also be confidently stated that this is the maximum benefit the system is likely to produce.

This means that it reasonable to assume that BAS will result in a reduction in pedestrian fatalities of greater than zero and less than 12 percent. Within this estimate it is likely that the true answer will lie somewhere in the mid-range of values.

However, it must be noted that with the data currently available, any estimate of benefits that aims to produce a more specific single answer within that range will carry a substantial risk of either under or over estimating the real benefits of the system in pedestrian accidents. It should also be noted that in a wider context BAS will also be expected to have benefits for car occupants (e.g. 6.5-9 percent of all car occupant fatalities, Page *et al*., 2005) that have not been considered in the equal effectiveness study.

Further, more extensive and more rigorous accident analyses would be required to increase confidence in any more specific estimate of the benefits. This would probably need to include a statistical analysis similar to that carried out by Page *et al*. (2005) but with a larger data sample and possibly considering comparisons using a range of different analytical techniques.

Whatever characteristics of the system are assumed in order to generate a specific prediction of the benefits of BAS in terms of accident reduction, to achieve those benefits in reality will require that the actual systems fitted to vehicles perform to at least the level assumed in the accident analysis.

The test procedure proposed by ACEA would, if implemented, go some way toward achieving that target. However, the test procedure considers only two types of system: pedal speed emergency detection with automatic application of full ABS braking, and pedal force emergency detection with proportional boost of braking pressure. There is already evidence that emergency detection could be enhanced by using multiple detection criteria and there is evidence that there are existing systems that fall into neither of the existing categories. In addition to this, the procedure assumes both types of system are equally effective, which is not currently proven, and only provides a minimum standard for one aspect of performance, which is the minimum amount by which braking is boosted above driver demand.

The performance in respect of the systems' ability to accurately detect an emergency situation is not assessed. In the short term, the BAS test procedure could be made considerably more robust by adding a requirement that the BAS activation threshold for each type of system must lie within a specified range.

In order to maximise the benefits of BAS it is necessary to increase the understanding of the relative effectiveness of different brake assist systems that operate on different principles. It was clear from the literature that a range of different systems are already in use and that these may have different effects on the behaviour of drivers. This suggests that there may be scope for standardising and optimising the systems such that they help the largest proportion of drivers, with the minimum effect on ordinary driving. It is likely that this would have the potential to provide an additional safety benefit compared with the variety of systems currently on the market. Once this understanding is gained, the proposed BAS test procedure could be enhanced such that it ensures high minimum standards in all critical areas of performance. Preferably, this procedure should be independent of the specific technical methods employed by the manufacturer such that the minimum standard does not restrict innovation or require frequent adaptation to technical progress.

It is considered that the potential refinements of the standard brake assist systems that are described above could be investigated and, if proven beneficial, implemented in a relatively short time frame. Enhanced brake assist and collision mitigation systems based on pre-crash sensors are likely to offer further benefits in the long term but require a considerable amount of further research and development before they can be proven to be an effective and reliable pedestrian protection system.

10 Review of technical restrictions

The Directive requires that if, as a result of the feasibility assessment, it is considered necessary to adapt the provisions of phase two, to include a combination of passive and active measures, it must achieve at least the same level of protection as the existing provisions of phase two. Further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of “at least the same level of protection” of the Directive. Since TRL’s original proposals (Lawrence *et al.* 2004a) did not find any support from the experts in the area, they are no longer pursued.

10.1 Input from vehicle manufacturers

To gain a greater understanding of the current stage of research and development with respect to providing protection for pedestrians and meeting the requirements of phase two of the EC Directive, as described in Section 2, European vehicle manufacturers and first tier suppliers were asked for information. Following these requests, the authors were invited to attend meetings with nine European car manufacturers or manufacturing groups and one first tier supplier. The authors, Mr Lawrence and or Mr Hardy, attended meetings with these car manufacturers and first tier supplier.

At these meetings the authors gave an outline of their approach to this EC feasibility study and an outline of the type of changes to phase two of the EC Directive that could be proposed to improve the test methods or to take account of feasibility issues, as this was the main topic of the discussions. All of the vehicle manufacturers visited explained that they were concentrating their main research and development efforts on meeting phase one of the EC Directive. For phase two of the Directive, most had just produced a list where they felt that pedestrian protection restricted or conflicted with vehicle functionality or other regulatory requirements. Some also had examples where they had modified existing or new vehicles, using a combination of tests to physical prototype vehicles and mathematical simulations of the vehicle and test tools. It was clear from the discussion that in many cases these restrictions or conflicts could be completely or partially overcome by making changes to the vehicle design. However, these changes would have a number of implications to the vehicle’s appearance, functionality and so forth. All of the manufacturers made statements to the effect that various aspects of the requirements of phase two of the EC Directive were not feasible. They all agreed that the type of changes to phase two of the Directive, that the authors had outlined, would reduce the perceived conflicts but none provided data in the meetings that could be used to determine the extent of these restrictions or conflicts or to help set new feasible protection requirements for phase two of the EC Directive. At each meeting the manufacturers were asked to provide additional data that could be used to set achievable phase two requirements, but only one manufacturer has supplied data to assist with this. The main restrictions or conflicts with the requirements of phase two of the EC Directive given by the manufacturers are presented and discussed in the following sections.

10.2 Design conflicts

The design of a vehicle has to meet a number of styling and functionality requirements in order to obtain customer satisfaction (sales). It must also comply with a number of legislative requirements (safety, emissions, etc.) to obtain vehicle type approval, so that it can be sold.

As discussed in Section 2, the pedestrian test methods and performance criteria can be simply expressed as a requirement for the vehicle to provide a minimum crush depth and to generate a force whilst crushing that must not exceeded a specified level. Although not dictating the overall design of vehicles these requirements overlap with a number of other important vehicle requirements such as occupant crash protection, vehicle structural rigidity, driver view, packaging of components (including all engine variants), styling and low speed damage protection or limitation. These overlapping requirements are presented and discussed in the following sections.

10.2.1 Damageability tests

10.2.1.1 Insurance crash tests

The procedure for conducting low speed, offset crash tests to determine the damage and necessary repairs to a motor vehicle after such impacts, is published by the RCAR (Research Council for Automobile Repairs, 1999). These standard insurance tests are intended to reflect typical low-speed impacts and provide the typical level of damage that insurers are experiencing and paying for every day; these tests are now used by the RCAR members. The procedure consists of two tests, one for the front where the car is driven at a speed of 15 km/h into a fixed barrier with a protruding facing unit that overlaps the vehicle front by 40 percent. The second test, to the rear bumper, uses a similar protruding face attached to a movable trolley, which is propelled into the back of the stationary car, again at 15 km/h. This test procedure or variations of it are being used to assess the damageability and repair costs of vehicles to obtain insurance ratings. RCAR has also produced design guidelines to optimise the performance of private cars, car derived vans and people carriers of the monocoque design (Research Council for Automobile Repairs, 1995). The advice given in the design guidance covers many aspects of the vehicle structure, some of which may conflict with design issues necessary for compliance with the EC pedestrian protection Directive.

The RCAR design advice suggests the incorporation of crush tubes or crash boxes at the bumper mounting points, or the provision of the bumpers with a stroking capability for energy absorption and instant recovery. Provided that these energy-absorbing measures are behind a load-spreading device such as the bumper beam, they will not constitute local high loading areas dangerous to pedestrians. In some cases crush tubes are currently positioned in front of the bumper beam and any dangerous examples are likely to fail the pedestrian legform test. However, in most cases moving them behind the bumper beam would not be a problem and this solution is frequently seen in newer designs because it is also likely to give more real-life vehicle damage protection. Such energy absorbing systems behind the bumper beam could potentially be used to provide pedestrian protection. However, in practice, because the kinetic energy to be absorbed in the insurance test is so large, the stiffness of the crumple system will be too great for the pedestrian test to initiate crumpling. Therefore, any pedestrian protection will have to be added in front of the bumper beam.

Where it is not possible to alternate the positioning of the tow hook in accordance with the steering configuration, the RCAR guidance is that the tow hooks should be designed so that they collapse downwards and if necessary, break off under 15 km/h impact conditions. An alternative suggestion that is likely to be of greater benefit to pedestrians is for the towing eye or hook to form part of the vehicle tool kit and not actually be mounted on the vehicle until required.

These insurance tests produce some measure of a vehicle’s damageability and they are often followed by a repair study that assesses the repair costs in terms of parts and labour. These damageability results and repair costs are then used to help set an insurance rating for the vehicle model. As they focus on overall costs the same rating can be achieved with low damageability and high repair costs or with higher damageability and low repair cost solutions. In Europe, the approach tends to be to balance these two factors whereas in North America and Canada the emphasis is more on minimising damageability, as required by their legislation (see Section 10.2.1.2). As a low insurance rating is an advantage in selling cars, manufacturers strive to keep damage and repair costs low. Both good damageability and pedestrian protection require impact energy to be absorbed in a controlled manner, therefore the addition of pedestrian protection could have some affect on a car’s insurance rating. If pedestrian energy absorbing systems are added on top of the current damage mitigation systems then they may reduce damageability and insurance costs to some degree (depending upon the damageability and repair cost of the added pedestrian energy absorbing system itself), but if they replace or degrade them then they might add to insurance costs.

10.2.1.2 Bumper legislation

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. The Canadian 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. As already noted in Section 10.2.1.1, a good resistance to damage and providing pedestrian protection both require impact energy to be absorbed in a controlled manner. However, large forces are permitted when absorbing the large quantities of energy involved in these regulatory bumper tests (so long as damage is limited), whereas in the pedestrian bumper test there is an effective limit on the force via the legform acceleration criterion. Some matching of these conflicting requirements can be achieved if a combination of flexible bumper facia and energy absorbing foam is used. With this arrangement, comparatively stiff foam would be needed for the legform test due to the small area of contact and this foam would generate a far bigger force in the barrier and pendulum tests because the contact area would then be larger. However, although this might help to match the different stiffness requirements of these two tests, the pedestrian requirement is still likely to be lower, particularly for the Canadian test. Therefore, the pedestrian protection would have to be added on top of the current damage mitigation systems, requiring an increase in crush depth. However, foam introduced between the outer plastic bumper facia and the bumper beam for pedestrian protection would also be effective in providing protection in some car park knock type situations and could reduce damage in minor knocks, particularly if it recovers afterwards.

Clearly the requirements of both tests can be met, if an appropriate compromise is found between bumper stiffness and crush depth, but overall a larger crush depth will be needed to pass both tests than the minimum needed just to meet the Canadian 5 mph test. This additional crush depth can only be found by some combination of lengthening the car, or moving back or making thinner underlying hard structural members such as the bumper cross member and the ends of the chassis rails; changes such as this have other implications.

10.2.2 Occupant protection crash tests

The EC Directive 96/79/EC (European Parliament and Council of the European Union, 1997), pertaining to the frontal impact of motor vehicles, specifies a test in which the vehicle to be tested impacts a barrier with a deformable front face (of comparable stiffness to the front of another car) at 56 km/h, with 40 percent of the vehicle front overlapping with the barrier. To pass, the vehicle must protect the occupants, in this case as represented by a Hybrid III dummy in each of the front seats, against injurious interactions with the vehicle structure. Other criteria are concerned with the ability of the occupants to escape after an impact, for example, that it must be possible to open at least one door following the test. The level of protection necessary to fulfil these requirements demands that the occupant compartment of the vehicle remains suitably intact. This in turn implies that the structure of the vehicle in front of the occupant space absorbs a sufficient proportion of the impact energy. To achieve this, vehicle manufacturers direct the impact force towards the chassis of the vehicle and tailor the collapse of the ‘rigid’ elements of the chassis to limit the forces on the occupant. Also the packaging arrangement is designed to maximise the available crush depth forward of the occupant compartment. This design ambition manifests itself by bringing the main chassis longitudinal rails, or some replaceable, deformable element thereof, as far forward in the vehicle as is possible. This is combined with strong cross-members linking the chassis rails and the upper longitudinal load paths e.g. bumper cross-beam and upper cross-member (the bonnet latch and upper cooling pack support). These cross-members not only provide a link to absorb energy in the offset frontal crash test but also provide torsional rigidity for good handling and a distributed contact path for improved compatibility.

Because of the high energies involved in frontal impacts, the stiffness of the structures provided to absorb this energy is far higher than that required when hitting the legs of a human. Therefore any pedestrian protection at the bumper and bonnet leading edge must be added in front or on top of these structures.

10.2.3 Other vehicle requirements

10.2.3.1 Ramp angle

Obviously, in use, vehicles need to be able to contend with abrupt changes in road gradient and to be able to override small steps such as kerb edges and speed control ramps. Therefore, each manufacturer is likely to have a series of internal design standards for this depending on the type and use of the vehicle model. This is expressed as the vehicle's ramp angle and is the angle between the front wheel contact patch and whichever part forward of this gives the smallest angle to the horizontal. These internal standards are likely to be slightly different between manufacturers but it is thought that a typical value for a normal passenger car would be about 14.5° to non-structural elements such as a rubber apron on the spoiler and about 16° to structural elements such a steel beam behind the spoiler. The angles for sports cars, which often have less ground clearance and a longer overhang, will be lower than these, but will be accepted by owners who are likely to expect a vehicle of this type to have a lower ramp angle. Likewise the angles for off-road vehicles should be greater than those for saloon cars.

As identified in Section 2, one solution to reducing the knee bending angle is to provide a deeper and more vertical bumper front face and one option for achieving this is to move the spoiler forwards (moving it downwards would also help).

However, if one makes the assumption that current design principles are related to the actual use of vehicles and not just the intended use (which is most likely to be the case for saloons and sports cars), then the scope for changes is small.

The only other options to achieve both the desired more vertical front face for pedestrian protection and the required minimum ramp angle are to move the bumper face rearwards and the front wheels forwards. However, again the scope to make such changes is limited by packaging and functional requirements.

10.2.3.2 Cooling requirements

If the spoiler / bumper lower edge is moved forward to improve pedestrian protection then it will normally be necessary to raise it as well in order to maintain the current minimum ramp angle for the vehicle type concerned. By bringing the lower edge of the spoiler / bumper up, the available surface for controlling airflow is reduced. In many cars, this surface is critical for providing airflow onto the cooling system of the vehicle, passing air through the radiator, or radiator and air conditioning condenser. Any reduction of airflow to cool the engine due to a smaller air intake area could result in engine overheating in some current designs, particularly when providing a high level of power for sustained periods (towing and hill climbing). Therefore, for some vehicles where cooling is already difficult, extra measures will be needed. This could take the form of more powerful cooling fan(s), more efficient radiators or more efficient ducting. However, this is likely to occupy a greater volume than current fans and therefore add to packaging conflicts. Ultimately airflow requirements for cooling might restrict the adjustments in spoiler / bumper shape that can be made to provide pedestrian protection.

10.2.3.3 Headlamps

Headlamps are normally positioned within the bonnet leading edge test area and, depending on styling, are either tested directly on the lens or indirectly by being positioned beneath the bonnet leading edge. One option would be to move the main lamp units away from the bonnet leading edge; however, lighting regulations specify a minimum height for headlamps so for most saloon cars the scope to move them is limited. A second option is to provide the necessary energy absorbing capacity in the headlamp, either by making the headlamp lens and reflector box collapsible or by allowing the whole headlamp unit to move bodily into the vehicle when hit. Making the headlamp unit deformable is thought to be the most practical method and this was used on the Honda Civic, which came close to meeting the upper legform requirement, giving a maximum bending moment of 333 Nm and a force of 5.51 kN (Lawrence *et al.*, 2002). This can be compared against the current phase two limits of 300 Nm and 5 kN respectively. The second method of absorbing energy by allowing the whole headlamp unit to move bodily can only be used with low weight headlamps but it does require room for it to collapse into and mountings that are vibration free in normal use but that collapse on impact. However, heavier headlamps would require weaker collapsible mountings and modern headlamps are becoming increasingly heavy. The complete headlamp unit must house the lens, bulbs, reflectors, bulb fittings (and electrical power units for high light intensity outputs) and in some cases motors for vertical height (zenith angle) adjustment and in the future, lateral (azimuthal) beam adjustment. Therefore modern headlights can have a mass in the region of 3 kg. One vehicle manufacturer visited showed results of an upper legform test into an un-mounted (suspended) headlamp unit weighing 3 kg. This produced impact force of approximately 2.5 kN due to just the inertial forces of accelerating the headlamp, which suggests that absorbing energy by collapsible mounts may be difficult or impractical for heavy headlights. However, the features that make some modern headlights heavy are to improve illumination, which at night should help drivers to avoid some pedestrian accidents. Modern headlamps are large, expensive items and look set to become more so with the introduction of directional beams. Therefore a conflict is perhaps inevitable between improved illumination and pedestrian impact protection considerations which, as discussed above, is likely to be provided by deformable or frangible headlamp and / or mounting. This could result in high replacement costs, but this may be resolved through designing them so that instead of having to replace the complete unit, it is only required to replace the low-cost parts that are designed to fail on impact.

10.2.3.4 Bonnet leading edge

The car manufacturers visited provided little data on the feasibility of meeting the bonnet leading edge test. Some assumed or predicted a low efficiency in absorbing energy, others higher efficiencies. Many overlaid the required deformation over cross-sectional drawings of current or modified vehicles and concluded the test to be infeasible because they overlapped stiff points such as the upper cross-member and cooling pack. Most pointed to the poor current performance in Euro NCAP tests and the low incidence of femur and pelvis fracture to say that the test was incorrect and unnecessary. This was discussed in Section 3.

Conventional bonnet latches provide an area of localised stiffness at the front of the bonnet. As such they create a problem area for both upper legform and also, for some vehicles, for the child headform tests. To resolve this, latches with deformable elements or the ability to sink into the locking platform, in association with deformable bonnet stops or spring mounted stops, will be needed to meet the current phase two of the Directive when meeting the upper legform performance criteria becomes mandatory. It has been suggested by one manufacturer that the requirements of phase two imply a bonnet latch, and front of bonnet in general, that will be susceptible to plastic deformations just through closing the bonnet. Other problems associated with the necessary weakening of the latch and surrounding area are that in a frontal crash it would result in higher forces at the hinges, which may tear off. This would mean that the bonnet makes less contribution in an accident and might be pushed through the windscreen. With a very weak latch, deformations may occur in the manufacturing process. There is also a performance requirement for the latch to be durable for the lifetime of the vehicle. The combination of all these factors creates an issue for the feasibility of meeting the EC Directive phase two requirements for the front of the bonnet and in particular the latch area.

Whilst research and current good vehicles indicate that the current bonnet leading edge test requirements of phase two of the Directive are feasible for vehicle shapes that attract a low severity test, the current requirements are thought to be infeasible for many taller vehicle shapes. Updated test energies have been proposed in Section 3.3.3.3 and these may extend the number of feasible vehicle shapes. However, the current energy cap set at 700 joules is likely to need to be reduced to make the test feasible for most vehicle shapes.

The current upper legform energy cap 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 calculation included allowances for a number of factors including, efficiency with which the vehicle absorbs energy by deforming, corrections for the impactor mass in front of the load transducers which mean that the force on the vehicle can be slightly higher than the force criterion and an allowance for the energy absorbed by the impactor's foam flesh. However, it did not include a correction for the manufacturer's allowance for approval and conformity of production, discussed below in Section 10.2.5. All of the manufacturers visited who made vehicle shapes that attract significant test energies thought that it would not be practical to provide the necessary crush depth to absorb 700 J particularly when they added their allowance. One manufacturer provided simulation data for a large saloon car where they had revised the design to try to meet the phase two requirements; the results showed that it could absorb the required test energy of 600 J with a force of 6 kN (phase two maximum is 5 kN) in a crush depth of 122 mm; however, the modifications necessary were not thought to meet functionality requirements for bonnet edge flutter or safety hook requirements. Examination of the simulation results shows that the energy absorbing efficiency of the bonnet leading edge structure was only about 50 percent; had it been optimised to absorb energy more efficiently (manufacturers often claim efficiencies of 60 to 70 percent), then it is reasonable to assume that it could have been made to pass. Nevertheless, lower efficiencies are possible for complex areas such as the bonnet leading edge where components serve a number of functions and where a number of different structures and components meet. Based on this one result and considerations of the practical minimum crush depths needed to absorb energy it is thought that an energy cap of 500 J would make this test feasible. Therefore, an energy cap line set at 500 J instead of the current 700 J has been included in the proposed new energy look-up-graph in Figure 3.10 in Section3.3.3.3.

A further concern raised by one manufacturer was for one box M1 vehicles (typically mini MPV's) where the front face and windscreen are essentially flat and the front occupants are positioned very close to the front of the vehicle. Depending on their size, the windscreen base of these vehicles could be involved in the upper legform test or be part of the child headform test area. For this type of vehicle, providing occupant protection and structural integrity of the passenger cell is very difficult and it is thought that there will be some incompatibility between occupant and pedestrian protection. There appear to be two options to resolve this. One is to exempt some parts of this type of vehicle from pedestrian tests. In this case it is recommended that this be done on a vehicle model by vehicle model basis, depending on where the occupant protection features conflict with pedestrian ones. It is noted that this might be difficult to manage within a Directive-type regulation. Alternatively the manufacturers can restyle the vehicle by adding a short energy-absorbing nose that would both provide pedestrian protection and add to the occupant protection. Although it is acknowledged that this second option would effectively outlaw one current vehicle style, it is not thought that adding a nose would have any serious implications on vehicle requirements (functionality or regulatory).

10.2.3.5 Wing stability

To reduce the severity of a head impact to a wing edge, it is important to provide the correct stiffness and crush depths. The wing edge is normally attached to an extension of the inner wing or to the upper longitudinal reinforcing load member. Currently the wing edge and joint often form a rigid box-like shape and for some vehicles there is insufficient space to absorb the headform energy between the wing edge and the strong underlying upper longitudinal load member. In many cases minor adjustments to the design can release sufficient clearance. However, current wing edges are designed to accommodate external forces such as a person pushing on the wing or sitting or leaning on it. In addition, the rear edge of the wing must be well supported to prevent it intruding into the door opening area in minor accidents. These requirements conflict with the low stiffness requirements for a child headform with a mass of 2.5 kg.

10.2.3.6 Bonnet

As for the wing edge, manufacturers are concerned that the low mass of the 2.5 kg child headform impactor, used in phase two of the EC Directive, will require the bonnet stiffness to be very low which would make it vulnerable to damage.

Other requirements of the bonnet are that it must be torsionally stiff enough not to plastically deform when opened from one side rather than from the middle. The bonnet must also be rigid enough to prevent fluttering at high speeds due to aerodynamics and wind forces. Both of these requirements of the bonnet may be tested in sub-system tests by the manufacturers and have been shown to provide practical limits for how deformable the bonnet can be.

For large vehicles such as Sports Utility Vehicles and off road vehicles, the height of the bonnet leading edge may be close to a Wrap Around Distance (WAD) of 1000 mm. Therefore the child headform test zone would start only one headform radius back from the bonnet leading edge reference line, whereas in normal saloon cars there is a larger gap between the bonnet leading edge reference line and the start of the child zone. Therefore for these large vehicles, the child headform test may impinge on body features such as the headlamp mounting and the bonnet lock and underlying upper cross-members. It has been suggested by one manufacturer that for SUVs, it is not feasible to design enough reduction of stiffness into the area around the headlamps to meet the HPC < 1000 limit for the 2.5 kg headform, even at a reduced impact speed of 30 km/h.

Therefore, there may be some conflict between a bonnet that is soft enough and has adequate crush depth below, with the functional requirements of a bonnet that can be opened and closed without damage and not flutter at high speed, and the necessary underlying components such as the headlamps and upper cross-member.

10.2.3.7 Windscreen scuttle

To protect the head of a pedestrian from making a hard contact with a windscreen wiper spindle, the spindles should be located in a position shielded from impact by the rear edge of the bonnet and at a depth below the bonnet for appropriate energy attenuation before impact. When impacted by the headform directly or indirectly the wiper spindles need to be capable of deforming or moving down. However, to function in rain, to resist wind loads at high speed, to withstand freezing-on and snow loads, requires strong and rigid mountings. This conflicts with the need for it to deform for pedestrian protection. One approach to overcome this conflict is the use of rigid but frangible wiper mountings. This method is used on the Honda Civic and failed as intended when tested in the Euro NCAP test with an adult headform. However, as reported by Lawrence *et al.* (2002), only one of the two frangible mountings failed in a 2.5 kg child headform test, giving a HPC of 1539. Two other hard spots are often found in the scuttle areas. The first is where an air-intake chamber for the vehicle interior is formed, typically between the base of the windscreen and the engine bay, by extending up the engine bay bulkhead (firewall). This extension typically makes a hard point at the rear of the bonnet because it is used to support the bonnet and to seal the engine bay. However, in prototype vehicles this extension was being replaced with a deformable plastic trough. The second point is the base of the windscreen, which as well as supporting the windscreen also provides a further cross-member to improve structural integrity. However, a solution for this area has already been found in the Honda Civic where a ‘C’ sectioned member is used to provide the necessary structural properties and there is also a cantilevered windscreen support, which can deform under head impact.

Feasibility may be particularly difficult for vehicles with bonnets of such a length that nearly all of the bonnet top test area is within the child zone but where small adult areas exist close to the base of the windscreen. Accident data considered by IHRA suggests that head contact for larger children can be up to a wrap around distance of 1700 mm. One solution, for vehicles with a small adult headform test area, would be to allow the manufacturer to nominate to use the child headform in the adult area or to nominate the adult zone, point by point, to be tested with either the child headform or the adult headform. However, as this relaxation is only needed for vehicles with a small adult test area it is suggested that, if this option is used, it is restricted to vehicles where all parts of the bonnet rear reference line are 1700 mm or less from the current transition line of 1500 mm. Both EC proposal and the GTR have moved the transition zone to 1700 mm. This change is likely to move this feasibility problem to a different group of vehicle sizes and or styles. However, the justification for this type of relaxation is far weaker with a 1700 mm transition line because it is already at the rear of the zone identified by accident data and it is not included in the GTR.

10.2.4 Cosmetics

Styling and / or aesthetic considerations are very important to the car buyer when deciding which car model to purchase. Therefore, these features are also very important to the car manufacturers, who not only strive to make their cars attractive but also to create a brand style. However, it is difficult to judge the importance of these considerations against providing pedestrian protection. For some vehicle types a compromise may be comparatively easy to find where some room is already available and the style is such that changes for pedestrian protection will have little impact on appearance. However, for some current vehicle types such as sports cars and large executive cars, changes for pedestrian protection might detract from the vehicle’s appearance. For example more crush space in the wheel arch area could be released by fitting smaller diameter wheels, but this would go against the current fashion for this type of vehicle to have large wheels.

To take the upper legform test area as an example, the bonnet leading edge area provides interesting pedestrian protection, packaging and aesthetic conflicts. Until recently, to look pleasing to a potential car buyer it appeared desirable for a saloon type vehicle to have a low bonnet leading edge. However, this fashion is less apparent now, with taller front ends becoming more popular, for example the Volvo S40 and the Audi A4. A low bonnet leading edge causes the packaging of the engine components to be difficult and there is very little space available in this region. To absorb the energy from an upper legform test, as detailed in the EC Directive, sufficient crush depth is required. If it is not possible to provide this space due to packaging issues then the only options are to make the underlying package items deformable or to change the vehicle shape by raising the bonnet leading edge. This will dramatically change its appearance and the risk is that customers will not like the adjusted image for the type of car they were considering purchasing.

Therefore styling and aesthetics considerations may be in conflict with the pedestrian protection requirements of phase two of the EC Directive.

10.2.5 Approval and conformity of production

Modern design methods used to develop new cars make extensive use of computer simulations to show if the design will comply with safety regulations. However, by their nature, computer simulations due not give a perfect evaluation of a vehicle’s real-life performance. For current regulations this is allowed for by the manufacturer providing a margin of protection above the minimum legislative requirement. These modern design methods combined with engineering judgment and experience mean that manufacturers have a high confidence that their design will pass the current regulatory approval test before a representative physical vehicle is made. Manufacturers are able to take advantage of this confidence by reducing the amount of prototype testing, and save time and investment by committing themselves to producing production tooling, etc. at a comparatively early stage in the vehicle’s development. However, it is very likely that pedestrian protection performance will be more difficult to predict accurately because the impact energies are far lower than normally found in vehicle to vehicle or vehicle to roadside object type accidents.

Manufacturing processes are inherently prone to slight variations from one item to the next. This is a problem for vehicle manufacturers because vehicles are made from large numbers of components; small variations in these might influence the overall safety performance of each car made. Also the necessary tolerances on impact velocity, direction, etc. within the pedestrian test methods will also give rise to some further variation in test results. To ensure that the first vehicle used in the approval tests and all of the vehicles subsequently produced will or would be able to meet legal requirements for that vehicle, the manufacturer normally designs the vehicle to be inside the requirements by as much as 20 to 25 percent. This is usually taken to be the acceptable approach when considered against the consequences of failing to meet the regulatory requirements of:

- failure to obtain type approval of a new model at a late stage in its development – rectifying this might be very expensive.
- withdrawal of the type approval for the model until necessary improvements have been made if manufacturing variations of vehicles produced after type approval are shown to take some examples outside the regulatory requirements - implying substantial financial losses for the vehicle manufacturer.

One vehicle manufacturer has suggested that a larger margin may be required for the bending angle criterion in the legform test, but as can be seen in Section 3, proposals have been made to tighten the tolerances on this test to reduce this variation.

The net effect of the manufacturers' allowance is that the vehicles will be safer than implied by the minimum regulatory test requirement. This would be beneficial as it would result in additional casualty savings. However, where it is difficult to provide the minimum regulatory requirement, the need for this additional margin of safety could make the task even more difficult and thus adversely affect the feasibility of meeting the legislation. In this case the legislative protection requirements could be adjusted so that the protection provided, including the manufacturers' allowance, equates to what is currently required.

10.2.5.1 Failure to comply and difficult areas

The problems for vehicle manufacturers to accurately predict the pedestrian protection performance of a vehicle during the design stage are exacerbated by the large test areas on the vehicle, which reflects real-life pedestrian accidents. Therefore, there is a risk that a manufacturer could have nearly completed the development of a new vehicle and made all of the associated investment, before finding that one small and difficult to change area exceeds the performance requirement. This problem is addressed to some extent in the first phase of the EC Directive by the use of a manufacturer nominated zone with less protection for the head. Currently the second phase of the EC Directive removes this option; however, unless this principle is included in phase two and extended to all the tests areas, there is a risk that some vehicle designs would need extensive and expensive modifications at a late stage in their development if one small area is found to exceed the performance criteria by a small margin.

There are a number of 'difficult areas' highlighted above such as the wing edge and scuttle for the headform test and it is thought that similar areas are likely to be found for the other tests. For the upper legform test, areas such as the joint between the bonnet and wing and the joint between the cooling pack and headlamps, could prove to be difficult stiff points. Similarly for the bumper, areas around the ends of the chassis rails and towing eyes could prove to be difficult due to excessive stiffness or insufficient crush depth. The proposal for manufacturer nominated zones in the paragraph above, to help prevent late and costly failures in compliance, could also be used to improve feasibility for these difficult areas. It is noted that the current draft of the GTR includes such relaxation zones for the bumper and bonnet top test area.

One manufacturer provided simulated headform test data for the bonnet top, bonnet latch, bonnet to wing edge, wiper spindle and the hinge area. These results suggested that a HPC of 2000 was feasible at an impact speed of 40 km/h using a child / small adult 3.5 kg headform. Their only concern was for the wiper spindle of small vehicles where it would be in the child test area and in this case the simulation results were HPC 2031. However, Lawrence *et al.* (2002) tested the wiper spindle of the Honda Civic at 40 km/h using a 2.5 kg headform and this was shown to give a HPC of only 1539. As the principal problem in these difficult areas is that of excessive stiffness due to functional requirements, then it can be concluded that better results should be possible with the adult headform. In addition as reported in Section 7, Table 7.1, tests of three locations on the wing edge of the Honda Civic at 40 km/h, using a 3.5 kg child headform, gave a worst HPC of 1523. Therefore, overall it appears reasonable to conclude that a HPC of 2000 would make these difficult areas feasible.

10.2.6 Restrictions due to overlapping test zones

To provide effective pedestrian protection it is necessary for each contact point on the vehicle to be sufficiently soft to keep the loading on the pedestrian’s body part concerned below the injury threshold. By breaking the impact up into discrete phases and concentrating on certain ‘most at risk statures’, it is possible that features dangerous at later stages of an accident or to other statures might be encouraged in the individual sub-system tests. However, if as intended by EEVC (European Enhanced Vehicle-safety Committee, 2002a), these undesirable features are failed by the next test then they too will have to be made to provide effective protection and a revised solution will have to be found for the first test. Thus in this case the overlapping of test zones will be beneficial. In the current second phase of the Directive, the combination of test methods and test zones is intended to achieve this effect. However, overlapping of different requirements for different pedestrian statures can in some cases either provide less appropriate protection or areas where one part of the vehicle must pass two different requirements which will generally require larger crush depths. Obviously the removal of one or more of the tests could negate this method of discouraging inappropriate designs.

10.2.6.1 Legform tests

In the legform to bumper test, the femur section of the legform impactor often makes a contact with the bonnet leading edge at some stage during the impact. This can be beneficial in reducing the lateral bending angle of the impactor’s knee. One manufacturer showed simulation results where the stiffness of the bonnet leading edge had been optimised to achieve the best knee bending angle in the legform test. They concluded that there was a conflict between the legform test and the upper legform test because, for the range of car shapes considered, these results showed that the optimal bonnet leading edge stiffness for the legform test did not always match that required for the upper legform test. However, it was pointed out that as the femur section of the legform is not intended to control the bonnet leading edge stiffness, then the failure of any overly strong bonnet leading edge in the subsequent upper legform test was in fact the two tests working together as intended.

10.2.6.2 Upper legform

The front upper cross-member needs to be comparatively strong because it provides the mounting for the bonnet lock, the upper fixing for the cooling pack and forms the necessary link between the upper load paths in the inner front wing area. For vehicle shapes that warrant large upper legform test energy, one option is to move the upper cross-member slightly more rearwards in order to obtain sufficient crush potential in front of it. However, for some vehicles this could result in it being moved into or close to the child headform test zone. In many cases this will mean that the bonnet lock, striker, etc. are behind the main upper legform deformation area. In this case it is thought that by providing sufficient clearance between the bonnet top and the cross-member, and by the use of a collapsible or push through bonnet striker (as described in Section 11), it should be possible to provide protection for the child headform. For vehicles where the bonnet leading edge is on or behind the 1000 mm wrap around line, the Directive already includes a relaxation by moving part of the child headform test zone back one headform radius. Therefore for both vehicle shapes, it is not thought that the potential overlap, which reflects the real-life overlap between children and adults, is insoluble, particularly when the changes to the second phase of the EC Directive proposed in Section 3 and later in Sections 10.4.1.4 and 10.4.1.5 are taken into account.

10.2.6.3 Headform tests

In phase two of the EC Directive, the headform test switches from the child test to the adult test at the 1500 mm Wrap Around Line (WAL) between the child and adult test areas. It is obviously almost impossible to have a step change in the stiffness each side of a line, (unless the line falls on a joint in the structure) so it is not practical to have an optimum stiffness for the different headform masses. Therefore the only solution is to bias the stiffness towards the lighter child headform and to have a larger crush depth in the transition area than required for just one headform mass. As discussed in Section 3, this overlapping requirement matches real-life accident data which show that there is an overlapping zone hit by the heads of both tall children with lighter heads and short adults with heavier heads. This overlapping requirement means that a larger crush depth is required in this area. Large crush depth under the bonnet (and wing edges if within the test area) is difficult to provide and could result in the bonnet height having to be significantly increased in this area, which has implications for view angles. Therefore, there could be feasibility problems in this transition area, particularly for some styles of vehicle. However, the change in child headform mass recommended in Section 3 from 2.5 kg to 3.5 kg would reduce the differences in mass between the two headforms and therefore this feasibility problem. The use of one of the alternative 4.5 kg adult headforms instead of the phase two 4.8 kg headform was discussed in Section 3 and it should be noted that use of the slightly lighter 4.5 kg headform would further reduce the difference between the two headforms and therefore further reduce the feasibility problems around the transition between child and adult. In addition, it is recommended that a zone within the main bonnet top test area, where the performance requirements are less demanding, be introduced to help improve the feasibility in areas where protection is particularly difficult. This relaxation zone could take a similar form to the nominated one third HPC 2000 zone in phase one of the Directive.

10.2.7 Worldwide harmonisation

The use of different test methods and test tools in regulations in different countries could also lead to problems for vehicle manufacturers who wish to sell the same vehicle models worldwide, as the vehicles will have to meet the applicable regulations for all regions. At the simplest level, this may just cause further testing expenses. However, where test methods are different from one region to the next, then some areas of the vehicle might have to pass more than one test requirement. At present there are two approved pedestrian protection regulations, the EC Directive and the Japanese MLIT pedestrian head procedure. Other pedestrian test procedures such as IHRA, GTR and ISO could also be incorporated in legislation in the future. Therefore, there are already different pedestrian requirements in two different countries / regions. This is only a problem for vehicles approved worldwide if there is a conflict between the test requirements. If the proposals to change the headforms used in the second phase of the EC Directive are accepted then there will be no significant conflicts between any of the current pedestrian test procedures. Although some pedestrian procedures have more demanding (higher speed) tests and some tests of extra areas of the vehicle, provided that the most demanding requirement is met then the vehicle should also be able to pass the others.

It is also possible that pedestrian protection requirements could conflict with other regulatory requirements, as discussed above in Section 10.2. Although no fundamental conflicts have been found, it is thought likely that for some types of vehicle it may be difficult to meet both phase two of the EC pedestrian protection Directive and the most demanding bumper damageability requirements, those of Canada. It is recommended that the Canadian authorities consider whether they have the correct balance between minimising vehicle disablement / repair costs and pedestrian protection. If, due to their demographic, environment and climatic situation or any other special national requirements, it is shown that the consequences of vehicle disablement due to damageability are more serious than the potential savings in pedestrians injured then it might be reasonable not to have full harmonisation and special national editions of a vehicle model would be justified.

10.2.8 Limitations of deployable systems and conflicts with surfaces that remain

As discussed in Section 6, only deployable or pop-up bonnets, triggered by some form of bumper contact switch, are thought to be sufficiently well developed for use in the near future. Systems of this type are likely to be arranged so that they only deploy at speeds broadly around 40 km/h and do not deploy at very low or very high speeds. One reasonable requirement would therefore be to require the system to absorb sufficient energy in the down position that it would be safe for head impacts at a speed of, for example, the minimum trigger speed plus 10 percent. It would also be reasonable to require it to deploy with sufficient speed that it would be safely raised before head contact so that protection is provided with full bonnet lift at speeds of up to at least 55 km/h. This may also require the upper activation cut-off velocity to be set with some safety margin, to minimise the risk of the head of a pedestrian striking an upward moving bonnet. However, it may be that in high-speed impacts it is on balance safer to be hit by a still deploying bonnet rather than by one that has not been deployed, particularly when the bonnet is in the stabilisation phase rather than the main lift phase; in this case the upper activation cut-off velocity should be set to a higher value. It should also be noted that the lower and upper activation cut-off velocities will relate to vehicle speed, and in the case of head-on and tail-on pedal cycle impacts this could mean that the system does not deploy in accidents where the closing speed is close to the 40 km/h speed that the test procedures are designed for.

Although the rules suggested above are reasonable they will probably need to be tailored for each vehicle and system. If these or similar rules are applied then the protection provided will generally match or exceed (due to larger crush depths) that of a passive deforming solution, up to the upper activation cut-off speed, but above that speed it would provide less protection than a non-deploying system. Depending on the cut-off speed this would mean that a small number of generally above-average strength pedestrians would not be saved in high-speed accidents. Nevertheless, as pop-up solutions, due to their cost, are thought likely to be used only on vehicles where conventional deformation methods are not practical, this compromise is thought acceptable.

A further possible complication with deployable systems is how the pedestrian would interact with it when impacts overlap with the remaining ‘fixed’ surfaces. It is thought that there could potentially be two main areas of concern. The first is the wing edge and the second is the scuttle area behind the raised bonnet.

It is recommended that the side reference lines be determined with the bonnet down, as otherwise the edges of raised bonnet could in some cases inappropriately form the side reference lines. Also, the area where impact points can be chosen (at least a headform radius in from the side reference lines), should be established with the bonnet down. However, if there are impact points on the wings these should be tested with the bonnet deployed, even if this means that the headform when aimed at the selected ‘impact’ point first makes a glancing impact with the edge of the bonnet instead or as well as a wing impact. In such cases the headform will be deflected so that it does not make first contact with the selected ‘impact’ location. As this would probably happen in real life, the normal tolerance on achieving the correct impact location should be waived. Manufacturers that design in a deployable bonnet will want to avoid the complication of testing the wing edge, which is often a difficult area to make safe, so they are almost certainly going to ensure that the deployed bonnet covers the full width of the ‘effective’ tested area, i.e. the full width that receives a significant impact, although the wing may still see a low-energy secondary impact. In the case of a double contact with bonnet and wing, irrespective of which was the defined impact, these should both be considered as part of the main impact for the purposes of determining the HPC value. For vehicles with a pop-up bonnet inside the side reference line the test authorities will be able to select test positions with the worst combination of bonnet and wing edge impact.

For vehicles where the headform test area extends behind the rear edge of the pop-up bonnet, it is again recommended that the rear reference line and a line one headform radius forward of it, be marked in the non-deployed position and the bonnet be tested in the raised position. Again the authorities will be able to select the worst combination of bonnet and scuttle impact for the head. In this case it is possible to imagine that in real life, some undesirable loadings could occur to the pedestrian's neck for example. It is not thought possible to provide a generic rule to examine the risk of this type of loading but it is recommended that manufacturers provide proof that this risk has been considered and minimised, when they provide the proof required in the Directive that the system works as intended.

In a similar way some deployable systems may affect measuring up and testing for the bumper and bonnet leading edge tests. These could include deployable systems in those impact areas if they used pre-impact trigger systems. Deployable bonnets could affect both bumper and bonnet leading edge impacts if they deployed before or during those phases of an impact with a pedestrian. This would probably not be the case with post-impact triggering but probably would be with pre-impact triggering. The bonnet leading edge reference line should be determined with the bonnet deployed if the bonnet is likely to be deployed for the bonnet leading edge stage of a pedestrian impact. This reference line is sensitive to the bonnet angle so bonnet deployment could change it even though the bonnet only pivots about this area. It is suggested that manufacturers should provide appropriate information for this case along with other data required to show that the system works as intended (as required by the Directive).

With any system involving airbags the impactor will not make first contact with the defined 'impact' location, so the normal tolerance on achieving the correct impact location should be waived or modified as necessary to be a tolerance on impact trajectory instead.

Consideration will be needed with each deployable system as to whether it can be deployed and then tested at some later time or whether the impactor will have to be delivered at approximately or precisely the correct time, as determined from simulation or dummy tests. A correctly timed impact could be achieved by linking the propulsion system release to the trigger circuit of the deployable system.

The development of a prototype sensor legform designed to test the trigger system of a pop-up bonnet is described in Section 7.2. This prototype sensor testing legform was designed to test a specific type of bumper contact switch. It is thought to be essential that each type of trigger be tested as it is to be used on the vehicle, with a test device that matches the human properties that the trigger system is intended to be sensitive to. The trigger test tool must also represent the full range or worst-case pedestrian statures and pedestrian motions likely to occur in real life. In most cases it is thought that this means that the sensor test tool will not be the same as the EEVC legform impactor. For deployable systems, because of the need to tailor the sensor test device to the technology used, it is not possible to provide firm rules for the test programme needed to show that it 'works as intended' as required in the Directive. However, it is recommended that some form of generic protocol be produced, to guide the testing of both the trigger and the whole deployable system to show that it works as intended. A protocol was proposed by Chinn and Holding (2003) in their guide to assessing active adaptive secondary safety systems. One concern raised in Section 3.1.4 was that sub-systems tests do not take account of an earlier contact which might in some circumstances compromise protection intended for a later contact (i.e. the shoulder collapsing a bonnet before head contact may remove the protection for the head). This may be of particular concern for pop-up bonnets which are very likely to be more poorly supported than conventional (non-pop-up) bonnets. This is because most, if not all, conventional bonnets have some support along the wing edges and along the back. However, a pop-up system is normally only supported at the front and at the two corners at the rear so it is far more likely to collapse before head impact if other parts of the pedestrian make heavy contact. Therefore, a protocol should include an assessment of the risk of earlier contacts compromising protection for later contacts. Some compromising may be acceptable for unusual impact scenarios such as heavy shoulder contact, because it might also be shown that this reduces the subsequent head impact velocity; however, it would only be acceptable if it is shown that this is true for all impact types and pedestrian statures.

To meet the HPC requirement using the minimum crush depth, the bonnet must have a uniform and appropriate deformation stiffness. Pop-up bonnet systems offer the benefit of increasing the available crush depth over the hard underlying structures in the engine bay. However, due to the short time available for activation the bonnet must be stiff enough to avoid plastic deformations when lifted and to avoid excessive oscillations during the lifting and arresting phases. As failure to trigger would be unacceptable, the triggering algorithm is likely to be set such that it will give the benefit of the doubt to the pedestrian, so that on some occasions it will fire the bonnet when unnecessary (e.g. when hitting a traffic cone). In this case damage to the bonnet during the lift would be unacceptable because it would result in prohibitively high repair or resetting costs. Excessive bonnet oscillation excited during the lift and arrest phases could add to the head acceleration and increase the risk of head injury. This should also be minimised.

It can be seen that there could be some conflict between the stiffness required to provide pedestrian head protection and that needed for the bonnet to operate as required. Some mathematical simulation results were provided by a sports car manufacturer of a bonnet that was designed to comply with phase one of the EC Directive. These showed that it met the phase one requirements, but when tested to phase two there were some high child HPC values in the hinge area and around the reinforcement that had been added to resist damage during activation. It is thought likely that this problem could not be resolved fully by optimising the bonnet for phase two. However, the increase in child headform mass proposed in Section 3 is thought likely to partially or completely resolve this problem and the option to nominate any remaining problem areas for the relaxed test requirement should remove any final concerns regarding feasibility.

10.3 Discussion of feasibility

When proposing the negotiated agreement, ACEA also proposed that a feasibility study was required for the second, more difficult phase. This proposal was accepted by the European Commission, included in the Directive, and a specification was produced for a feasibility study (Lawrence *et al.*, 2004a). By supplying data to Lawrence *et al.* (2004a), the car industry has taken the opportunity to present formally their data and observations on feasibility issues. Two of the manufacturers that were visited reported results of tests / simulations on experimental vehicles, consisting of a combination of a modified mule vehicle and simulated vehicles, that were made to meet, as far as was thought feasible, the phase two requirements. In addition, one manufacturer presented results of a vehicle close to launch, that was designed to meet phase one but had also been assessed to phase two using mathematical simulation. These results highlighted a number of feasibility issues but made no suggestions as to what changes were necessary to make phase two feasible. Subsequently, one manufacturer supplied results of a programme of mathematical simulations that was aimed at showing the maximum protection that could be achieved in phase two. These results were particularly useful as they took into account the possible changes to phase two that had been discussed.

One way to determine whether the pedestrian protection requirements are fundamentally in conflict with current vehicle designs is to examine test results. The Honda Civic was tested by Euro NCAP using EEVC WG10 test methods (Euro NCAP, 2001) and again by Lawrence *et al.* using EEVC WG17 test methods (Lawrence *et al.*, 2002). The Lawrence *et al.* (2002) test results showed that much of the Civic's bumper and the bonnet leading edge passed the EEVC WG17 requirements with the remainder close to passing and some areas of the bonnet top passed the child headform requirement, with much of the remaining areas being reasonably close to passing. EEVC WG17 introduced a small reduction in the bonnet top test area by changing the bonnet rear reference line definition. This resulted in no adult tests in the Lawrence *et al.* (2002) study of the Civic however; the windscreen base was tested in the Euro NCAP tests and two adult headform passes were obtained.

Although no one car in the Euro NCAP programmes of pedestrian tests has met all of the protection requirements of phase two of the EC Directive over the full test area, the results have shown that areas of some of the vehicles can comply with the requirements. Examination of Euro NCAP data show that examples of areas passing each of the test tool performance requirements (to EEVC WG17 and Directive phase two) can be found on many vehicles, although not necessarily for all of the test area or all of the test tools on the same vehicle. These results show that the stiffness and crush depth required for pedestrian protection are already considered acceptable in some areas of current designs. However, before more conclusions on feasibility are drawn from the Euro NCAP data, it is important to determine whether the manufacturers of the cars tested were making any strenuous efforts to provide pedestrian protection. Over the years that the Euro NCAP test programme has been running, many of the cars have been tested at TRL and, when time was available, they have been examined to determine the cause of good and poor pedestrian protection. Although not exhaustive, this monitoring has suggested that, with some recent exceptions, little effort has been made to provide pedestrian protection. This is thought to be due to manufacturers responding to consumers showing less interest in pedestrian protection than in occupant protection. However, the improvements seen in the some recent models where effort was made to enhance pedestrian protection show that significant protection is feasible, although the protection does not necessarily meet in full the current requirements of the second phase of the EC Directive.

The JARI report on the development and assessment of the Flex-PLI (Konosu and Tanahashi, 2003b) criticised the EEVC WG17 impactor for, amongst other things, not matching the knee bending corridor selected by JARI. However, the WG17 corridor, that the impactor was designed to meet, is very different from that selected by JARI. The situation regarding knee bending stiffness has been discussed in Section 3.1.1.1 and the authors of the present report have concluded that on the basis of the information currently available the EEVC WG17 knee joint stiffness is more appropriate to represent the living human than the lower stiffness selected for the Flex-PLI legform impactor. Nevertheless, others may come to a different conclusion and recommend that a lower stiffness be used in the WG17 legform for a new regulation. The knee bending ‘ligaments’ of the WG17 impactor could easily be modified to meet a different (lower) bending stiffness requirement such as that proposed by JARI but, changing the stiffness would have consequences for 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. The study made use of the 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 two following tables have been copied from the report to WG17, (Staines, 2005).

Table 10.1: 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 at the best location and with the phase one requirements 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 JARI proposal 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, if changes to the knee bending stiffness are to be considered then a study of the effects on feasibility should be carried out before any decision is made. This also applies to using the current version of the Flex-PLI.

Table 10.2: 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

10.4 Implications of feasibility issues for the Directive

For compliance of a vehicle with the EC Directive and the ensuing type approval, all variants of the vehicle must be covered. This includes all combinations of available engines, power-trains, equipment and trim. Therefore the 'worst case' combination needs to be taken into account for the design envelope. Considering head and upper leg impacts, this would probably be the largest engine variant as this is likely to give the smallest available crush depth between the bonnet outer skin and the hard underlying engine surface. If compliance with the Directive is not thought to be feasible for the 'worst case', as has been suggested by manufacturers, then unless some changes are made to phase two some types of cars would need to be removed from the market due to the 'technical impossibilities' of passing the requirements. Worse still, if it proves unfeasible to make vehicles that have the entire test area meeting the phase two performance criteria, it will be impossible to obtain approval for new vehicle designs.

Proposals have been made to improve the test methods and these changes would also have the effect of improving the feasibility of meeting phase two of the Directive. Overall, the authors' have concluded that pedestrian protection to meet these revised requirements could be feasible in principle, without the need for additional changes to take account of the feasibility problems outlined above. However, when all the vehicle performance requirements discussed above are considered in conjunction with the wide range of vehicle styles and variants currently available, the authors have concluded that it will be necessary to introduce additional feasibility measures.

The author's understand that the GTR (Informal Working Group on Pedestrian Safety, 2006), with the additional requirements for the upper legform test to be carried out with targets for protection and brake assist systems to be fitted to all cars, is likely to form the basis for an EC proposal for legislation to replace the current Directive (2003/102/EC). For the bumper and the bonnet top the differences between the GTR and phase two of the current Directive are thought to be sufficient to address the feasibility issues discussed above. For the bonnet leading edge a combination of proposed changes to improve the test method described in Section 3.3.3.3 and the use of the test for monitoring purposes with target, rather than mandatory, protection requirements will resolve feasibility issues for this area. Although some of the differences between the draft GTR and the current phase two Directive requirements are not necessarily regarded by the GTR group as being for feasibility reasons they are listed below under feasibility as this is also their effect.

10.4.1 Improvements to the test methods and changes for feasibility

For this study, data have been gathered on feasibility issues from a number of sources including discussions with car manufacturers, examination of cars with good pedestrian protection and the authors’ experience over a number of years. These issues have been judged primarily against the current requirements in the second phase of the EC Directive. However, a number of changes to improve the test methods have been suggested in Section 3. As most if not all of these changes affect the feasibility of providing protection, they also need to be considered when proposing changes on feasibility grounds.

As discussed in Section 3.3, one effect of legislative requirements is that, in practice, car manufacturers have to achieve a higher level of protection than the minimum requirements. This higher level of protection is required, firstly, to ensure that the first few vehicles produced for regulatory approval tests actually pass. Secondly, following approval they are required to ensure that when the vehicle is in mass production that the ‘worst’ combination of manufacturing and test variations would not result in a vehicle that would exceed the performance requirements. The net effect of this is that manufacturers typically aim to be inside the protection requirements by about 20 or 25 percent and, in addition, they will have to allow some extra crush depth in case the vehicle is slightly softer than intended. These manufacturers’ additional tolerances are likely to mean that typically most vehicles will protect a greater portion of the population at the intended impact speed and be safe for most pedestrians at slightly higher speeds than the intended impact speed, which in the case of the second stage of the EC pedestrian protection Directive is 40 km/h. Obviously, with most regulations this is not a problem as it results in additional savings; however, in this case these extra margins make the regulation less feasible. As concluded above, it is necessary to introduce additional measures to improve feasibility. One option for doing this is to increase the performance criteria by the manufacturer’s allowance. The net effect of this option will be that the average performance of the cars produced will meet the intended protection levels but some cars, or locations on them, will be slightly worse than intended and some slightly better.

The proposal, in Section 10.2.5.1, that for each test area the manufacturer should be allowed to nominate part of the test width or test area as a ‘difficult area’, attracting a less demanding protection requirement, is thought to significantly improve the feasibility of the second phase of the Directive. This principle has been included in the GTR for the bumper and headform test methods. For brevity this concession is referred to as a ‘nominated relaxation zone’ in the following Sections.

Below, the changes to the test tools, methods and criteria proposed in Section 3 are considered, along with the GTR proposals.

Although these proposals are for a complete package that could be used to revise the phase two test methods and requirements, there are a few technical issues where some further work might be required.

10.4.1.1 All test methods

The EC Directive does not have a tolerance for the accuracy with which impact speed is measured and it is suggested that a tolerance of ±0.02 m/s (or the tighter GTR tolerance if shown to be feasible) be added for all test procedures. This will help manufacturers by reducing test variability.

10.4.1.2 Legform test

Although manufacturers have expressed some concerns about meeting the legform test requirements of phase two of the Directive, most appeared to have concluded that it could be feasible. There are no new technological developments to aid the protection of pedestrians in the bumper area that are at a stage of development so as to be available for use to meet phase two of the Directive. There are a number of functional and legislative requirements that overlap with this test, but overall the data reviewed suggest that protection to the phase two requirements is possible. Proposals have been made to improve the legform-to-bumper test method in Section 3 and these are also thought to reduce the difficulty of meeting the protection requirements, by making the test easier to pass or by making it more repeatable. These proposals are listed below:

- Add a shoe thickness allowance so that the foot end of the impactor is required to be 25 mm from the ground at first contact;
- Halve the legform height and verticality (in the longitudinal plane) tolerances at first point of contact to ±5 mm and ±1°;
- Increase the knee bending angle performance criterion from 15° to 19° (as recommended in Section 3.3.1.4);
- Add new requirements for the relative humidity to be controlled to 35 ±15% in the vehicle test and to 35 ± 10% in the legform dynamic certification test.

All but the second of the above proposals are included in the draft GTR. Although reducing the tolerance for the position of the legform at first contact would help to reduce test variability it is not thought essential to include this suggestion in a revised phase two regulation.

The draft GTR changes affecting the feasibility issues for this test are listed below:

- Increase the acceleration protection requirement for the bumper from 150 g to 170 g.
- Allow manufacturers to nominate bumper test widths of up to 264 mm in total, for testing with an acceleration protection requirement of 250 g. *(This will provide a more controlled relaxation than currently allowed in phase one where derogation (no test) is allowed for a removable towing hook. It is thought more reasonable not to link this relaxation to specific features such as towing eyes so that it can be used for any difficult area.)*

10.4.1.3 High bumper test

There are no new technological developments to aid the protection of pedestrians in the bumper area that are at such a stage of development so as to be available for use to meet phase two of the Directive, so it will be necessary to absorb the test energy by deformation.

Proposals have been made to improve the upper legform to high bumper test method in Section 3 and these are also thought to make the test more appropriate and more repeatable and they are listed below:

- Revise the definition of the ‘Upper Bumper Reference Line’ so that the centreline of the upper legform impactor is aligned with the centre of the bumper structure. The revised wording proposed in Section 3.3.2. (This has already been included in the draft GTR with the exception of the suggestion to improve the figure). *(Originally the upper bumper reference line was only used to determine the bumper lead for the bonnet leading edge test. When adopting this line for their new high bumper test, WG17 failed to notice that for the higher ‘high bumpers’, this would result in the upper legform to bumper test not being centred about the 'real' bumper front face.)*
- Where permanent towing hooks are positioned beneath a high bumper, in such a position that they are not contacted by the upper legform impactor in the test, then they must be set back at least 150 mm behind the front face of the bumper.
- Add a new requirement for the relative humidity to be controlled to 35 ±15% in the vehicle test and to 35 ±10% in the upper legform dynamic certification test.

All but the second of the above proposals are induced the draft GTR.

The draft GTR changes affecting the feasibility issues for this test are listed below:

- Increase the force and bending protection requirement for the high bumper from 5 kN to 7.5 kN and from 300 Nm to 510 Nm.

- Allow the manufacturer to opt for a high bumper test when the lower bumper reference line height is ≥425 mm and <500 mm. *(Also, at heights above 500 mm the GTR requires the high bumper test.)*

10.4.1.4 Upper legform to bonnet leading edge test

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. There are no new technological developments to aid the protection of pedestrians in the bonnet leading edge area that are at such a stage of development so as to be available for use before the introduction of phase two of the Directive. However, even though it is recognised that this test may be used for monitoring purposes only and the results used to develop further any test requirements, proposals have been made to improve the upper legform to bonnet leading edge test method in Section 3 and they are listed below:

- Change the angle of the straight edge used to determine the bonnet leading edge reference line from 50 degrees to the vertical to 40 degrees. *(This will identify more accurately the centre of the upper leg impact. Note, however, that the draft GTR uses the bonnet leading edge reference line determined with a straight edge angle of 50 degrees to the vertical when defining the front of the headform test area.)*
- Replace the current upper legform test energy graph and interpolation rules with the revised one proposed in Section 3.3.3.3. *(These revised energies are based on simulations made with a more biofidelic pedestrian model than previously used and include an additional adjustment to make them more representative of a 'live' human.)*
- Replace the current test velocity curves with the revised one proposed in Section 3.3.3.3.
- Add a new requirement for the relative humidity to be controlled to 35 ±15% in the vehicle test and to 35 ±10% in the upper legform dynamic certification test.

Proposals have been made for changes to take account of feasibility issues discussed in earlier parts of this section and are listed below:

- Make it a monitoring test with target, rather than mandatory, protection values.
- Reduce the energy cap from 700 J to 500 J. *(This should make the test feasible for taller vehicles.)*
- Change to protection requirements to targets with increased force and bending moment protection requirements from 5 kN to 6.25 kN and from 300 Nm to 375 Nm. *(These changes to the force and bending moment criteria are to take account of the manufacturers' 20 percent approval / conformity of production allowance.)*

10.4.1.5 Child and adult headform tests

Research and current good vehicles show that large parts of the headform test area can provide significant levels of head protection; however, protection to the phase two requirement for the full area is not thought to be 'feasible' in problem areas such as the wing edge and bonnet hinge area. The concern about the feasibility of providing the low stiffness implied by a 2.5 kg child headform, and the change in bonnet stiffness needed between the child and adult head test areas, are addressed by the proposed changes of mass to both headforms and the provision of a relaxation zone.

Proposals have been made to improve the child headform test method in Section 3, which are thought to make the test more appropriate; the proposals are listed below:

- Replace the 2.5 kg child headform impactor with a 3.5 kg headform impactor for testing the child test area.

- Replace the 2.5 kg child headform specification with the draft GTR 3.5 kg headform specification.
- Replace the 2.5 kg child headform certification method with the draft GTR 3.5 kg headform dynamic certification method and limits.
- Replace all references to spacing for child test point selection based on the radius and diameter of the 2.5 kg headform (65 mm and 130 mm) with those of the for the 3.5 kg headform (82.5 mm and 165 mm).

The draft GTR changes affecting the feasibility issues for this test are listed below:

- Replace the 4.8 kg adult headform impactor with a 4.5 kg headform impactor for testing the adult test area.
- Replace the 4.8 kg adult headform specification with the draft GTR 4.5 kg headform specification.
- Replace the 4.8 kg adult headform certification method with the draft GTR 4.5 kg headform dynamic certification method and limits.
- Revise the head protection requirements in line with the draft GTR:
    - The HIC recorded shall not exceed 1,000 over a minimum of one half of the child headform test area and 1,000 over two thirds of the combined child and adult headform test areas. The HIC for the remaining areas shall not exceed 1,700 for both headforms.
        - In case there is only a child headform test area, the HIC recorded shall not exceed 1,000 over two thirds of the test area. For the remaining area the HIC shall not exceed 1,700.
- Revise the headform impact speed to 35 km/h in line with the draft GTR.
- Revise the transition between the child and adult headform test areas to a wrap around distance of 1700 mm.

11 Review of system costs

To limit the severity of an impact for a pedestrian when hit by a car, protective features need to be designed into the vehicle. Any feature introduced to protect pedestrians may compromise other features of the vehicle design, as discussed in Section 10. In addition to any compromise, or 'trade-off,' the pedestrian protection feature will also have associated costs. These associated costs are likely to consist of costs for development, production, fitting, etc. The following section attempts to derive the production costs for each of the individual features needed to protect pedestrians.

The features for which a cost is to be derived come from a breakdown of the general performance that a pedestrian friendly vehicle would exhibit. For example, in the bumper area, it is known that the correct stiffness, force distribution and crush depth are required. To achieve this it may require having the bumper beam set well back from the leading edge, having a spoiler well forward with respect to the bumper and tailoring the energy absorption by insertion of foam between the bumper facia and the bumper beam. These design characteristics are the features that will be used to give costs for providing the protection. To simplify the issues required to provide protection for pedestrians, the features have been separated into the areas that would be tested in phase two of the EC Directive as these are the regulatory tests that will assess pedestrian protection.

The design requirements for protection of pedestrians as identified in the following sections and in Section 2, may force compromises with the issues raised in Section 10. Ideally, to account for the feasibility of the system and give values of the greatest available accuracy, costs from the vehicle manufacturers are required. However, manufacturers are not yet in a position to provide such costs because they are concentrating on meeting phase one. The one exception found to this was with a vehicle manufacturer who was incorporating a pop-up bonnet system to meet phase one. In addition, cost data for a pop-up bonnet system were also available from a tier one supplier. It is thought that the pop-up system could be refined to meet the proposed modified phase two requirements, without additional cost. Therefore these costs can be used unchanged for a phase two pop-up bonnet system.

By estimating costs based on the proposed revised phase two requirements, the costs should relate to feasible solutions. However, they will not completely take into account the more intangible trade-off between changes in styling and manufacturing costs.

The proposed changes to the test methods outlined in Lawrence *et al*. (2004) were a combination of improvements to the test methods and changes thought necessary for feasibility. However, as has been mentioned previously, in Section 1.1, these proposals by TRL did not find any support from the experts in the area, so they are no longer pursued. This updated study, however, has not been able to rework most of the costing study from the 2004 feasibility report. Therefore some of the costs obtained do not directly relate to the current proposals, but nevertheless can provide guideline costs.

The aim of this and the following section is to produce estimates of the average additional costs for pedestrian protection for each main class of vehicle sold in Europe. However, in order to identify the pedestrian protection changes needed, with the necessary detail to produce cost estimates, it was decided to examine in detail two existing vehicles to identify the changes necessary. These detailed changes were then subjected to a cost study on the basis of making a totally new vehicle design. The new vehicle would be of the same vehicle segment and have similar architecture to the existing vehicle.

Two vehicles were selected for the detailed cost exercise, a Landrover Freelander and a Ford Mondeo. These vehicles were selected because it was thought that between them they provided an example of all of the changes necessary to make the whole vehicle fleet meet the proposed revised phase two of the EC Directive, with the exception of a pop-up bonnet. The detailed cost exercise has the advantage that the consequences of these changes can also be identified along with the costs of incorporating them in a complete functioning vehicle. These costs are effectively for a completely new version, the next generation, of Freelander and Mondeo with pedestrian protection but not for the whole European vehicle fleet. Nevertheless, as they provide costs for all of the changes likely to be necessary to enable the fleet to comply with the revised phase two Directive requirements, they can be used with suitable weighting to determine a generic cost for each vehicle segment. These can then be combined to produce an estimated fleet cost. The process of weighting and combining these costs to produce a fleet cost is described in Section 12 following.

For these two vehicles, the areas needing improvement for the protection of pedestrians were identified and modifications were suggested to address the issues.

11.1 Estimating the changes needed

As noted in Section 2, the three design concepts needed for pedestrian protection are sufficient crush depth, appropriate deformation stiffness and appropriate force distribution. Where a vehicle is deficient in one or more of these concepts, with regards to that required to meet the proposed requirements for phase two of the EC Directive, then modifications will be required. To establish whether any and what modifications are required, it is necessary to know what is required to meet the proposed phase two criteria. For each of the sub-system tests the protection measures can be estimated in terms of crush depth, stiffness and profile and these will be different for different vehicle styles and sectors. The practical minimum crush depths have been estimated for the two vehicles selected for each sub-system test. These have been calculated by making a number of assumptions including meeting the criteria or criterion. The results of these calculations are presented below for each of the test areas and are made on the basis of the proposed changes to the phase two requirements summarised in Section 10.4.1.

Other changes necessary to obtain the required shape and stiffness are proposed later where a series of specific changes have been proposed for the two vehicles.

11.1.1 Legform to bumper

For the purposes of the crush depth calculation, it is assumed that manufacturers use a 20 percent allowance on criteria. This means that the manufacturers' target values were for costing purposes about 150 g (190 g x 0.8) and 15.2 degrees (19° x 0.8), though for the current proposal the acceleration target value would be 136 g (170 g x 0.8).

As discussed in Section 10, it is proposed to have a relaxation zone, a maximum total of 264 mm of the legform test width; for this the acceleration limit will be increased to 250 g which will give a manufacturers' target of 200 g.

As tibia acceleration is the criterion that dictates crush depth, it is possible to make a calculation of the required practical crush depth for a tibia acceleration of 190 and 250 g by making the following assumptions:

- Manufacturers' targets are ~150 and 200 g
- Overall energy efficiency of the impactor flesh is 25 percent
- Thickness of the flesh is 25 mm
- Proportional crush of the flesh is 80 percent of thickness
- Energy efficiency of the bumper structure is 65 percent
- Energy absorbing materials in the bumper bottom out at 10 percent of their original thickness (i.e. 90 percent crush)

Energy efficiency here is the ratio of the average acceleration to the peak acceleration, with the latter taken to be the manufacturers' target acceleration.

These parameters can be used to give crush depths of 62 mm for the 190 g zone and 45 mm for the 250 g relaxation zone.

The 45 or 62 mm of pedestrian protection crush will also help the vehicle pass the Part 581 bumper test, as described in Section 10. Therefore some of the crush depth allocated to passing the Part 581 test can also be allocated to pedestrian protection. The Part 581 test requires the bumper to absorb the energy of a pendulum of the same weight as the vehicle, impacting the bumper at 2.5 mph (4.0 km/h), with the impacting face of the pendulum representing a standardised bumper, 24 inches (0.61 m) wide. The contribution that the crush depth of the pedestrian protection bumper makes to passing this test can be estimated using the following calculation chain:

The kinetic energy in the pendulum can be found from Equation 11.1:

$$E = \frac{mv^2}{2} \qquad \text{Equation 11.1}$$

For the Part 581 bumper test 'v' will be 2.5 mph (1.11 m/s). The pendulum mass has to equal the vehicle mass; if this is assumed to be 1000 kg, then the formula gives an energy of 617 J. For the similar Canadian bumper test, the speed is 5 mph (2.24 m/s) so using the same assumed mass, the pendulum energy for this test would be 2464 J.

The contact area of the pendulum acting on the pedestrian protection energy absorbing material will be approximately the pendulum's width (24 inches), multiplied by its effective depth. As the depth of the bumper face part of the pendulum is narrower than most bumpers, its depth will control the contact depth. The pendulum depth increases from 4.5 inches (114 mm) at the face to about 6 inches (152 mm) at the rear. If an average depth of 5.25 inches (133 mm) is assumed then the contact area will be approximately 24 x 5.25 inches, which equals 126 inches^2 or 0.08 m^2.

The crushing force per unit area of the bumper energy absorbing material (typically foam) for the pedestrian test can be estimated through the relationship of force divided by impact area. For a flexible bumper facia, the impact area is approximately 120 mm wide (as can be seen in Figure 11.1 below, where Hexcel was fitted behind the bumper facia of an experimental bumper) multiplied by the height of the bumper, which is likely to be approximately 200 mm.

Figure 11.1. Crush of Hexcel following a pedestrian legform test

Therefore the area is about 0.024 m^2. If an effective mass of the legform of 5.2 kg is assumed (the effective mass will be lower than the total mass due to the knee deforming) and an average impact acceleration of 100 g, then the force can be calculated by multiplying these as follows:

$$5.2 \text{ kg x } 1000 \text{ m/s}^2 = 5.2 \text{ kN}$$

An estimate of the pedestrian foam's crushing force per unit area can then be obtained by dividing the force by the area, which gives a value of 217000 N/m^2.

The force of the bumper on the pendulum is equal to the crushing force per unit area of the foam multiplied by the pendulum contact area:

$$217000 \text{ N/m}^2 \times 0.08 \text{ m}^2 = 17.3 \text{ kN}.$$

The pendulum energy removed by the pedestrian foam is the force multiplied by the distance. For the 190 g width, the force is 17.3 kN and the usable crush depth is 56 mm, which gives 970 J. For the 250 g nominated relaxation zone, a larger force is allowed which permits the crush depth to be reduced; however the stronger energy-absorbing material permitted will absorb about the same amount of energy per unit area as in the main zone, over the available crush depth. Therefore, the relaxation zone can be ignored in this calculation.

Both the American and Canadian tests require that the vehicle suffers no visible damage in these tests, so it is important to prevent the impact pendulum penetrating so deep into the bumper that it makes contact with other parts such as the headlamps, bonnet and grille. It is thought likely that because of this, the car manufacturer will currently design to absorb all of the bumper test energy in a crush depth of about 50 mm. A universal world bumper will have to meet the most demanding world requirement, which is the Canadian test. A pedestrian bumper system at the front will absorb some of the bumper test energy and the current protection system (normally crush cans) can be used as a second stage to absorb the remaining energy. Using the assumptions above, the remaining energy will be for the 190 g zone:

$$2464 - 970 = 1494 \text{ J}$$

If an energy absorbing rate of 2464 J in 50 mm is assumed for this second stage then this remaining bumper test energy, 1494 J, can be absorbed in 30 mm of crush. Therefore it can be estimated that the current crush depth of 50 mm will need to be increased to 92 mm (62 + 30 mm). This gives an extra bumper crush length of 42 mm. Had the two crush depths been completely isolated then the crush depth would need to have been extended by 62 mm, the complete pedestrian crush depth for the 190 g zone. However, with some overlapping of the crush depths, only 42 mm of additional crush depth is needed to accommodate the required 62 mm of pedestrian crush depth, so 20 mm of existing crush space has been recovered. This additional crush depth can either be obtained by extending the vehicle length or by improving the efficiency or crush depth of the high speed crash protection zone, so that some of the current length used for high speed protection and packaging of un-crushable elements is available for pedestrian protection. Although it is likely that improvements in energy absorbing efficiency and reductions in the size of engine and transmission packages can be achieved, it has been assumed for this costing exercise that the vehicle will be lengthened.

Obviously, these are very rough calculations so they need to be used with caution, but it seems reasonable to conclude that the pedestrian and the Canadian bumper test requirements are not completely incompatible and can be met with a relatively compact two stage stiffness system. However, this is only true if a flexible bumper facia is used so that the area involved in the pedestrian test is lower than that in the Canadian bumper test.

11.1.2 Upper legform to bonnet leading edge

This section considers costs for a bonnet leading edge test. At the time these calculations were made, it was not known what might eventually be decided for this area, so the basis of calculation was the proposals made for feasibility in Section 10.4.1.4. While this area is not tested in the GTR it is understood that the EC proposal may include it as a monitoring only test (as it is in phase one). The costs obtained here therefore provide an indication of the costs that might be incurred in meeting the target values.

Again it is assumed that manufacturers will make an allowance of 20 percent on criteria. In this area it is assumed that any additional crush depth provided for pedestrian protection will have no benefit for damageability or occupant protection. As the relaxation zone will be used for difficult areas, the remaining bonnet leading edge test area will have to meet the more demanding criteria of the sum of forces being no more than 6.25 kN and the bending moments being no more than 375 Nm. The load transducers are not located where the impactor contacts the vehicle; the contact force can be estimated, given that the impactor mass in front of and behind the load transducers is known (the former is nominally 2.55 kg). The required crush depth can then be estimated in a similar way to the method used for the lower legform to bumper test.

As the test energy is selected on vehicle shape, the crush depth necessary to absorb it is not fixed but is dependent on the vehicle shape at the test location. Therefore, before these assumptions can be used to calculate the crush depth needed for a specific vehicle, the test energy has to be found using appropriate values of Bonnet Leading Edge (BLE) height and bumper lead in conjunction with the new energy look-up graph (Figure 3.11).

11.1.2.1 Landrover Freelander

The bonnet leading edge height reference line was marked on the Landrover Freelander using the revised straight edge angle of 40° to the vertical and this showed a typical BLE height of 980 mm and a bumper lead of 165 mm (typical but both vary across the width). Using the new energy curves and energy cap, it can be found that the Landrover Freelander attracts a 500 J BLE test.

Using a similar method and assumptions to those for the bumper, an estimated crush depth requirement of 107 mm is calculated, including a 10 mm allowance for crushed material.

The current Freelander BLE structure has some capacity to absorb energy by deformation; the deformation in the Euro NCAP tests of this vehicle has been estimated from the recorded force to be 78 mm. This leaves a requirement for an additional 29 mm of crush depth. The Euro NCAP results suggest that the current BLE is too stiff, so some change to the stiffness will be needed in addition to this extra crush depth. Any changes to the BLE height or the bumper lead to make the vehicle more pedestrian friendly can change the BLE test energy and therefore the required crush depth. In the case of the Freelander the test energy was kept unchanged through small and similar forward movements of both the bumper and BLE.

11.1.2.2 Ford Mondeo

The Mondeo was also measured using the revised BLE straight edge angle. This gave a typical BLE height of 714 mm and a bumper lead of 111 mm. However, it was decided to extend the bumper to enable it to pass the legform test, giving a revised bumper lead of 126 mm. The revised dimensions attract a 454 J BLE test energy.

Using these figures and the same assumptions as before for the crush depth calculation, the necessary crush depth required to pass the test can then be calculated as110 mm, including an allowance of 10 mm for the residual crushed material.

If the Euro NCAP test results from 2001 are considered, the existing crush depth available in the bonnet leading edge (BLE) can be estimated. These Euro NCAP tests were from a phase where the tests were performed to the WG10 procedures. Based on information from the test, a crush depth of 115 mm was estimated.

Hence it was found that the Mondeo already has 5 mm of spare crush over that required. However, the existing crush depth is likely to be too stiff as the original test recorded a high peak impactor force, greater than that required for the proposal in Section 10.4.1.4. As the crush depth to peak force relationship is non-linear, it is difficult to establish the effect of the spare 5 mm and the ‘too stiff’ bonnet leading edge. With this knowledge though, it is expected that manufacturing changes could be made to meet the proposal in Section 10.4.1.4, without significant redesign of the structures participating in an impact to the BLE of a Mondeo, at the centreline. The modifications required over the whole width are discussed in more detail in Section 11.2.3.2.

11.1.3 Headform to bonnet top

Again it is assumed that manufacturers will make an allowance of 20 percent on criteria and that in this area any additional crush depth provided for pedestrian protection will have no benefit for damageability or occupant protection. The test is typically not perpendicular to the bonnet top so the crush depth required is determined by the velocity normal to the bonnet rather than the full test velocity. Also, little energy is absorbed by the impactor's skin. The energy efficiency assumed, 75 percent, can be higher in this case because the criterion used, HPC, is not based on a peak value of a transducer output. The required crush depth of 5 mm was estimated in a similar way to the method used for the lower legform to bumper test, for both vehicles being considered.

The abrupt change between child and adult test areas in phase two of the Directive is intentional, because in practice this will result in a zone that is safe for the heads of both children and adults. However, as a result, additional crush depth will be required in the region of the transition Wrap Around Distance (WAD) for all vehicles that have an adult test zone (i.e. where the test area exceeds the transition WAD). If it is assumed that, because of this, the adult headform will have to be slowed using a stiffness appropriate for a child, then the maximum crush depth needed in this area can be estimated using similar methods and assumptions as before and the ratio of adult to child headform mass, i.e. 1.3. Because most structures tend to become progressively stiffer, the overall efficiency for the adult will be better than implied by these assumptions.

11.1.3.1 Landrover Freelander

These test requirements and assumptions can be used for the Landrover Freelander to find the required practical crush depths. For the Freelander, the bonnet top angle is approximately equal to 5°. This gives a total crush depth for the adult headform of 82 mm for the main area and 61 mm for the relaxation zone. Likewise, for the child a total crush depth of 59 mm and 44 mm respectively can be calculated.

In the area near the child to adult transition the estimated crush depth is likely to be about 85 mm for the main area and it is thought that the relaxation zone will be just used for any small difficult areas in this child to adult transition zone.

11.1.3.2 Ford Mondeo

With the Ford Mondeo, the bonnet top angle is in the range of about 9° to 13° to the horizontal (11° was used for the calculation) at the front of the child area and in the range of 6° to 9° to the horizontal (7.5° used) at the rear in the adult area. Using the nominal bonnet angles of 11° for the child and 7.5° for the adult and the assumptions above, the practical crush depths required to meet the HPC criteria can be found for the Mondeo. This gives a total crush depth for the adult headform of 85 mm for the main area and 64 mm for the relaxation zone. Likewise, for the child a total crush depth of 69 mm and 52 mm respectively can be calculated.

In the area near the child to adult transition the estimated crush depth is likely to be about 90 mm for the main area and it is thought that the relaxation zone will be just used for any small difficult areas in this child to adult transition zone.

11.2 Protection features

Following the crush depth calculations, the authors' engineering judgment and experience was used to propose modifications that would enable these vehicles to meet the proposed changes to the phase two requirements summarised in Section 10.4.1. To make it possible to calculate the additional cost of pedestrian features, on the basis of including them into a total new vehicle design for the same vehicle segment with similar architecture, detailed specific solutions were proposed.

11.2.1 Landrover Freelander – modifications

The modifications required for the Landrover Freelander, in order to meet a revised version of phase two of the EC Directive, including the proposed changes (amendments made to reflect feasibility issues), are presented in the following sections. These modifications are broken down according to the pedestrian test which requires that modification.

11.2.1.1 Legform to bumper

For the legform tests, 62 mm of crush depth with energy absorbent material of the correct stiffness is needed to meet the performance criteria for this test, in particular the tibia acceleration.

As described in Section 11.1.1, through the addition of a pedestrian friendly bumper 20 mm of existing crush space may be recovered. This is based on the contribution of the pedestrian friendly bumper towards the crush depth currently used to minimise costs for repairing bumper damage in low-speed impacts. Therefore the first modification is to reduce the crushable-box linkage, between the longitudinal chassis rails and the bumper face, by 20 mm in length. The effect of this on the bumper beam position is shown in Figure 11.2 with the old position shown in black and the new position dotted in red.

Figure 11.2. Bumper beam moved rearwards by 20 mm due to the reduction of the length of the collapsible box elements between the chassis rails and the bumper beam

The other 45 mm of crush depth required for the pedestrian legform test could be obtained through movement of the bumper facia forward. This is shown in Figure 11.3 with the new bumper facia position shown by the red lines. As the bumper has little curvature when viewed from above, it should be easier to maintain a consistent gap between the bumper beam and the bumper facia; however, any problem areas where the gap is small could be nominated for the relaxed test requirement.

To control the energy attenuation of the legform impactor or pedestrian leg, an energy absorbing material is required between the bumper facia and the bumper beam. On the Honda Jazz, this energy absorption potential is given by a collapsible U/box-section element on the front of the bumper beam, as shown in Figures 11.4 and 11.5. From these images the deformable section can be seen on the right. However, the crush initiation towards the edge does not extend along the entire section, which may present a problem with the initiation of the desired deformation. A better initiation solution may be developed along the lines of that shown in Figure 11.6. Alternatively, energy absorbing foam could be used between the bumper beam and the bumper facia.

Figure 11.3. Bumper facia moved forwards by 45 mm

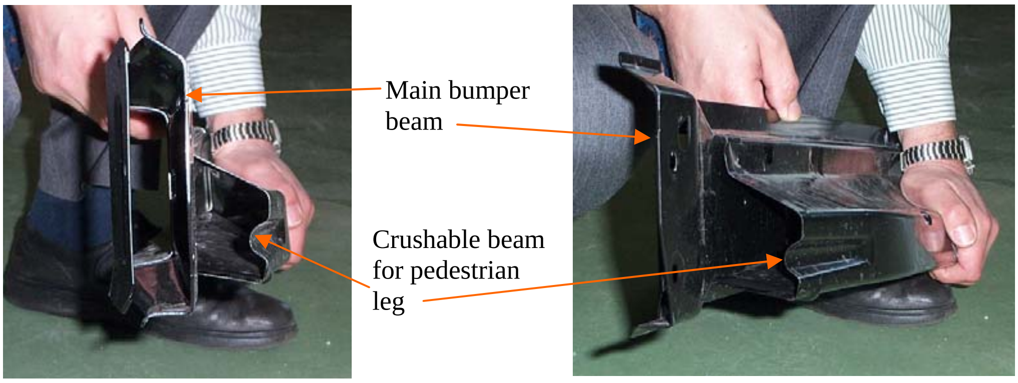


Figure 11.4. Honda Jazz bumper beam showing the section profile

Figure 11.5. Honda Jazz bumper beam oblique image

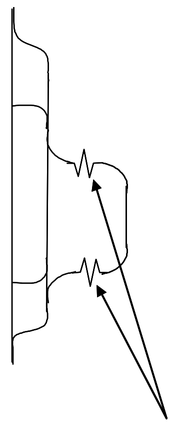


Figure 11.6. Revised bumper beam with improved crush initiation potential along the entire beam

Currently this vehicle has a high bumper and the above collapsible bumper beam solution, with sufficient crush depth, could be made to pass the high bumper upper legform test. However, the addition of a spoiler would lower the bumper and not only would this make it eligible for a legform test, but it would reduce the risk of knee injuries. In the authors' opinion the spoiler would also improve vehicle efficiency and stability by controlling the air-flow beneath the vehicle. Therefore, the more expensive option of a spoiler was selected for the Freelander for the costing exercise (in Lawrence *et al*. 2004a). However, as part of this current update, the issue of whether spoilers are needed for off-road vehicles will be reconsidered in the light of the draft GTR and related EC proposal (see Section 12.1). The spoiler would be required to give a low load path for the legform impactor. However it would also impinge on the ramp angle required for off-road use; therefore a spoiler for on-road use will be fitted. This could be a pivoted or drop-down system, operated either manually, remotely or automatically, or a bolt-on system that could be removed before off-road use. For this costing exercise, the bolt-on option has been chosen. The new spoiler would bolt onto existing structures in the bumper and under-tray so that when removed, the vehicle would still have an effective bumper system for off-road use. The spoiler is shown by the red lines in Figure 11.7. The two points for attachment of this spoiler would be at the high most rearward point in the wheel arch (which would need a new fixing point) and at the front centre. This would be achieved by extending the top of the spoiler into the top of the existing lower air intake cavity in the bumper facia and fixing the spoiler using the existing attachment screws (see Figure 11.8). The load path in the spoiler, for rigidity and for the protection for the legs of a pedestrian, needs to be of the correct stiffness. This rigidity may be gained through the use of a ribbed under-tray similar to that used in the Volvo S40 and shown in Figure 11.9. The ribbed under-tray will be fitted between the lower edge of the spoiler and the fixings of the existing engine splashguard or alternatively to new fixings in the sump-guard shown in Figure 11.10.

The protection for pedestrians that is offered with the introduction of a spoiler containing a low load path is only effective when the spoiler is fitted. For this reason it is desirable for the protection of pedestrians that the spoiler is always fitted when the vehicle is being used on the roads. However, some vehicle owners may prefer the look of their vehicle without the spoiler and not use it for all of the time they drive on roads. Therefore, it is essential that two things happen: firstly that vehicle owners are informed of the importance of the spoiler and secondly that manufacturers of a vehicle with a deployable or bolt-on spoiler are not held liable for any injuries to pedestrians should an accident occur where the spoiler was not fitted.

To re-assure vehicle manufacturers that they will not be held accountable for the actions of the vehicle owners, some expression stating this could be incorporated into the EC Directive relating to the protection of pedestrians and other vulnerable road users before and in the event of a collision with a motor vehicle.

Figure 11.7. New detachable bolt-on spoiler to provide low load path for the leg

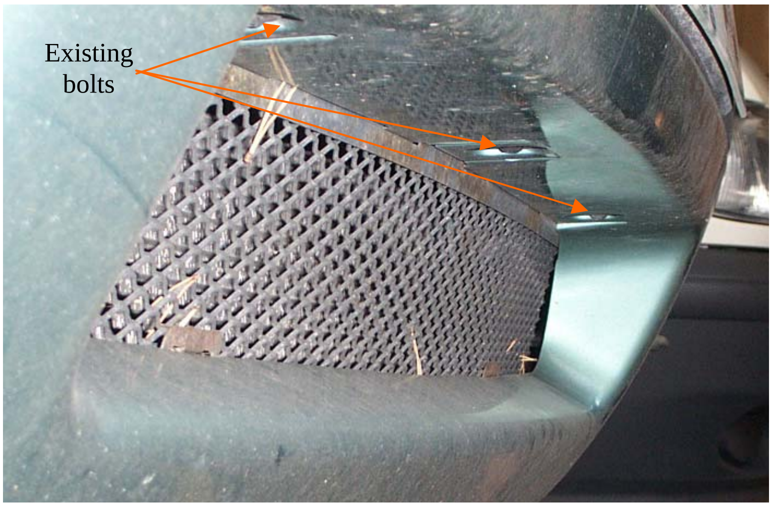


Figure 11.8. Top flange of the bolt-on spoiler would be fixed where marked (the air intake would be maintained in the new spoiler)

Figure 11.9. Ribbed under-tray and bumper facia from the Volvo S40

Figure 11.10. Underside of Freelander showing metal and plastic bumper support where the new spoiler would be fixed

Following the introduction of the energy absorbing bumper beam and low spoiler load path, the stiffness of these elements would need to be tailored to give the optimum performance in the legform test. This optimisation process would be achieved initially using mathematical simulations of the components and then the integrated system, followed by some practical validation testing.

11.2.1.2 Upper legform to bonnet leading edge

For this vehicle it has been estimated that a total crush depth of 107 mm is needed to meet the more demanding upper legform criteria that are proposed for most of the BLE width. The crush depth that the current structure already offers has also been estimated from Euro NCAP upper legform test results. It is thought that the additional crush depth obtained by extending the bonnet forward to match the extended bumper, along with the crush depth already in the current vehicle, will provide sufficient depth to meet the more demanding upper legform criteria. Therefore the modifications in this area are redesigns of the existing elements to make full use of the crush space and to obtain the optimum stiffness. Any problem areas that cannot be made to meet this requirement could be nominated for the less demanding relaxation zone test.

The consequences of extending the leading edge of the bonnet (BLE) to match the extended bumper are shown in Figure 11.11. The matching is achieved by extension of the bonnet and wing and moving the headlamps forward to provide the same shape as before.

The extension of the bonnet, as shown in Figure 11.11, makes no fundamental change to the shape of the bonnet. However, to optimise the bonnet stiffness, it is also necessary to modify the underlying structure of the bonnet.

Figure 11.12 shows a schematic (lateral view) representation of the existing bonnet leading edge area in the Freelander. The proposed modifications to this area are shown in Figure 11.13. These modifications consist of the extension of the bonnet locking platform to match the extension of the vehicle as described above and the re-profiling of the bonnet reinforcing layer or inner skin, to follow the line of the outer skin more closely. This should make the bonnet edge more readily deformable. Associated with this is the required lengthening of the bonnet-lock striker. Reducing the thickness of the front edge of the bonnet means that a taller bracket is required for the rubber seal on the bonnet to contact; however, as this will be in the child headform test area, a deformable, plastic or metal support has been used. The bonnet lock has also been moved back to remove it from the bonnet leading edge area and allow greater crush depth in front of it. As moving the current lock would require a pocket to be made in the main box of the bonnet lock platform, which would have compromised its strength, the lock has instead been integrated into the cross-member by allowing the striker to pass through a tube in the box member to engage with a latch below. As the lock components beneath the cross-member are thin, it will not interfere with the cooling pack beneath. Again, as the bonnet striker will be in the child headform test area, it has been arranged so that it will not prevent the bonnet from deforming locally, as it can push through the lock and bend as necessary.

As mentioned above, the headlamps need to be brought forward with the extended bumper. However, with this forward position, a further requirement of the protection for pedestrians in the bonnet leading edge region is for the headlamps to be deformable. Deformable headlamps with deformable lenses and reflector boxes are currently being developed to provide pedestrian protection and are already fitted to the Honda Civic and the Volvo S40. As with most current vehicles, the headlamps will need to be tailor-made to match the styling requirements for the specific model although sharing of some components may be possible.

The changes for the bonnet leading edge proposed above will provide the crush space necessary to achieve the pedestrian protection requirements. However, a further stage of optimisation will be needed to obtain the optimum stiffness of these elements. This optimisation process would involve initial mathematical simulations of the components and then the integrated system, followed by some practical validation testing.

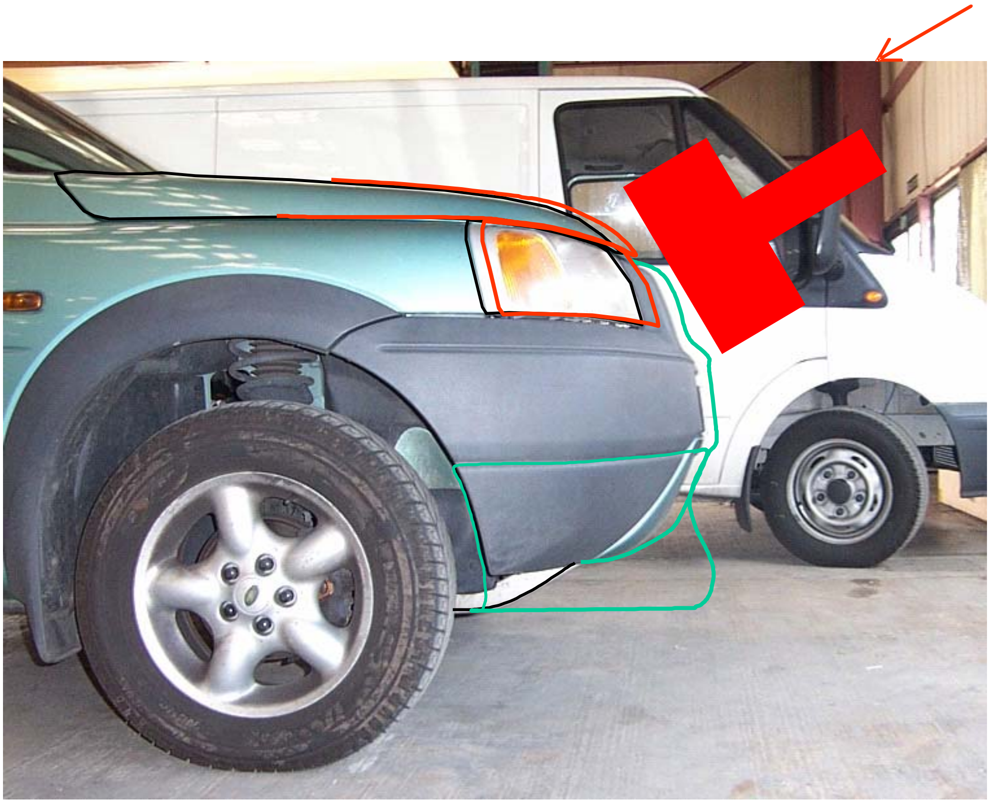


Figure 11.11. Bonnet leading edge changes following the bumper extension

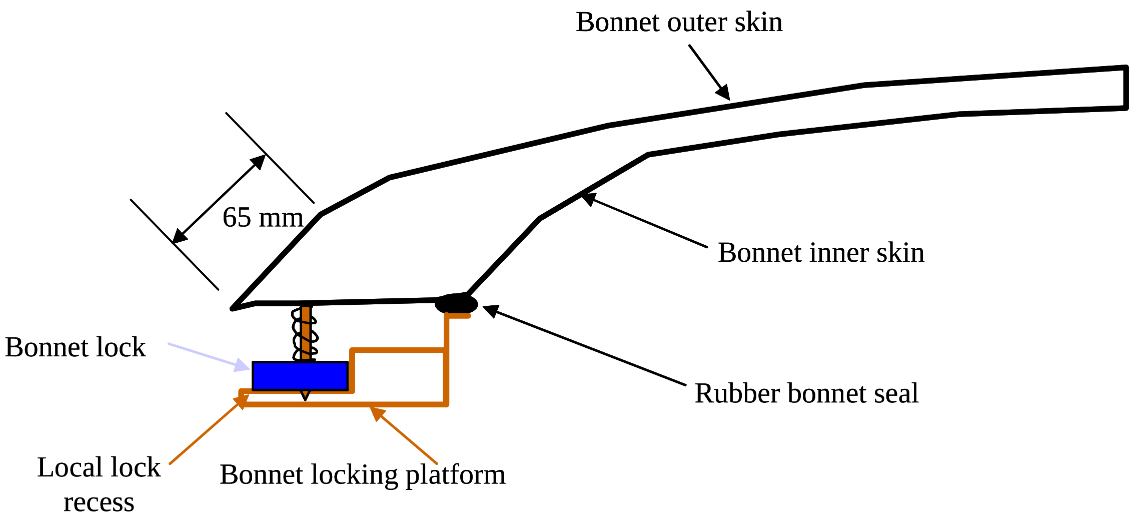


Figure 11.12. Existing bonnet reinforcement in the BLE region

11.2.1.3 Headform to bonnet top

For the headform tests, there are four different requirements for crush depth that come from testing with both the adult and child headform impactors over the two regions of HPC requirements (i.e. main area and relaxation zone). With the bonnet top, crush depth alone will not satisfy the requirements of the proposed phase two of the Directive. The stiffness and deformation of the bonnet is also critical. Therefore any assumption that the requirements can be met through the provision of adequate crush depth in the bonnet top also requires tailoring of the bonnet stiffness. The Freelander already has an aluminium bonnet which is likely to provide approximately the required pedestrian protection stiffness except where there are heavy reinforcements or underlying hard components. Therefore, for much of the bonnet area all that should be necessary is a revised, more homogenous bonnet under-frame. The revised under-frame would be refined and evaluated through the use of mathematical simulations, followed by full-scale validation tests.

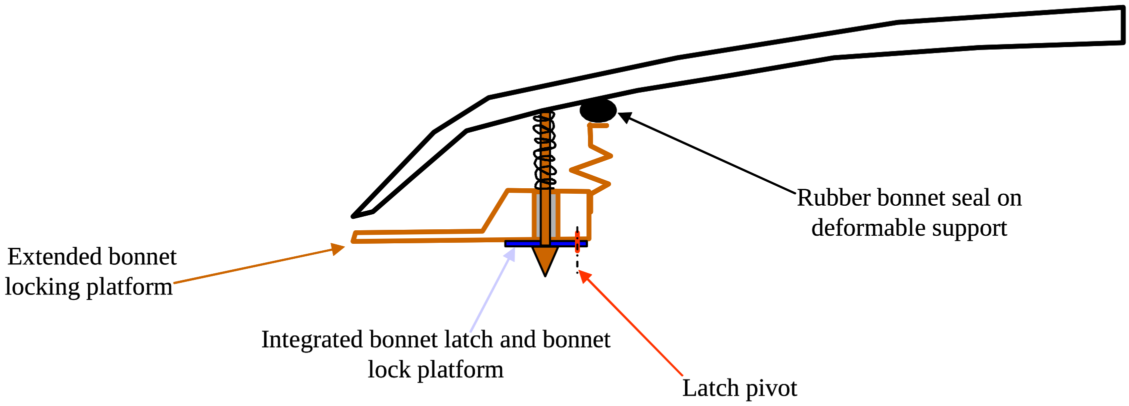


Figure 11.13. Bonnet reinforcement changes in the BLE region

The Freelander has a clamshell type bonnet, which covers the parts that normally constitute the wing edges. Taking into account the requirement to test a headform radius within the bonnet side reference line, for this vehicle the wing edges are outside or well beneath the tested surface. For wing edge child and adult headform tests, the impacts will be directed onto the edge of this clamshell bonnet. In the child ‘wing edge’ area, the clamshell bonnet of the Freelander already has a crush depth starting at about 60 mm at the front and increasing to about 80 mm at the rear. For the adult, the available ‘wing edge’ clamshell bonnet crush depth starts at about 80 mm at the front and increases to about 100 mm at the rear of the wing.

These available crush depths are already sufficient to meet the more demanding requirement along most of its length, once the stiffness of the structure has been optimised. For the more difficult child to adult transition area, use of the option to nominate for the less demanding requirement should also mean that no changes to the current styling and construction are needed to release more crush depth. Examination of the current bonnet edge structure also suggests that only minor changes will be required to optimise the stiffness. Therefore minimal changes are thought necessary to meet the more demanding protection requirements and any remaining problem areas could be nominated for the less demanding test.

Based on an examination of the vehicle, the support for the base of the windscreen is thought to consist of an extension of the firewall backed by a U shaped section to form a closed box cross-member, as shown in the ‘current’ diagrams in Figure 11.14. This type of closed box section is likely to be far too stiff for pedestrian protection; however, as this part is also an important cross-member, modifications for pedestrian protection should not reduce its strength in stiffening the structure. The solution adopted in the Honda Civic for pedestrian protection is to use a C-shaped cross member, as can be seen in Figure 11.15. To provide this type of solution in the Freelander, one of the sides of the box section has been removed as shown the ‘new’ diagrams in Figure 11.14. Due to the windscreens in both the Civic and the Freelander being curved, the shape of this C-shape section will need to progressively change from the centreline to the sides, to take account of this curvature. This curvature is accommodated in the Honda Civic C-section by changing the length of the top part of the C-section, as shown in Figure 11.15 and this is also included in the modifications for the Freelander, see Figure 11.14.

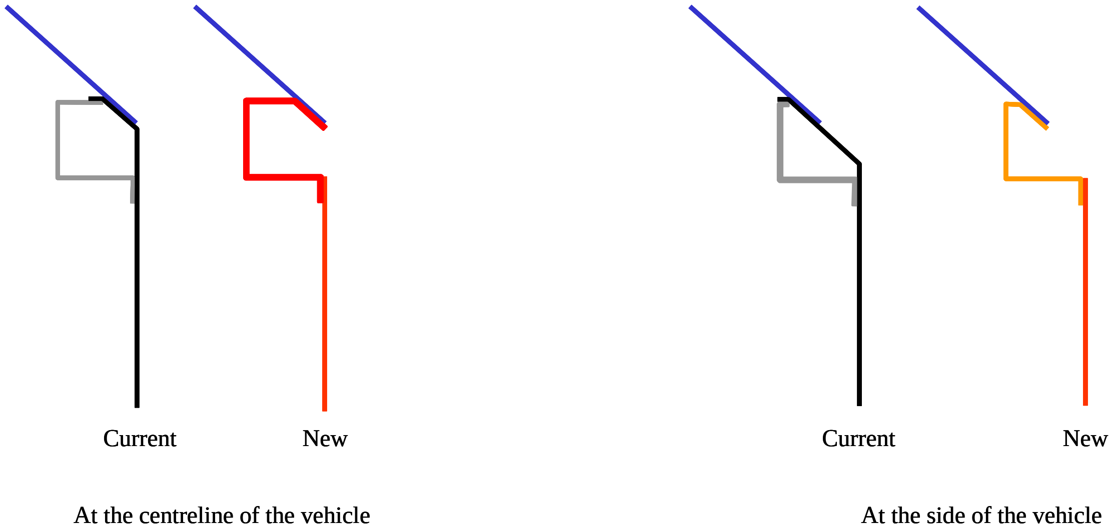


Figure 11.14. Schematic representation of the current and modified sections at the windscreen support

Figure 11.15. Honda Civic C-section of the upper bulkhead

Again some refinement of the design will be needed to tune the stiffness of the system using a combination of mathematical simulation and component testing and it is likely that some local stiffening of the C-section may be needed at the centre where the overhang is largest.

There are three problems for the protection of pedestrians in the windscreen scuttle area.

The first of these is the forward extension of the firewall to form the scuttle heater / ventilation air chamber. This comprises an angle section coming from the firewall with a rubber seal on the top, which supports the rear edge of the bonnet. To reduce the stiffness of this element, fold initiators in the form of corrugations will be added. Figure 11.16 shows a schematic representation of the current and modified structure.

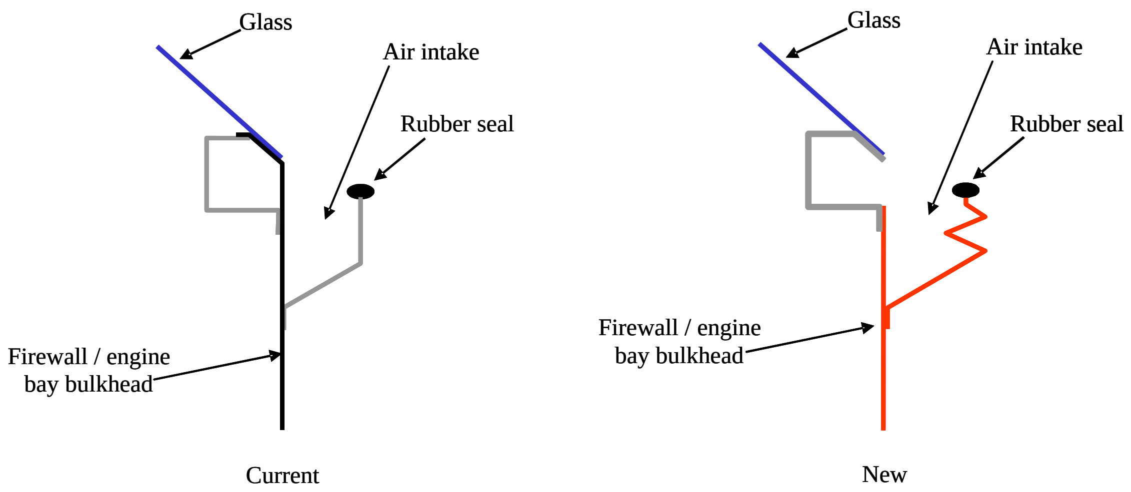


Figure 11.16. Schematic representation of the current and modified sections for the extension of the firewall to form the scuttle heater / ventilation air chamber

The second of the issues for pedestrian protection in the windscreen scuttle area is the potential for contact with the wiper mechanism. At present the wiper mechanism operates from rigid linkages to the two spindles. These offer hard points for a pedestrian head impact. To make the wiper mechanism more pedestrian friendly, the linkages should be made to be frangible, as in the Honda Civic (Figure 11.17), so that they break off when impacted by the head of a pedestrian.

Figure 11.17. Honda Civic - frangible wiper spindle mounting following test (in place and removed)

It is interesting to note that since the Civic was produced, Honda has developed a more generic frangible system where the spindle bosses and frangible elements are combined. This approach means that these most expensive parts can be used unchanged across all or most of the Honda vehicle family with different low cost linkage arms, etc., see Figure 11.18. This approach means that the cost of wiper tooling can be spread across several models and not solely attributed to one model, as in the study of the Honda Civic by Lawrence *et al.* (2002).

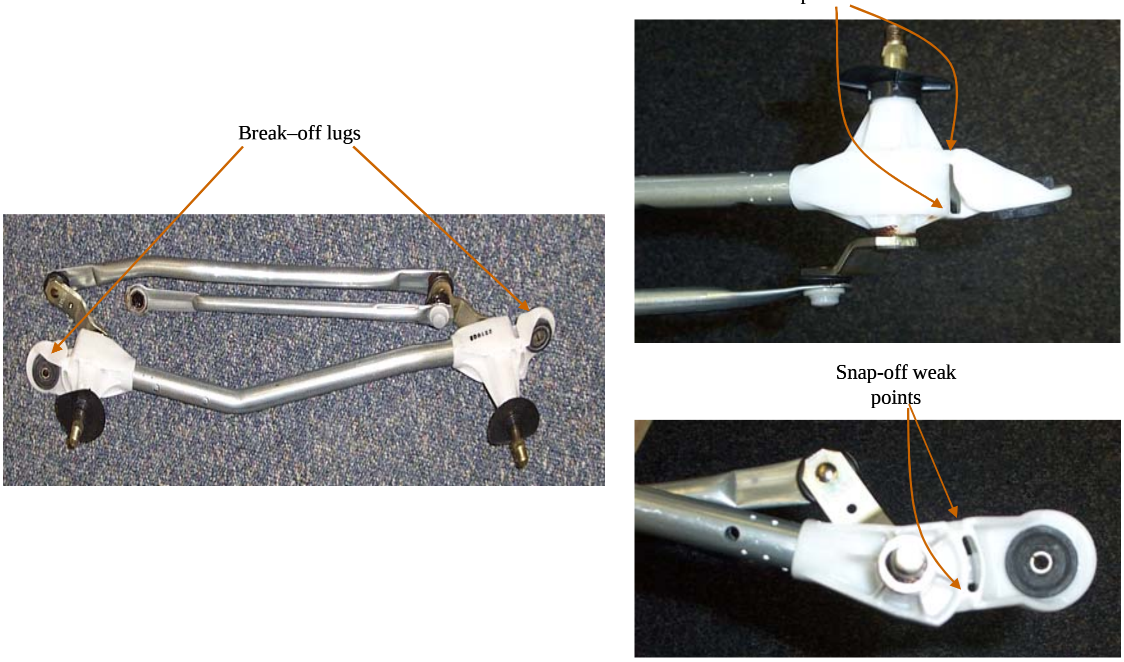


Figure 11.18. Honda Jazz pedestrian wiper system

An alternative to the frangible wiper system is to mount the wiper mechanism lower within the scuttle so that it cannot be contacted by the head. This solution can be seen in the latest VW Golf (Mk. V). The frangible solution will be used for this costing exercise.

The final problem points in this area are the hinges; however, as can be seen in Figure 11.19, the hinges themselves are well to the outside of the vehicle, approximately on the side reference lines. So, they will not be directly involved in a headform test as the test area starts one headform radius (82.5 mm) inside the reference line.

Figure 11.19. Bonnet hinge

Although the hinges will not be involved directly in a headform test they are likely to influence the crushing of the edge of the clamshell bonnet. Therefore, shear bolts will be used for the hinge attachment; these bolts will use a similar waisted design to that shown in Figure 11.20.

Figure 11.20. Necked shear screw - similar waisted design to be used for hinge bolt

Within the engine bay of the Freelander, the fluid reservoirs, the box containing the air filter, the fuse box and the engine top all represent high points. They are close enough to the bonnet that should a headform test be directed to the bonnet above one of these features, then the headform would interact with that feature (see Figure 11.21). At the moment these features or their mountings are too stiff to gently decelerate a headform when impacted. Therefore, to achieve the required HPC value for such an impact, these features need to be moved or to be made less stiff. The clearances between these features and the underside of the bonnet were measured by closing the bonnet onto a pillar made from modelling clay, see Figure 11.21.

Figure 11.21. Measurements of Freelander's under bonnet crush space - V6 variant

The coolant reservoir is positioned above the McPherson strut on the right side of the engine bay, with a clearance to the bonnet of 10 mm. As the container is pressurised it is not thought feasible to make it crushable, so it will be moved to a new location in the engine bay. Although under-bonnet space is at a premium in the largest engine variant, it should be possible to find a new location where it can be mounted. Currently the reservoir appears to be mounted higher than is necessary for it to meet the requirement for it to be above the highest point in the cooling system, so it could be mounted lower to increase clearance. Alternatively a revised container and filler cap design could be used to achieve the same capacity in less height, either in the original or a new position.

The washer fluid reservoir is mounted close to the radiator in the front of the engine bay with a clearance to the bonnet of 30 mm from the top of the filler neck section. This filler neck will be made deformable by introducing a larger crank in the neck.

The brake and power steering fluid reservoirs are mounted at the rear and the right of the engine bay, respectively. To aid protection for pedestrians in a head impact, the attachment of the power steering reservoir to the engine bay structure will be made to be frangible, so that it will push down by using slotted or deformable mountings. For the brake fluid reservoir this will necessitate the replacement of the current rigid combined mounting and fluid connections to the brake master cylinder with flexible pipes along with a deformable or frangible mounting bracket. A similar arrangement to this was used for the brake fluid reservoir on the Honda Civic, see Figure 11.22.

Figure 11.22. Deformable brake fluid reservoir of the Honda Civic

The air filter in the Freelander is located on the left side of the engine bay and is contained within a box. The fuses are also located on the left and in some variants of the Freelander they are also contained within a box. The clearance from the top of these boxes to the bonnet is between 20 and 30 mm. To increase the protection for pedestrians in this area, both of these boxes should be made to be deformable by the use of fold initiators and, if necessary, revised plastic materials.

The clearance measured between the engine top cover and the bonnet underside was of the order of 35 mm and some deformation space is probably available in the cover and the under-bonnet sound proofing mat (for control of noise, vibration and harshness), which is likely to provide an additional 10 to 15 mm of crush depth. The crush available in this area will be insufficient to meet the relaxation zone requirement for the adult. For a new vehicle of this type some small saving in engine height and engine mounted height may be achievable. For a vehicle of this size it should be possible to arrange for the child to adult transition to be approximately in the area of maximum available clearance, in the gap between the bonnet locking platform and the highest points on the engine. This can be combined with adjustments to the bonnet curvature and engine height to create a zone with the necessary clearance for the transition area. The scope for lowering the high engine parts is larger in this type of vehicle because it is mounted very high, but if necessary in addition or alternatively, the bonnet line towards the rear can be raised by about 15 to 20 mm to achieve the required clearance for the adult headform test. This should have no effect on the forward view angle for the driver, as the current view angle exceeds the angle of the bonnet to such an extent that the bonnet leading edge is the only part of the bonnet that interferes with view angles. However, for the purpose of this costing exercise, it will be assumed that, for a new vehicle, sufficient clearance will be achieved using a combination of a smaller more efficient engine and improved packaging.

11.2.2 Landrover Freelander – pedestrian impact cost implications

Modifications that are suggested as being necessary for the Landrover Freelander to meet the proposals in Section 10.4.1 for phase two of the EC Directive are shown above in Section 11.2.1. In response to these modifications, Menard Engineering Limited first considered the feasibility of these proposals and revised them where necessary using their specialised vehicle engineering experience. They then produced an estimate of the extra costs for pedestrian protection that would be incurred in producing a totally new vehicle of the same class and similar architecture. Although based on the changes to the Freelander, they calculated costs for a more generic off-road vehicle. Therefore costs for parts have been calculated for more commonly used materials than are used in the Freelander.

The report on the Freelander, produced by Menard Engineering Limited, is presented, unchanged, below.

Freelander – Pedestrian Impact Cost Implications

26 April 2004

Contents

Menard Engineering Ltd, Leafield Technical Centre, Langley, Witney, OX29 9PF

General Assumptions
This report is based upon the TRL Report on the Landrover Freelander and the modifications required to meet a revised version of Phase 2 of the EC Directive on Pedestrian Protection. It assumes an estimated vehicle volume of 60000 per annum.

The On-Cost figures show the estimated cost effect of the Pedestrian Protection legislation on a New Vehicle Design (not for modifying an existing vehicle).

The costs exclude design and development.

1. Front Bumper Facia

Workscope
Front Bumper Facia depth increased by 45mm forward.

Notes
For this exercise it is assumed that the Front Bumper Facia will be a design based on the existing Freelander, using similar fixings, Fog Lamp, Grilles, etc. It will be a one piece painted Injection Moulded part using PC + PBT Blend material. The costs below are given for a full new Bumper Facia and the Pedestrian Impact On-Cost is for the additional tool size and part material due to the depth increase.

The Grilles, Fog Lamps, Parking Distance Sensors and Headlamp Wash Systems which can all be fixed to the Front Bumper System should also be considered with respect to Pedestrian Protection. The Mounting Designs for these items should be such that in an Impact they allow the movement of the items rearward or allow them to breakaway without leaving any sharp objects. The On-Cost for doing this to make them Pedestrian Impact friendly could be considered as minimal.

Facia Piece Part Costs
Front Bumper Assembly (excluding Fog Lamps) = £ 70

Pedestrian Impact On-Cost = £3

Facia Tooling Costs
Front Bumper Facia = £900,000

Pedestrian Impact On-Cost = £10000

2. Front Bumper Energy Absorbing Foam (Alternative to item 8)

Workscope
Front Bumper Energy Absorber.

Notes
Although some vehicles have Energy Absorbing material for Low Speed Impact requirements, for this exercise it is assumed that the Front Bumper System does not currently contain any Energy Absorbing material between the Bumper Beam and the Bumper Facia. There are various materials available such as Steel Pressed Beams (also costed in this study), Aluminium Honeycombs and EPP Moulded Foams. For this exercise we have chosen EPP Moulded Foam. The Density of the Foam will be in the region of 60g/l and this will be confirmed by Analysis to meet the requirements of both Low Speed and Pedestrian Impact requirements.

Note that although this could be considered as an On-cost for Pedestrian Impact the Energy Absorber could already be a requirement due to Low Speed Impact requirements and any tailoring to meet Pedestrian Impact will have minimal cost effect.

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Foam Piece Part Costs
Front Bumper Foam = £10

Pedestrian Impact on Cost = £10

Foam Tooling Costs
Front Bumper Foam = £18000

Pedestrian Impact on Cost = £18000

3. Front Bumper Lower Spoiler

Workscope
Removable Front Bumper Lower Spoiler System. Bolted on the Bumper Facia and to the new ribbed Front Undertray.

Notes
This type of Front Bumper Lower Spoiler is of potential detriment to Off-Road driving therefore there is a requirement for the Spoiler to either be mechanically / electrically lowered and raised or to be able to be unbolted and removed by hand when going Off-Road. For this exercise the simpler option of the Spoiler been removed mechanically by hand for off-road use is to be considered.

(If a Spoiler System which can be raised and lowered mechanically or electrically is to be considered then the design study could be based on similar mechanisms for Rear Spoilers. However this will be a significant on cost)

There is an issue on non-replacement by the user when they return to on-road driving and possible liability. The use of an electronic sensor linked to a message on the Instrument Panel message display area which will inform the driver the Spoiler has been removed is a possible option which can be considered.

For this exercise the Spoiler is considered as an Injection Moulding (PC + PBT Blend) similar to the existing Bumper. It is also to be a painted finish.

The Spoiler will be designed to meet Aerodynamic and Cooling requirements with no detriments using analysis. It will also have to meet all Ground Clearance and Kerb Height requirements.

The Spoiler will incorporate apertures to give Air Flow access to the Lower Grille Area on the Main Bumper Facia.

The Upper Fixings will use existing fixing positions in Lower Grille Area and a new fixing in the Wheelarch area.

The Lower Fixings to be to the new Front Undertray.

The Spoiler could be considered as one Assembly with the new Front Undertray so can be removed as one unit.

Piece Part Costs
Front Bumper Lower Spoiler Moulding & fixings = £30.00

Pedestrian Impact On Cost = £30.00

Tooling Costs
Front Bumper Lower Spoiler Moulding = £300,000

Pedestrian Impact On Cost = £300,000

4. Front Undertray

Workscope
Ribbed Front Undertray supporting the Front Lower Spoiler.

Notes
For this exercise the Front Undertray will be an Injection Moulded (PP) part. Although for lower cost and on lower volume vehicles RRIM could be used.

The Fixings are to use existing available fixing positions for the Engine Splash Guard. Some additional Fixings may be required to give adequate support.

The Undertray will be fixed to the Front Lower Spoiler with J-Clips and Screws and could be considered as one Assembly with the Spoiler for ease of removal. When the Front Lower Spoiler is removed for Off-Road use then the Front Undertray will also have to be removed.

The Structural Rib pattern to Support the Spoiler will be designed with the aid of Analysis techniques.

The Undertray will also be designed to not be detrimental to the Cooling and Aerodynamic requirements with the aid of Analysis and Testing.

It should be noted that we are assuming that this Undertray is covering the Front Section of the Engine Bay only and is not considered as a Full Engine Bay Undertray.

It should also be noted that many new vehicles have Undertrays to meet NVH, Aerodynamic and Cooling requirements but for this exercise we are assuming that it is a new item fitted to support the Lower Spoiler, as on such an off road vehicle it is unlikely an Undertray will be in the required area. However if an Undertray is already a requirement for a new vehicle and is in the correct area to support the Spoiler then designing it to support the Spoiler should be achievable for a negligible On cost (A few additional fixings at an On-cost of £1.00)

Piece Part Costs
Undertray Moulding & Fixings = £6.50

Pedestrian Impact On Cost = £6.50

Tooling Costs
Undertray Moulding = £150,000

Pedestrian Impact On Cost = £150000

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5. Front Wiper System

Workscope
Front Wiper System with breakaway Wiper Spindles

Notes
The Wiper System will be a Supplier Design and Development based on existing systems. Breakaway Wiper Spindles will be designed as part of the new Wiper System. It can be assumed that newly designed Wiper systems will incorporate this feature anyway and that to meet Pedestrian Impact a new car will use these new Wiper Systems, which may be used across a range of vehicles. The cost difference for these Wiper Systems will be minimal (depending upon volume) but for this exercise we will assume some on-cost to piece and tooling to cover their use as opposed to using a current carry-over system.

Costs for the breakaway mounts, piece and tooling prices see item 21 of this report.

Piece Part Costs
Front Wiper System (including motor) = £25

Pedestrian Impact On-Cost = £3.4

Tooling Costs
Front Wiper System = £170,000

Pedestrian Impact On-Cost = £25,500

6. Headlamps

Workscope
Headlamps designed as Pedestrian Impact friendly.

Notes
The Headlamps will be designed with breakaway mountings (part of the main moulding) and with deformable Polycarbonate lenses and reflector boxes.

Current design trend is to use polycarbonate lenses therefore there would be no requirement to change lens material for pedestrian impact legislation.

The deformable lamp structure would be accommodated by the design of flexible or breakaway mounting lugs/brackets. If this was identified as a requirement at the beginning of a project there would be negligible on-cost to the lamp.

However if a breakaway mounting system is adopted a repair kit would need to be designed and tooled. So the piece price and the tooling costs would be treated as after Market sales costs.

Piece Part Costs
Headlamp System = £35 (single pocket type) to £100 (Xenon type)

Pedestrian Impact On-Cost = £0

Tooling Costs
Headlamp System = £2.5 Million

Pedestrian Impact On-Cost = £0

Repair Kit Piece Part Costs
Repair Kit = £0

Pedestrian Impact On-Cost = £0

Repair Kit Tooling Costs
Repair Kit Tooling = £0

Pedestrian Impact On-Cost = £0

The following cover areas of the vehicle for Body in White :-

07. Head Lamp bracket moved foreword.

Workscope
Head Lamp bracket moved foreword by 45mm.

Notes
The head lamp one piece pressed steel panel would require all the fixing positions to have crushable mounts, the mount may need depressions with cut away portions into the steel work or dog legged fixing flanges, on impact the mounts would collapse giving a crushable zone area. The number of tooling operations would increase from three to four ops, for this exercise separate LH & RH tools sets.

This type of panel manufacture with deformable mounts would be required to support and hold a glass lens with a plastic headlamp casing, but as we are suggesting the use of a deformable Polycarbonate lens and reflector boxes, this steel head lamp panel costs are not required.

Piece Part	**Costs LH & RH are**	**+ £ 0.00p**
Press Tooling	**Costs LH & RH are**	**+ £ 00,000**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

08. Pressed front Bumper Beam with initiators (Alternative to item 2)

Workscope
Bumper Beam to have pressed depressions.

Notes
Bumper Beam to have pressed depressions into the top and bottom panel surfaces to act as crush initiators; this will require three press tooling operations. This will be a new pressed steel panel and become an assembly with the current front beam; a new fixture is required to locate and spot weld the two together.

Pressed Piece Part	**Costs one compt are + £ 3.28p**
Press Tooling	**Costs one compt are + £ 150,000**
Assembly piece part	**Costs one assy are + £ 1.12p**
Assembly Tooling	**Costs one fixture are + £ 13,370**

The crush cans between the Main front Bumper beams are to reduce by 20mm to allow extra room for the beam, the savings on the piece price and the tooling costs for the inner and outer parts LH & RH are as follows:

Pressed Piece Part	**Costs one compt are + £ 0.25p**
Press Tooling	**Costs one compt are + £ 8,500**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

09. Front Spoiler rear fixing points.

Workscope
Front Spoiler sheet metal rear brackets.

Notes
New lower Spoiler to have two new rear brackets LH & RH to support the plastic assembly each side of the front fender, weld nuts to be assembled into the wheel house flange two per side. The steel brackets to be produced in three operations LH & RH together in a double pressed tool, the bracket to be bolted to the front fender through two weld nuts which have been projection welded into position, or alternatively welded to a nut plate which then is spot welded to the front fender.

A holding fixture and an upper electrode will be required to fix the weld nut to the fender or an extra clamp unit fitted to the front fender fixture, for this exercise the higher cost has been used.

Pressed Piece Part	**Costs LH & RH are + £ 1.64p**
Press Tooling	**Costs LH & RH are + £ 70,000**
Assembly piece part	**Costs LH & RH are + £ 0.20p**
Assembly Tooling	**Costs one fixture are + £ 1,960**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

10. Under Tray fixing rail.

Workscope
Fixing support rail required between under tray and engine splash guard.

Notes
New front spoiler will require rear support, the added under tray to be fixed to the front of the engine splash guard by a steel rail, this will provide sufficient stiffness to the front spoiler for front impact. The steel rail to be produced in three operations, this part will be bolted to the under tray for ease of front spoiler and under tray removal when Vehicle is in the off road mode, but spot welded to the engine splash guard.

A spot weld fixture is require to locate and clamp the two components together prior to spot welding taking place.

Pressed Piece Part	**Costs one compt are + £ 1.19p**
Press Tooling	**Costs one compt are + £ 117,000**
Assembly piece part	**Costs one assy are + £ 0.50p**
Assembly Tooling	**Costs one fixture are + £ 6,982**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

11. Bonnet Outer Panel extended.

Workscope
Bonnet outer panel extended by 45mm to match the front bumper position.

Notes
The front Bonnet outer panel area will extend foreword and therefore a percentage of 5% extra costs for the sheet steel and size of the pressed tooling set has been considered for this current exercise. The number of press tool - operations considered are four ops running in a 500 to 800 ton press, with auto sheet load and unload for the first press and manual load then auto unload for the parts there after.

The Hemming operation of the outer flange to the inner panel [the clinch flange] for this exercise to be performed on a free standing Hemming fixture, the fixture will increase in size, therefore a percentage of 2% extra costs for the final assembly has been considered for the current exercise.

The current Bonnet Outer panel material is manufactured from aluminium sheet, for this report we have given costs for steel component which could be the higher volume option for a new brand of Vehicle.

Pressed Piece Part	**Costs one compt are + £ 0.40p**
Press Tooling	**Costs one compt are + £ 19,000**
Assembly piece part	**Costs one assy are + £ 0.30p**
Assembly Tooling	**Costs one fixture are + £ 4,900**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

12. Bonnet Inner Panel extended.

Workscope
Bonnet inner panel extended by 45mm to match Bonnet outer and the front bumper position.

Notes
The front Bonnet inner panel area will extend foreword and therefore a percentage of 5% extra costs for the sheet steel and size of the pressed tooling set has been considered for this current exercise. The number of press tool - operations considered are three ops running in a 500 to 800 ton press, with auto sheet load and unload for the first press and manual load then auto unload for the parts there after.

The current Bonnet Inner panel material is manufactured from aluminium sheet, for this report we have given costs for steel component which could be the higher volume option for a new brand of Vehicle.

Pressed Piece Part	**Costs one compt are + £ 0.34p**
Press Tooling	**Costs one compt are + £ 16,000**
Assembly piece part	**Costs are as above in section 11**
Assembly Tooling	**Costs are as above in section 11**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

13. Bracket Mounting for latch to Bonnet Inner.

Workscope
The bracket mounting position of the Latch to the Bonnet locking platform must move rearwards,

Notes
The position of the Latch to the Bonnet locking platform must move rearwards, therefore a new steel support bracket produced in three operations will be required to secure the latch pin, weld nut, washer and the spring loaded collar to the Bonnet inner panel. The new bracket will be spot welded to the under side of the Bonnet inner panel, extra back ups, clamping and location pins will be required on the existing assembly fixture.

The above bracket is required due to the Bonnet inner panel front section being reduced in size to weaken it for frontal impact, allowing no room for securing the latch to the inner panel,

Pressed Piece Part	**Costs one compt are + £ 0.85p**
Press Tooling	**Costs one compt are + £ 94,000**
Assembly piece part	**Costs one assy are + £ 0.29p**
Assembly Tooling	**Costs one fixture are + £ 3,815**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

14. Extension Support to Bonnet Locking Platform.

Workscope
The Bonnet inner and outer panel have increased in depth by 45mm foreword, Bonnet platform upper part also to increase in length.

Notes
The Bonnet locking steel platform in this case consists of two components upper and lower parts, the upper part will extend foreword to support the increased length of the Bonnet assembly. For this exercise I have suggested that the platform will increase in width by 30%, therefore based on three press operations running in a 300 ton press, the piece and tooling prices have been calculated.

Pressed Piece Part	**Costs one compt are + £ 0.80p**
Press Tooling	**Costs one compt are + £ 48,000**
Assembly piece part	**Costs one assy are + £ 0.15p**
Assembly Tooling	**Costs one fixture are + £ 1,225**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

15. Modify Bonnet Latch and Bonnet Lock Platform – more latch rearwards.

Workscope
The Bonnet Latch assembly must move rearwards into the locking platform channel formed by the two components.

Notes
The latch assembly when mounted to the inner Bonnet panel must move rearwards, when the bonnet is closed the latch striker will enter a tube welded into the two piece Bonnet locking platform that will also contain the latch striker. The new steel latch pivot component will be produced in three operations running in a 100 ton press. The latch striker component to be located and clamped into the existing locking platform assembly fixture and spot welded into position.

Pressed Piece Part	**Costs one compt are + £ 1.03p**
Press Tooling	**Costs one compt are + £ 51,000**
Assembly piece part	**Costs one assy are + £ 0.58p**
Assembly Tooling	**Costs one fixture are + £ 3,185**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

16. Bracket support to mount rubber Bonnet seal.

Workscope

The Locking platform lower component to incorporate a crushable mount surface to fix the front Bonnet seal.

Notes

Due to the front Bonnet inner panel section reduction, the seal position is now higher in the Z plane, the lower locking platform to incorporate this vertical surface so that the Bonnet seal can be fixed to it.

It is assumed that the platform area will increase in size by 15%, therefore based on three press operations running in a 300 ton press, the piece and tooling prices have been calculated.

Pressed Piece Part	**Costs one compt are**	**+ £ 0.33p**
Press Tooling	**Costs one compt are**	**+ £ 22,500**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

17. Modify Front Fender Outers at front & rear top edge.

Workscope

The front Fender LH & RH to move foreword to meet the new position of the headlamp and to increase in height at the rear to suit Bonnet level.

Notes

The increase in the front Fender costs for LH & RH components has been based on an increase of costs by 5% for each hand. For this exercise each front Fender Outer is produced on its own set of tools for each hand, that being six press operations per hand, running in a 1000 ton press, the piece and tooling prices have then been calculated.

The current Front Fender Inner panel is manufactured as a plastic component, for this report we have given costs for a steel component which could be the higher volume option for a new brand of Vehicle.

Pressed Piece Part	**Costs two compt are**	**+ £ 0.54p**
Press Tooling	**Costs two compt are**	**+ £ 52,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

18. Modify Firewall Top section reinforcement to Base of screen.

Workscope
The firewall top section which forms the cross car box section at the base of the screen needs to be removed to form an open channel. This component is assumed to be a new part to a new product and has been costed that way.

Notes
The Firewall pressing is to be reduce in height in the Z plane to form an open section beneath the base of the front screen to give a crushable zone. For this exercise I have calculated a 10% reduction in panel area, and also include a tooling reduction. The panel tool process is based on four operations which take into account LHD & RHD components, and the steel panel to run in a 300 / 500 ton press. The piece and tooling prices have then been calculated.

Pressed Piece Part	**Costs one compt are - £ 0.38p**	**[this is a saving]**
Press Tooling	**Costs one compt are - £ 26,000**	**[this is a saving]**
Assembly piece part	**Costs £ nil**	
Assembly Tooling	**Costs £ nil**	

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

19. Reinforcement Diaphragms added to reinforce the base of the Screen.

Workscope
The reinforcement Diaphragms are to support the base of the front Screen and therefore will form part of the cross car box section complete assembly. This component is assumed to be a new part to a new product and has been costed that way.

Notes
These diaphragms have been added to give support to the base of the front screen, the new components will be produced in three operations and running in a 100 ton press. These parts will become part of the cross car box section complete assembly; it has been assumed the parts to be loaded into a hand applied fixture which will be loaded into the main cross car box assembly fixture and spot welded into position to complete the final assembled component.
A further assembly station may be required off line or bought in from a supplier, for this reason this cost has been left out.

Pressed Piece Part	**Costs 3 - compts are + £ 2.47p**
Press Tooling	**Costs 3 - compts are + £ 65,000**
Assembly piece part	**Costs one assy are + £ 0.87p**
Assembly Tooling	**Costs one fixture are + £ 9,432**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

20. Modify Firewall / Engine bay Bulkhead – add crush zone.

Workscope
The Engine bay Bulkhead to be modified by adding a crush zone into the front vertical face, the rear bonnet seal is fixed to this top surface.

Notes
This steel pressed component tooling operations would increase from three to four ops to produce the crushable zone in the vertical face, the press tools to run in a 300 ton press line. Any components welded to this surface may need to be repositioned, the changes to the surface should not affect the assembly of this part to the firewall assembly complete.

Pressed Piece Part	**Costs one compt are + £ 0.28p**	
Press Tooling	**Costs one compt are + £ 35,000**	
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

21. Casting required supporting Wiper Spindle and Mounts with crushable zones.

Workscope
The Wiper spindles and the mounting points to be manufactured from a suitable casting material with built in weak points to crush on impact for both LHD & RHD.

Notes
The Wiper spindle housing and its mounting lugs to the body in white nut weld plates, to have built in snap off weak areas designed within the casting basketry. This type of casting construction is required for both LHD & RHD positions, the manufacturing tooling costs could be spread across the range of variants for that make of Vehicle and types.

The assembly equipment required to connect all the wiper system components together should be no different to the existing production tools, therefore the on costs only cover the design & manufacturing tooling required to produce the LHD & RHD castings.

Pressed Piece Part	**Costs two compt are + £ 4.08p**	
Press Tooling	**Costs two compt are - £ 2,354 [this is a saving]**	
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

22. Bonnet Hinge fixed with breakaway bolts or bracket with crushable mounts.

Workscope
The Bonnet hinges to have built in crushable zones either breakaway bolts or deformable mounts to the Bonnet assembly.

Notes
The deformable mount route has been chosen for these costs, the upper half of the hinge steel leaf to be formed with crushable flange fixing points bolted to the Bonnet assembly.
This steel pressed component tooling operations would increase from two to three ops to produce the crushable zone in the vertical face; the press tools would produce LH & RH parts together and run in a 300 to 500 ton press. The assembly of the two half leafs with the changed form should not alter the production process at the supplies for the completed hinge.

Pressed Piece Part	**Costs two compt are + £ 1.30p**	
Press Tooling	**Costs two compt are + £ 24,000**	
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

23. Coolant reservoir to be relocated with crushable mounts

Workscope
Coolant reservoir container to be lowered repositioned and redesigned with crushable mounts.

Notes
This steel pressed component tooling operations would increase from two to three ops to produce the crushable mount zones, the press tools would run in a 100 ton press. The assembly cost of the bracket to the body in white will not alter but the production process would, for this exercise I have not included these costs as out lined below

Pressed Piece Part	**Costs one compt are + £ 0.25p**	
Press Tooling	**Costs one compt are + £ 20,000**	
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

24. Brake & Fluid Reservoirs & pipes, reposition bracket with crushable mounts.

Workscope
Brake & Fluid Reservoir container to be lowered repositioned and redesigned with crushable mounts.

Notes
The steel pressed component tooling operations would increase from two to three ops to produce the crushable mount zones, the press tools would run in a 100 ton press. The assembly cost of the bracket to the body in white will not alter but the production process would hence, no costs added for this.

Pressed Piece Part	**Costs one compt are**	**+ £ 0.25p**
Press Tooling	**Costs one compt are**	**+ £ 22,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

25. Air Filter and Fuse Box with crushable mounts – Remove engine cover.

Workscope
Air Filter and Fuse Box containers to be lowered repositioned and redesigned with crushable mounts.

Notes
These steel pressed component tooling operations would increase from two to three ops to produce the crushable mount zones, the press tools would run in a 100 ton press. The assembly costs for these brackets to the body in white will not alter but the production process would, for this exercise I have not included these costs as out lined below.

This crushable brackets would not be required if the Air Filter and Fuse Box plastic components where manufactured using a softer material and incorporated collapsible mounts in the plastic component, on impact this type of construction would deform out of the way. Therefore we can remove this piece price and tooling costs from the report.

Air Filter steel bracket

Pressed Piece Part	**Costs one compt are**	**+ £ 0.00p**
Press Tooling	**Costs one compt are**	**+ £ 00,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

Fuse box steel bracket

Pressed Piece Part	**Costs one compt are**	**+ £ 0.00p**
Press Tooling	**Costs one compt are**	**+ £ 00,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

26. Engine position – Engine mounts – Modifications required. [See Appendix B]

Workscope
The Engine bay package would require a great deal of re – engineering, this will effect Panel and assembly tooling Manufacturing production line processes and development costing. For this exercise, please refer Appendix B, as this is not in the scope of work for this report, but appendix B outlines the considerations if the engine is to be repositioned.

The costs for raising the bonnet are included in the bonnet and fender costs (items 11, 12, 17).

Summary of Costs

Ref no	Report Section	Part Description	New Items	Compt & Assy Tool type	Additional Manufacture piece cost / Vehicle	Additional Tooling / Assy costs per Programme	
1	FIGURE 2.0	FRONT BUMPER FACIA INCREASE DEPTH BY 45mm.		plastic	£3.00 £0.00	£10,000.00 £0.00	
2	FIGURE 2.0	FRONT BUMPER ENERGY ABSORBING FOAM MATERIAL FOR LOW SPEED IMPACT	#	foam	£10.00 £0.00	£18,000.00 £0.00	
3	FIGURE 2.0	FRONT BUMPER LOWER SPOILER REMOVABLE SPOILER BOLTED TO BUMPER FACIA	#	plastic	£30.00 £0.00	£300,000.00 £0.00	
4	FIGURE 9.0	FRONT UNDERTRAY UNDER TRAY TO SUPPORT FRONT LOWER SPOILER	#	plastic	£6.50 £0.00	£150,000.00 £0.00	
5	FIGURE 16 FIGURE 17	FRONT WIPER SYSTEM WITH BREAK AWAY WIPER SPINDLES AND FIXINGS		steel	£3.40 £0.00	£25,500.00 £0.00	
6	FIGURE 2.0	HEADLAMPS - DESIGNED AS PEDESTRIAN IMPACT FRIENDLY REPAIR KIT WILL BE REQUIRED - NO COSTS FOR THIS REPORT	#	plastic plastic	£0.00 £0.00	£0.00 £0.00	
7	FIGURE 2.0	FRONT HEAD LAMP - MOVED FOREWORD - NO COSTS FOR THIS REPORT - AFTER SALES. HEAD LAMP BRKT MODIFIED WITH CRUSHABLE FIXINGS-REQUIRED IF CLASS LENS ISUSED		pressed assy	£0.00 £0.00	£0.00 £0.00	
8	FIGURE 5.0 FIGURE 1.0	PRESSED FRONT BUMPER BEAM - ADD CRUSH INITIATION DEPRESSIONS. ADD FORM TOOL TO PRESS IN THE DEPRESSIONS. MAIN BUMPER BEAM MOVES REARTWARDS BY 20mm - CRASH CANS REDUCE BY 20mm	#	pressed assy pressed	£3.28 £1.12 -£0.25	£150,000.00 £13,370.00 -£8,500.00	
9	FIGURE 2.0	FRONT SPOILER REAR FIXING POINTS LH / RH. SHEET METAL BRACKET X 2	#	pressed assy	£1.64 £0.20	£70,000.00 £1,960.00	
10	FIGURE 9.0	UNDER TRAY FIXING RAIL TO ENGINE SPLASH GUARD TO GIVE SUPPORT TO UNDER TRAY & SPOILER.	#	pressed assy	£1.19 £0.50	£117,000.00 £6,982.00	
11	FIGURE 10	BONNET OUTER PANEL - [SHEET METAL PRESSING] EXTENDED 45mm FOREWORD		pressed assy	£0.40 £0.30	£19,000.00 £4,900.00	
12	FIGURE 11	BONNET INNER PANEL - [SHEET METAL PRESSING] EXTENDED 45mm FOREWORD WITH REDUCED FRONT BOX SECTION (see ref 11)		pressed assy	£0.34 £0.00	£16,000.00 £0.00	
13	FIGURE 12	BRACKET MOUNTING TO BONNET INNER - BONNET LATCH LOCKING LOCAL BRACKET TO SUPPORT BONNET LATCH WITH REINF PLATE AND NUT	#	pressed assy	£0.85 £0.29	£94,000.00 £3,815.00	
14	FIGURE 12	EXTENSION SUPPORT TO BONNET LOCKING PLATFORM SHEET METAL FORMED PLATE ADDED LENGTH.		pressed assy	£0.80 £0.15	£48,000.00 £1,225.00	
15	FIGURE 12	MODIFY BONNET LATCH AND BONNET LOCK PLATFORM REPOSITION LATCH REARWARD - ADD TUBE AND LATCH PIVOT	#	pressed assy	£1.03 £0.58	£51,000.00 £3,185.00	
16	FIGURE 12	BRACKET SUPPORT TO MOUNT RUBBER BONNET SEAL SHEET METAL DEFORMABLE SUPPORT - WIDTH OF CAR		pressed assy	£0.33 £0.00	£22,500.00 £0.00	
17	1.13.1	MODIFY FRONT FENDER OUTERS LH & RH. REPOSITION FRONT EDGE TO HEAD LAMP - INCREASE HEIGHT AT REAR TOP SURFACE.		pressed assy	£0.54 £0.00	£52,000.00 £0.00	
18	FIGURE 13	MODIFY FIREWALL TOP SECTION REINF TO BASE OF SCREEN. THE TOP SECTION OF THE PANEL TO B E REMOVED.		pressed assy	-£0.38 £0.00	-£26,000.00 £0.00	
19	FIGURE 14	REINF DIAPHRAGMS ADDED TO REINF TO BASE OF SCREEN - 3 OFF DIAPHRAGMS TO BE ADDED TO THE REINF ASSY TO SUPPORT CENTRE BASE SCREEN.	#	pressed assy	£2.47 £0.87	£65,000.00 £9,432.00	
20	FIGURE 15	MODIFY FIREWALL / ENGINE BAY BULKHEAD, ADD SWAGE FORM TOOL SWAGES TO BE ADDED TO FORM CRUSH ZONE.		pressed assy	£0.28 £0.00	£35,000.00 £0.00	
21	FIGURE 16 FIGURE 17	CASTING REQUIRED TO HOUSE WIPER SPINDLE - BREAK AWAY SPINDLES & MOUNTS. FIXING BRACKETS TO BODY - CRUSHABLE FIXING POINTS, LH & RH.		pressed assy	£4.08 £0.00	-£2,354.00 £0.00	
22	FIGURE 18 FIGURE 19	BONNET HINGE - TO BE FIXED WITH BREAK AWAY BOLTS - SHEAR BOLTS SPECIALS. NEW BRKT MOUNT HINGE FIXING TO BONNET WITH CRUSHABLE INITIATORS.		pressed assy	£1.30 £0.00	£24,000.00 £0.00	
23	1.13.4	COOLANT RESERVOIR TO BE RELOCATED NEW BRACKET REQUIRED WITH CRUSHABLE INITIATORS.		pressed assy	£0.25 £0.00	£20,000.00 £0.00	
24	1.13.4	BRAKE & FLUID RESERVOIRS & PIPES - CRUSHABLE BRAKE RESVR BRKT. FLUID RESERVOIRS & PIPES - CRUSHABLE FLUID RESVR BRKT.		pressed assy	£0.25 £0.00	£22,000.00 £0.00	
25	1.13.4	AIR FILTER , CRUSHABLE PLASTIC HOUSING - ENGINE TOP COVER TO BE REMOVED. FUSE BOX - CRUSHABLE PLASTIC HOUSING - NO COSTS FOR THIS REPORT.		plastic plastic	£0.00 £0.00	£0.00 £0.00	
26	1.13.4	ENGINE POSITION - ENGINE MOUNT - MODIFICATIONS. **[SEE DOCUMENT]** OR RAISE BONNET 15 TO 20mm.					
			TOTAL COSTS		£71.16	£1,162,145	2 (With foam bumper)
			TOTAL COSTS		£65.31	£1,299,015	8 (With pressed Beam)
					Piece costs per Vehicle	Added Tooling per Programme	

The above tooling costs can be spread over the model life (7 Years), hence divide the above by the number of years.

Notes for Consideration on Pedestrian Protection Legislation effects on Vehicle Design

To compliment the Piece and Tooling Costs details the following notes on the effects of Pedestrian Protection Legislation on Vehicle Design should also be considered. It should also be noted that the Piece and Tooling Costs do not include any Costings for any additional Design, Analysis and Testing.

Weight – Weight increases will occur due to additional components, deeper bumper, Lower Spoiler, higher Bonnet and longer vehicles. Any weight increase will have a negative effect on Emissions and Fuel Consumption Performance, as noted below.

Styling – Affects the Front End style on hood, bumpers, etc. Any concern that it will give a “chunkier” feel to vehicles and all will look similar is not really the case as Honda has successfully achieved the requirements with well styled vehicles that meet the current requirements. Vehicles will also be longer and have higher front ends but a capable design team should be able to accommodate this within any new style.

Package – It could be difficult to package Engines to give additional clearances (see attached notes). But designing systems as Pedestrian Impact friendly should be achievable especially working with the Supplier base. Forward vision Angle, Front Approach Angle, Kerb Strike Requirements, Airflow and Cooling performance can all be affected to their detriment.

Aerodynamics – The requirements to have a flatter Front end form will effect the Aerodynamic performance and potentially effect emissions, fuel consumption performance and vehicle NVH. The effects would be studied using CAE analysis and any issues resolved during the design process.

Emissions and Fuel Consumption – The combination of the weight increases and the Aerodynamic effects will have a negative impact on the vehicle’s Emissions and Fuel Consumption Performance, which may require modifications to the Engine and Powertrain Systems. Furthermore, these changes are likely to have an effect on Vehicle Performance, Ride and Handling, High Speed Stability, Steering and Braking. Another issue to consider is the issue of effectively a softer Front end on the Airbag Sensor Calibration. The Calibration will need to take this into consideration.

Durability, Reparability and Serviceability (Insurance Ratings) – The requirement for breakaway or deformable Parts and Systems effectively weakens them. This will have a knock-on effect to the Vehicle Durability, its reparability (Thatcham) and its serviceability. Accurate Analysis for these items will be necessary to develop a compromise solution between all vehicle requirements.

Vehicle Target Setting – As stated the requirements for Pedestrian Protection legislation can affect various areas of the Vehicle Attributes. When the vehicle targets are set at the beginning of the program consideration should be given to this.

Material Selection – When materials are selected Pedestrian Protection requirements should be considered. The use of new Energy Absorbing materials will be considered in the future to aid in meeting the requirements (e.g., Pedestrian Protection Shock Absorbing Liquid Packages, etc)

Fixing Selection – When Fixings are selected Pedestrian Protection requirements should be considered. Also the position and direction of the Fixings can be designed at an early stage to have no detrimental effects. (e.g., do not have any hardpoints or sharp points facing in a forward or upward direction)

Manufacturing Feasibility – The theory of solutions to meet the requirements should be backed up with approval from the OEM and Supplier Manufacturing Engineers. Often Panel Design, stampings and assembly Production tooling Manufacturing and Production on line and off line process methods are limited, (due to many factors) and may not be able to manufacture or assemble the required designs.

Additional Engineering Design Work – In theory there should be limited additional Engineering Design as these parts and Systems will be designed anyway on a new vehicle. However it should be considered that most "new" vehicles contain a large percentage of Carry-Over Parts and Systems. These Carry-Over items, if they effect Pedestrian Protection requirements, will have to be redesigned and replaced. The phasing in period for the legislation should allow for this. The Pedestrian Protection requirements should be considered and designed for during the early stages of the Design process. The use of Deformable or Breakaway systems may cause some additional work but examples of these systems are available to use as a basis for any new Designs.

Any parts that have to be redesigned to meet the legislation can potentially be carried over to use on other vehicles which will ultimately reduce their piece costs (but could increase the tooling cost due to the volume increase). It is very difficult to adjust the figures to reflect this without more detailed involvement in the actual designs and knowing what vehicle ranges are involved. However likely candidates to be able to be carried over are brackets, wiper system, headlights (styling permitting) and Underbody BIW. Therefore for this report we can make a statement by advising a percentage decrease in costs by some 15% for the wipers and the headlamp piece prices and tooling costs. These costs have been reduced in this report.

Additional Analysis Work – In theory the only additional Analysis work required is for Pedestrian Impact. Aerodynamic, Cooling and Vehicle Crash Testing will be done anyway on a new vehicle although some additional iterations may be required if the Pedestrian Impact requirements cause any changes.

Additional Test Work – In theory the only additional Test work required is for Pedestrian Impact. Aerodynamic, Cooling and Vehicle Crash Testing will be done anyway on a new vehicle although some additional iterations may be required if the Pedestrian Impact requirements cause any changes.

Active Pedestrian Impact Systems – If it is found that a new vehicle design cannot be packaged to give sufficient Engine Clearance to the Bonnet then an Active Pedestrian Impact System can be considered. This can take the form of the new developments in Pop-up Bonnets, which raise in the event of an impact with a Pedestrian to give additional clearance, or external Airbags. These systems are complimented with additional Sensors on the front of the vehicle to determine a Pedestrian Impact is taking place before activating the systems.
However these systems are new developments and will add significant cost and weight to a vehicle. So they are likely to only be considered in the higher vehicle specification ranges where the cost can be absorbed and where for package reasons the legislation cannot be met within the vehicle design.

Engine reposition to a Landrover Freelander to improve pedestrian impact.

The ACEA recommendation is to provide impact absorption to 65mm depth.
The WG17 recommendation is to provide impact absorption of 95mm depth.

Currently the engine has 35mm clear to the top of the engine acoustic cover.
Assuming this can be removed or is flexible to 15mm, an additional 15 – 20mm of clearance is desired to achieve compliance to the ACEA standard.

The following considerations will be applicable to re-positioning the engine:-

- Re-package engine & transmission assy to achieve desired top end clearance.
- Check ground clearance line (GCL) has not been encroached upon or exceeded.
- Sump reprofiling can improve ground clearance, but only in consideration of oil capacity, oil pick-up design change and consideration to serviceability for oil drain.
- New position of engine to be checked for clash conditions to engine bay, specifically the cooling pack and fan shrouds, as Front End Accessory Drive (FEAD) parts would assume a new location.
- All hoses: Cooling, Air system, Heater/ HVAC, Exhaust Gas Recirculation (EGR) & vacuum supply to servo, would need to be re-designed to the new package position.
- Fuel supply pipes will need to be redesigned.
- Engine mounts would need to be redesigned. Could impact on Torque Roll Axis (TRA) requiring full FEA work.
- Driveshaft angles / lengths would change, requiring redesign.
- Transmission and/or clutch bell housing may encroach on GCL preventing decking to desired limit, but some work on the bell housing may be possible.
- Clutch and transmission control linkages will need redesigning.
- Reservoirs for coolant, PAS, brakes and clutch may need work to permit flexibility in the event of impact.
- Fuel filter may need to be repositioned.
- Crankcase ventilation system piping will need redesigning.
- Carbon canister piping will need to be redesigned.
- Dip-stick may need to be lengthened after decking to improve serviceability.
- Check for FEAD serviceability with engine in new position. (Tooling access for belt removal & tensioning).
- Engine harness main connection may need lengthening.
- Exhaust downpipe change to accommodate reposition of engine. If close coupled Cat, Cat position and heat-shielding change may be required.
- If turbo is fitted. Ensure no temperature sensitive components are compromised. Adequate heat shielding may need to be repositioned / designed.
- If undertray is fitted, modifications may need to be made to provide clearance.

11.2.3 Ford Mondeo – modifications

The modifications required for a new large family car, based on inspection of the Ford Mondeo, in order to meet a revised version of phase two of the EC Directive, including the proposed changes (amendments made to reflect feasibility issues), are presented in the following sections. These modifications are broken down according to the pedestrian test which requires that modification.

11.2.3.1 Legform to bumper

For the legform tests, there are two different requirements for crush depth that come from the two performance widths. The first is a region for all but 264 mm of the bumper test width that must meet the more demanding requirement for the tibia acceleration. The second is a relaxation zone for which up to 264 mm of the test width can be nominated by the manufacturers to meet the less demanding requirement for the tibia acceleration. The corresponding crush depths necessary to meet the requirements for these widths are, for the main width, 62 mm and, for the nominated relaxation zone, 45 mm.

Through the addition of a pedestrian friendly bumper, 20 mm of existing crush space may be recovered from the low-speed impact energy management system. This is based on the contribution of the pedestrian friendly bumper towards the crush depth currently used to minimise costs for repairing bumper damage in low-speed impacts, as assessed in bumper testing. However, insurance ratings are important on a volume vehicle of this type and recovering less crush space would reduce the risk of other components being damaged, so it was decided to recover only 14 mm from the existing crush space. Therefore the first modification is to reduce the energy absorbing crush cans of the bumper beam, see Figure 11.23, which connect to the longitudinal chassis rails, by 14 mm in length. The effect of this on the bumper beam position is shown in Figure 11.24 with the old position shown in blue and the new position in red.

The bumper beam in the Ford Mondeo does not follow the outer skin profile of the bumper facia. The clearance between the outer facia and the bumper beam is greatest in the middle of the vehicle and smallest towards the ends of the bumper beam (see Figure 11.23 for the bumper beam). At the point of minimum clearance between the facia and the beam, there is approximately 20 mm separation. Therefore, in addition to the 14 mm crush depth gained through the rearward movement of the bumper beam, as shown in Figure 11.24, there is at least a further 20 mm available, making a total of 34 mm. Therefore a further 28 mm needs to be created to meet the required 62 mm crush depth for the protection of pedestrians in the main width and a further 11 mm to meet the required 45 mm of crush depth for the relaxation zone.

It is known that this ‘Hydro-form’ bumper beam is expensive to make so it is proposed that a more conventional steel or aluminium beam is used. However, as hydro-formed beams are unusual, no allowance will be made for any saving found by using a more conventional beam, when calculating costs for pedestrian protection.

To create the remaining 28 mm of crush depth required for the pedestrian legform test, the bumper facia will be moved forward. The amount by which the bumper facia needs to be moved forward is not immediately obvious as the curvature of the bumper beam is not known exactly. This curvature needs to be considered with respect to the quantity of the bumper surface that would be contained within the relaxation zone. It is anticipated that as the centre of the bumper beam would already pass the more stringent area requirements (with the correct crush stiffness) and as the worst area needs only a further 11 mm of crush depth to pass the reduced criterion, then the bumper may only need to be moved forward by about 15 mm. Therefore for this exercise, the increase in length required to give the necessary protection for pedestrians, and pass the revised criteria proposed for phase two of the EC Directive, shall be set to 15 mm. Due to the difficulty in accurately displaying this small change in vehicle length, it has not been included as a separate figure.

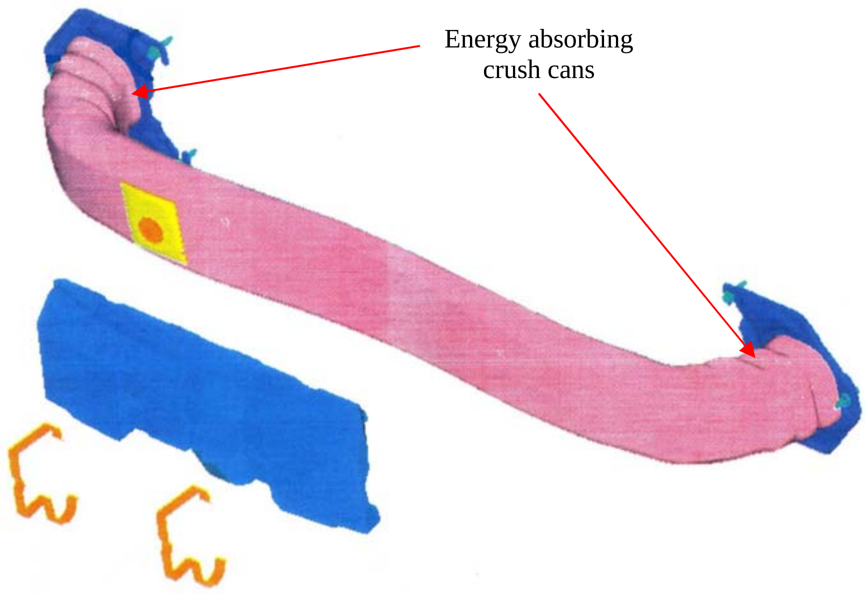

Figure 11.23. Mondeo bumper beam and clip-on energy absorbing foam

Figure 11.24. Bumper beam moved rearwards by 14 mm due to the reduction of the length of the energy absorbing crush cans of the bumper beam used to link to the chassis rails

As mentioned with the Landrover Freelander, to control the energy attenuation of the legform impactor or pedestrian leg, an energy absorbing material is required between the bumper facia and the bumper beam. The solution proposed for this feature is the same as that for the Freelander (see Figure 11.6). This is based on the bumper beam used in the Honda Jazz, as shown in Figures 11.4 and 11.5.

The bumper is required to give a low load path for the legform impactor. This low load path is required at the same forward position as the bumper's upper load path. Figure 11.25 shows a revised bumper (shown in red) based on the existing shape but with the bumper 15 mm forward as suggested above and with the lower edges brought even further forward to provide a low load path. As the ramp angle of modern cars can be considered to be critical, the extension of the bumper lower edge has been moved forward and upward to maintain the current ramp angle of about 16° (the approximate line from which the ramp angle is derived is shown in orange in Figure 11.25).

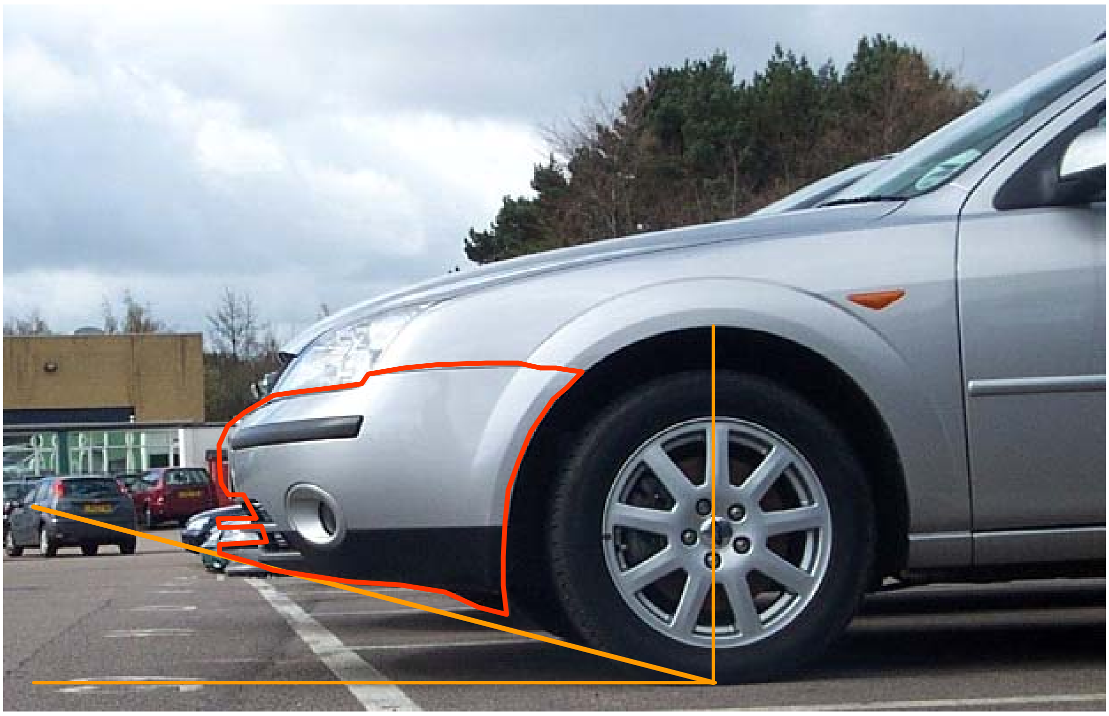

Figure 11.25. Diagram showing the bumper extension and spoiler re-profiling

The decision not to infringe on the ramp angle has a consequence for the cooling system of the car. By raising the lower edge of the bumper facia, the potential area for the intake of air is reduced. To account for this, the air intake area of the bumper facia that has been removed through the positional change needs to be reintroduced. Figure 11.26 shows the existing bumper air intake area of the Mondeo (shown in green) with the surrounding structural elements (shown in grey). Figure 11.27 shows the proposed changes to the bumper facia area. The lower bumper edge has been raised, which reduces the air intake area of the lower cavity. In response the upper cavity in the bumper facia has been widened and turned out at the upper edges rather than being curved in.

The modifications shown here are an initial thought and are open to subjective design alterations, where only the cosmetic appearance of the bumper facia is altered. However, the modifications exemplify those that would be necessary to maintain the air intake area.

The front edge of the spoiler normally has little support. Now that the spoiler has been brought forward, the support to the lower edge needs to be increased in order to minimise the knee bending angle. However, this strengthening must not be taken too far or it could introduce local injuries in the ankle area. To provide this support, it is proposed to use a ribbed under-tray similar to that used in the Volvo S40 and shown in Figure 11.28, fitted between the lower edge of the bumper and the cross-member beneath the cooling pack.

Figure 11.26. Existing bumper facia air intake design

Figure 11.27. Modification to the bumper facia required to maintain both the ramp angle and air intake area

Figure 11.28. Ribbed under-tray and bumper facia from the Volvo S40

Following the repositioning of the bumper beam, the introduction of an energy-absorbing material between the bumper beam and the bumper facia, and the introduction of a low load path in the bumper, the stiffness of these elements would need to be tailored to give the optimum performance in the legform test. This optimisation process would be achieved initially using mathematical simulations of the components and then of the integrated system, followed by some practical validation testing.

11.2.3.2 Upper legform to bonnet leading edge

Through consideration of the Euro NCAP upper legform test results for the Ford Mondeo, it was estimated that the Mondeo had crushed by approximately 115 mm on the centreline. Theoretical estimation of the proposals in Section 10.4.1.4, suggests that 110 mm of crush depth is required to pass the peak force criterion within the more demanding zone, therefore the Mondeo already has just sufficient crush space. However, the existing crush depth is likely to be slightly too stiff. It is thought that the change in crush force can be achieved by minor changes in the Bonnet Leading Edge (BLE) design that will have no additional manufacturing cost for the central area of the BLE. For these costings it has been assumed that a collapsible bonnet striker and deformable headlamps will be the only additional pedestrian features. The bonnet lock striker will be modified to make it deform more readily and be of the form of that already used in the Ford Focus C-Max, as shown in Figure 11.29.

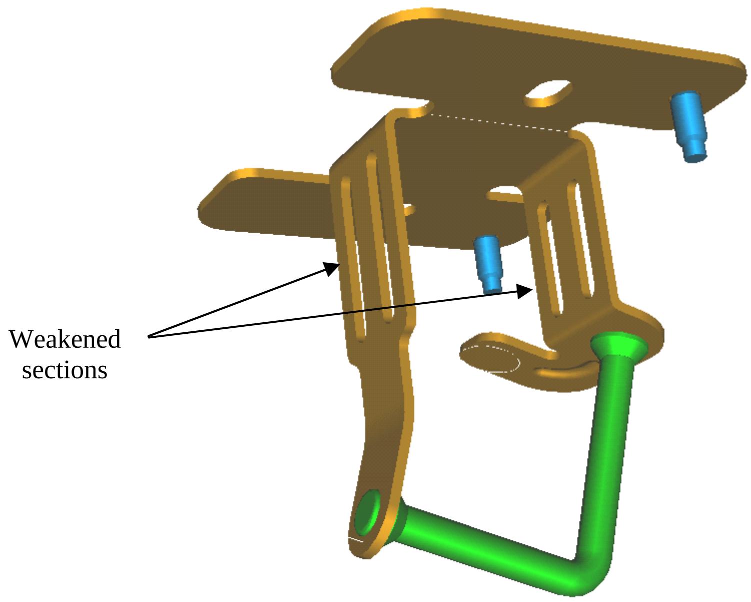

Figure 11.29. Weakened bonnet striker as used in the Ford Focus C-Max

As the BLE runs along the intersection between the bonnet and the headlamps, the headlamps will need to be made deformable. Deformable headlamps with deformable lenses and reflector boxes are currently being developed to provide pedestrian protection and are already fitted to the Honda Civic and the Volvo S40. Therefore, similar units will be used with styling to match the current Mondeo lamps. As with most current vehicles the headlamps are required to match the styling requirements for the specific model although sharing of some components may be possible. The alternative solution of mounting the headlamp on frangible mountings will not be used because it is thought that headlamps may become too heavy to be moved bodily back into the vehicle during an upper legform test. This additional weight is likely to be caused by the use of more powerful light sources and introduction of intelligent interactive adjustment of the headlamp direction and pattern to aid the driver seeing dangers to the side and around bends.

For any parts of the BLE width where it is difficult to achieve the desired stiffness, for example where the bonnet is supported by the uprights each side of the cooling pack, the manufacturer can nominate these for the less demanding relaxation zone requirements.

Following the introduction of the deformable bonnet lock striker and headlamps, the stiffness of the BLE and underlying elements would need to be tailored to give the optimum performance in the upper legform test. This optimisation process would be achieved initially using mathematical simulations of the components and then of the integrated system, followed by some practical validation testing.

11.2.3.3 Headform to bonnet top

For the headform tests, there are four different requirements for crush depth that come from testing with both the adult and child headform impactors over the two regions of HPC requirements (i.e. main area and relaxation zone). These minimum crush depths include an allowance for the residual depth occupied by the crushed material.

The bonnet top crush depth alone will not satisfy the requirements proposed in Section 10.4.1.5. The stiffness and deformation of the bonnet are also critical; therefore any assumption that the requirements can be met through the provision of adequate crush depth in the bonnet top also requires tailoring of the bonnet stiffness. To provide approximately the required stiffness of bonnet for the protection of pedestrians, the bonnet should have an underlying structure without localised stiff points. For the Mondeo this would mean revising the bonnet under-frame to have a more homogeneous stiffness. The Ford Focus C-Max has a more uniform inner bonnet skin to provide a more uniform stiffness for the assembled bonnet (see Figure 11.30). For these costings it will be assumed that this design will be adapted and refined to suit the Mondeo.

The stiffness of the bonnet and the supports along each edge would need to be tailored to give the optimum performance in the headform test. This optimisation process would be achieved initially using mathematical simulations of the components and then of the integrated system, followed by some practical validation testing.

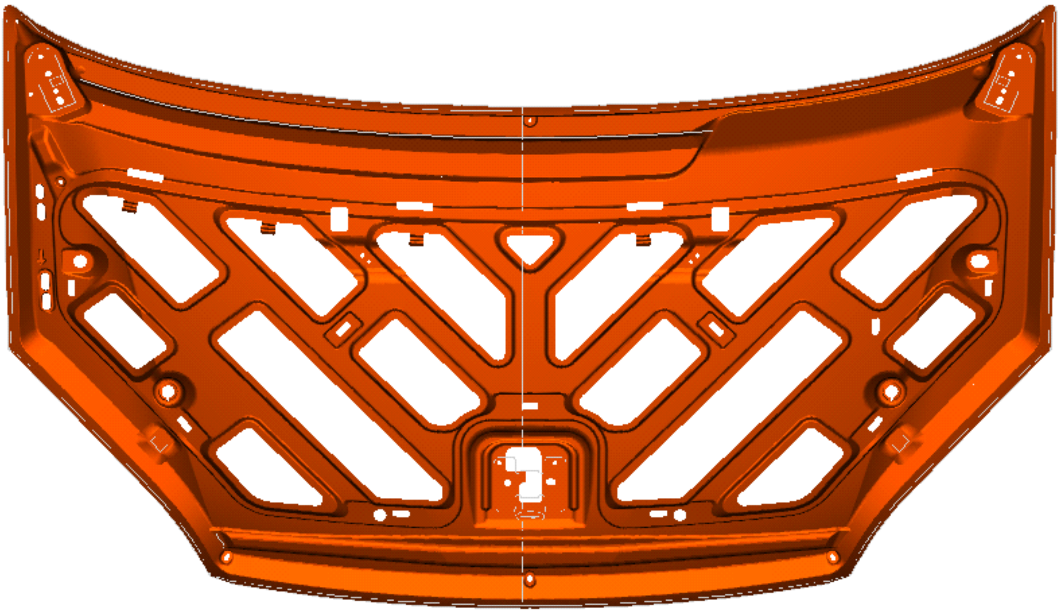

Figure 11.30. Ford Focus C-Max bonnet inner skin

To establish high points in the engine bay, measurements were made between the high features under the bonnet and the bonnet underside (sound-proof padding), and an allowance has been made for the thickness of the bonnet in the approximate crush depths that were estimated. These crush depth estimations, for one petrol and one diesel variant, are shown respectively in Figures 11.31 and 11.32. It can be seen, through comparison of the two figures, that the diesel engine variant is slightly larger than the petrol engine with the engine block being between 40 and 60 mm from the bonnet as opposed to 70 to 80 mm, respectively. The 70 to 80 mm clearance would be sufficient to meet the requirements for much of the head impact test area. Some of the remaining area would meet the relaxation zone requirement; however, some of the area with clearances down to 40 mm would not be sufficient. Therefore it is proposed to raise the bonnet 35 mm and revise the reinforcement plate on top of the McPherson strut tower (which most cars do not have), to obtain an extra 15 mm in this area. With a very slightly higher bonnet, it is thought that the test could be passed for the engine block area, using some of the allowed relaxation area.

It is useful to compare the engine to bonnet clearance in a larger engine variant, such as the V6 2.5 L petrol engine. To determine this, clearance measurements were made of the 2.5 L engine variant and compared with a smaller 1.8 L engine, for convenience the preceding model of Mondeo was used for this. It was found that the clearance of the high points were comparable between the two engine sizes but that the larger engine was close to the bonnet for a greater area of the bonnet, as a proportion. This has implications for the relaxation zone. The large engine block close to the bonnet would use too much of this area to make the rest of the bonnet top area feasible. To enable the entire bonnet top to be feasible with respect to passing the proposed requirements, the region of the engine block should be made to meet the main area HPC criterion. Most of the engine block area, but not all, would meet this requirement with the additional 35 mm of crush depth provided by raising the bonnet, as mentioned above. It is assumed that some savings in engine height in critical areas could be made with a new vehicle, by modifications to the components concerned or the engine covers, but for the purposes of these costings, these changes have not been included.

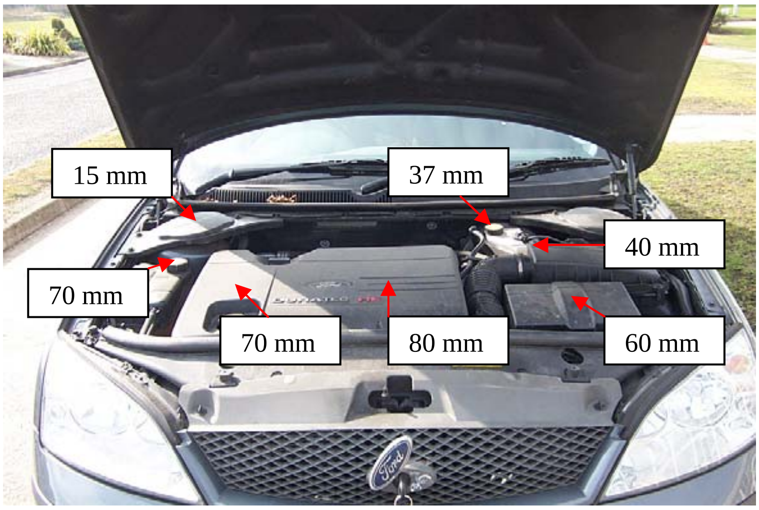

Figure 11.31. Approximate crush depth measurements (four-cylinder petrol variant)

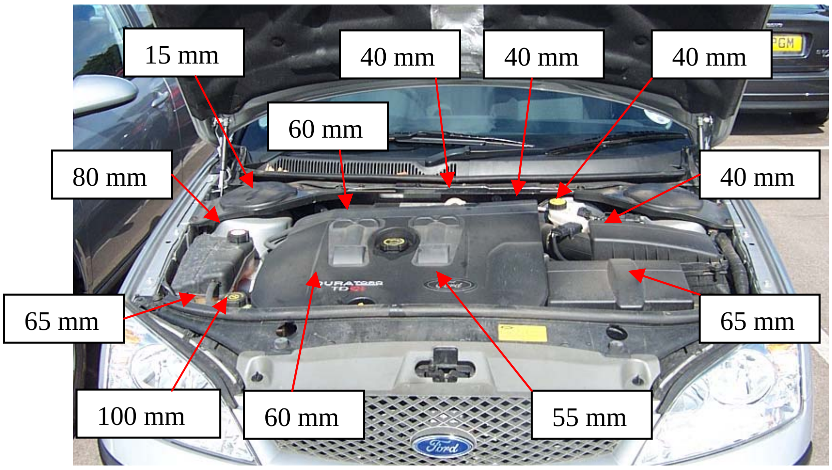

Figure 11.32. Approximate crush depth measurements (diesel variant)

To make the necessary 35 mm available, the bonnet would have to be lifted. Figure 11.33 shows a Mondeo with the bonnet lifted by 35 mm; the original bonnet is depicted by the green lines and the new position shown by the red lines. Associated with the raising of the bonnet is the extension of the wings to maintain the fit between the bonnet and wing edges; this is shown in Figure 11.34.

Another issue to be considered with the raising of the bonnet is the view angle for the driver. If the bonnet is lifted too far, then the angles through which the driver can see will be reduced. If the view angle is made too small, then the seating position for the driver would need to be raised along with the roof of the vehicle to allow for the same headroom. This will have associated weight, wind resistance and manufacturing costs and will not be a viable option for certain vehicles such as sports cars.

The legal minimum for a point directly in front of the driver is angle of 5° from the set point (equivalent to the position of the driver's eye) and uses an upper and lower height to cover some of the variation in stature seen in the population. Figure 11.35 shows a diagram on which downward view angles have been marked, shown by the orange lines. It was estimated that the existing Mondeo bonnet (green lines) allowed a downward view angle of approximately 8.6°. With the bonnet being lifted by 35 mm (red lines), this view angle has been decreased by almost 2°, making it approximately 6.6°. This is still within the legal limit and is therefore thought to be acceptable; however, it may not be ideal for the very short driver.

Figure 11.33. Bonnet lifted by 35 mm to provide the necessary clearance underneath

Figure 11.34. Raised wing edge to match bonnet

Figure 11.35. Revised view angles

After raising the bonnet by 35 mm, there are a few remaining high points which are dealt with below.

The current Mondeo McPherson strut reinforcing braces have a height of about 40 to 70 mm (as the towers are angled with respect to the braces). For a new vehicle, it should be possible to add reinforcement to the McPherson strut towers without the introduction of such high bracing beams. For these costings, it has been assumed that a more compact brace design can be produced with no extra cost.

Other high points in the engine bay are the air filter and the brake fluid reservoir. Both of these items could be made to be more deformable than they are currently. The air filter box will be made to be deformable by the use of fold initiators and, if necessary, revised plastic materials. For the brake fluid reservoir to be made frangible so that it will push down, it will be necessary to use slotted or deformable mountings. The current rigid combined mounting and fluid connections to the brake master cylinder will need to be replaced with flexible pipes along with a deformable or frangible mounting bracket. A similar arrangement to this was suggested for the Landrover Freelander and was used for the brake fluid reservoir on the Honda Civic, see Figure 11.22.

The wing edge of the Mondeo is supported on an in-turned section, raised above the wheel arch and upper longitudinal beam (see Figure 11.36). There is already sufficient crush depth available above the upper longitudinal beam to pass both the child and adult headform tests. However, to control the energy absorption, deformable elements would be needed under the raised wing edge. Examples of such elements are found in the Ford Focus C-max (see Figure 11.37). Figure 11.38 shows the position of these brackets when they are mounted on the wing edge of the Focus C-Max. However, removing the solid upstand and replacing it with these deformable brackets will leave a cavity which needs to be sealed to control under bonnet air flow / fumes, to prevent them reaching the occupant compartment. To provide this preventative measure, a deformable gas-management closing panel would also be needed between the upper longitudinal and the underside of the wing edges.

The base of the windscreen for a new Mondeo-sized vehicle will have a C-shape form similar to that used to provide pedestrian protection in the Honda Civic, as described in the Landrover Freelander modifications (see Figure 11.15). In the middle, where the overhang is greatest due to the curvature of the windscreen, some additional collapsible bracing within the C-section may be necessary.

The forward extension from the firewall, which forms the heater air intake chamber and wiper recess in the Mondeo, is too stiff. This comprises an angle section coming from the firewall, with a rubber seal on the top, which supports the rear edge of the bonnet. To reduce the stiffness of this element, fold initiators in the form of corrugations will be added to the angle section. Figure 11.39 shows a schematic representation of the current and modified structure.

The wiper spindles do not need modification as they are tucked under the bonnet and already pass the criterion proposed in Section 10.4.1.5 and this should be improved by the additional 35 mm of crush depth from raising the bonnet.

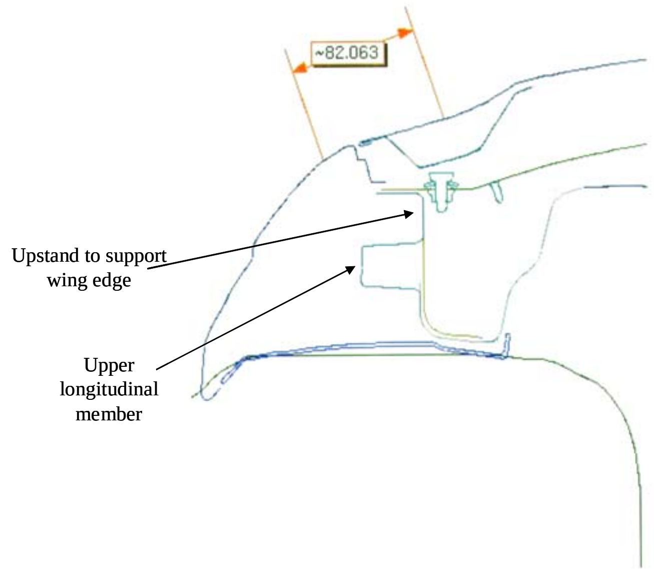

Figure 11.36. Cross section of the current Mondeo at the top of the wheel-arch

Figure 11.37. Deformable wing edge brackets used in the Ford Focus C-Max

The bonnet hinges in the Ford Mondeo, even though they are recessed into the engine bay, do not meet the requirements for phase two of the EC Directive (with a HPC of 2182, as tested in Euro NCAP). To meet the HPC requirement, the hinge will need to be made to be frangible. An example of a frangible hinge is available on the Ford Focus C-max (Figures 11.40 and 11.41). This design works through having a shear pin mounting at the rear of the hinge, where it is bolted to the vehicle. The shear pin is riveted onto the hinge and is waisted to initiate the shearing action. When impacted, this pin shears allowing the hinge to rotate into the engine bay. As well as being frangible, there also needs to be the available stroke depth for the sheared hinge to rotate into. It is believed that the necessary stroke depth will be available with the increase in the height of the wing edge.

For a vehicle of this size, the child to adult transition is likely to be towards the rear of the engine. It may be possible to provide the necessary crush depth in much of the transition area by raising the bonnet by 35 mm and by optimisation of the size and relative position of components. Any small problem areas remaining could be nominated for the lower relaxation zone. For the purpose of this exercise it has been assumed that this will be sufficient. However, the alternative of using pop-up bonnets for this sector has also been included in the costs for the fleet calculations in Section 12.

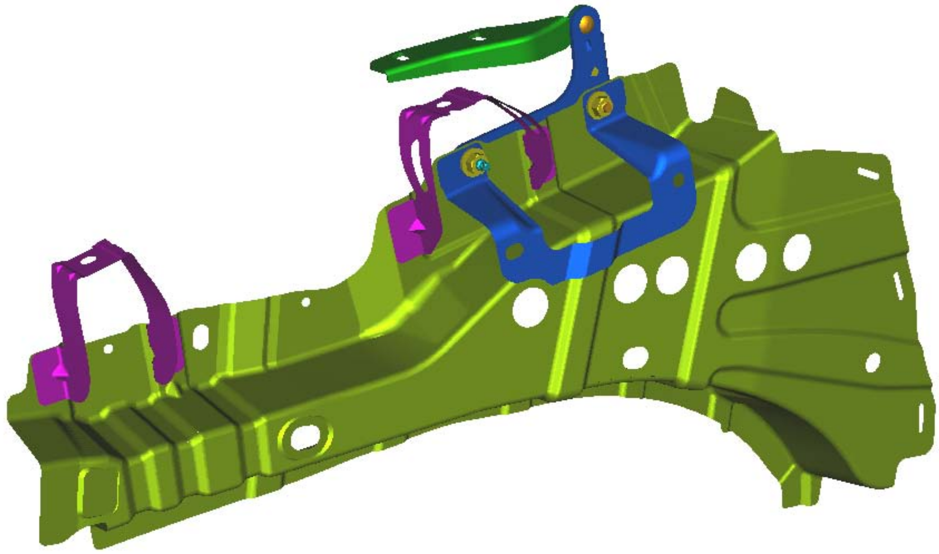

Figure 11.38. Position of deformable brackets when mounted in the Ford Focus C-Max

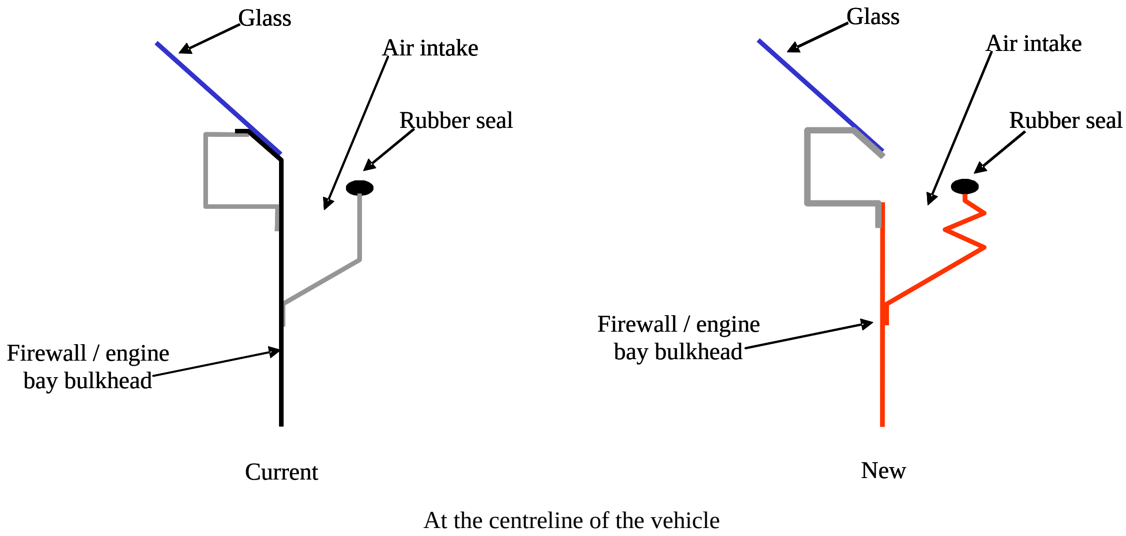

Figure 11.39. Schematic representation of the current and modified sections for the extension of the firewall to form the scuttle heater / ventilation air chamber

Another option is to raise the bonnet further; however, this will further reduce the view angles. In this case it may be necessary to raise the seating position and roof-line similarly to maintain an acceptable view angle. As discussed above, this could have implications for weight, wind resistance and manufacturing costs and it has been suggested by manufacturers that increased fuel consumption because of such changes might be significant. It is therefore interesting to look at the fuel consumption figures of two almost identical base vehicles, one with a high roof and one with a lower roof. It is thought that the Ford Focus and the Ford Focus C-Max are very similar with the exception that the C-Max is about 150 mm higher. Despite this it is interesting to note that although it is not possible to compare the consumption of identical engines, the fuel consumption of these two similar capacity vehicles are almost identical.

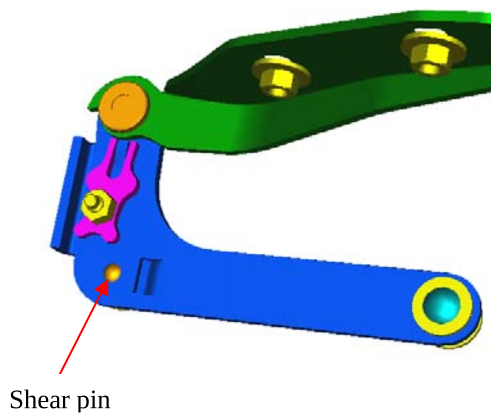

Figure 11.40. Shear pin hinge from the Ford Focus C-Max (engine bay side)

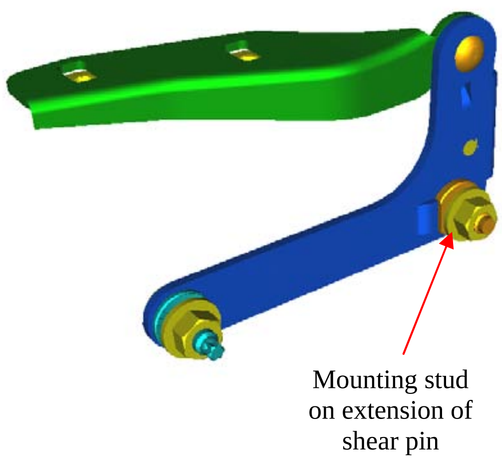

Figure 11.41. Shear pin hinge from the Ford Focus C-Max (wing side)

11.2.4 Ford Mondeo – pedestrian impact cost implications

Again, Menard Engineering Limited first considered the feasibility of these proposals for the Ford Mondeo, as described in Section 11.2.3 above, and revised them where necessary using their specialised vehicle engineering experience. They then produced an estimate of the extra costs for pedestrian protection that would be incurred in producing a totally new vehicle of the same class and similar architecture. Although based on the changes to the Mondeo, they calculated costs for a more generic vehicle of the same category.

The report on the Mondeo, produced by Menard Engineering Limited, is presented, unchanged, below.

Mondeo – Pedestrian Impact Cost Implications

26 April 2004

Contents

General Assumptions

This report is based upon the TRL Report on the Ford Mondeo and the modifications required to meet a revised version of Phase 2 of the EC Directive on Pedestrian Protection. It assumes an estimated vehicle volume of 180,000 per annum.

The On-Cost figures show the estimated cost effect of the Pedestrian Protection legislation on a New Vehicle Design (not for modifying an existing vehicle).

The costs exclude design and development.

1. Front Bumper Facia

Workscope

Front Bumper Facia depth increased by 15mm forward, the Spoiler area moved forward and upward and the Lower Grille configuration modified.

Notes

For this exercise it is assumed that the Front Bumper Facia will be a design based on the existing Mondeo, using similar fixings, Fog Lamp, Grilles, etc. It will be a one piece painted Injection Moulded part. The costs below are given for a full new Bumper Facia and the Pedestrian Impact On-Cost is for the additional tool size and part material due to the depth increase. It is assumed that the Upper Grille is not changed for this exercise.

The Spoiler Area, which is part of the main moulding, will be designed to meet Aerodynamic and Cooling requirements with no detriments using analysis. It will also have to meet all Ground Clearance and Kerb Height requirements.

The Spoiler Area will incorporate the Lower Grille Areas and they can be configured as shown on the TRL report subject to package and meeting the cooling requirements. If the new Lower Grille proposed shape does not cover the areas required for Cooling then some additional Ducting may be required. An allowance for this is also included in the costing. There will be an additional tooling cost for the grilles as they are longer.

The Grilles, Fog Lamps, Parking Distance Sensors and Headlamp Wash Systems
Which can all be fixed to the Front Bumper System should also be considered with respect to Pedestrian Protection. The Mounting Designs for these items should be such that in an Impact they allow the movement of the items rearward or allow them to breakaway without leaving any sharp objects. The On-Cost for doing this to make them Pedestrian Impact friendly could be considered as minimal.

Facia Piece Part Costs

Front Bumper Assembly (excluding Fog Lamps) = £65

Pedestrian Impact On-Cost = £3

Facia Tooling Costs

Front Bumper Facia and Grilles = £900,000

Pedestrian Impact On-Cost = £40,000

2. Front Bumper Energy Absorbing Foam (Alternative to item 8)

Workscope
Front Bumper Energy Absorber.

Notes
Although the existing Mondeo has Energy Absorbing material (for Low Speed Impact requirements) between the Beam and the Facia, for this exercise it is assumed that this Energy Absorbing material will have to be increased in area. There are various materials available such as Steel Pressed Beams (also costed in this study), Aluminium Honeycombs and EPP Moulded Foams. For this exercise we have chosen EPP Moulded Foam. The Density of the Foam will be in the region of 60g/l and this will be confirmed by Analysis to meet the requirements of both Low Speed and Pedestrian Impact requirements.

Note that although this could be considered as an On-cost for Pedestrian Impact the Energy Absorber could already be a requirement due to Low Speed Impact requirements and any tailoring to meet Pedestrian Impact will have minimal cost effect.

Foam Piece Part Costs
Front Bumper Foam = £5

Pedestrian Impact on Cost = £2

Foam Tooling Costs
Front Bumper Foam = £18000

Pedestrian Impact on Cost = £2000

3. Front Undertray

Workscope
Ribbed Front Undertray supporting the Front Lower Spoiler.

Notes
Front Undertray will be an Injection Moulded (PP) part. The Fixings are to use existing any available fixing positions for the Engine Splash Guard. Some additional Fixings may be required to give adequate support.

The Undertray will be fixed to the Front Lower Spoiler with J-Clips and Screws. The Structural Rib pattern to Support the Spoiler will be designed with the aid of Analysis techniques.

The Undertray will also be designed to not be detrimental to the Cooling and Aerodynamic requirements with the aid of Analysis and Testing.

It should be noted that we are assuming that this Undertray is covering the Front Section of the Engine Bay only and is not considered as a Full Engine Bay Undertray. It should also be of no detriment to Kerb Height requirements.

It should also be noted that many new vehicles have Undertrays to meet NVH, Aerodynamic and Cooling requirements but for this exercise we are assuming that it is a new item fitted to support the Lower Spoiler area of the Bumper.

However an Undertray is already fitted on the new Mondeo and is in the correct area to support the Spoiler. Designing it to support the Spoiler further should be achievable for a negligible on cost (Some additional fixings and ribs) which is shown below.

Piece Part Costs
Undertray Moulding & Fixings = £5

Pedestrian Impact on Cost = £1.50

Tooling Costs
Undertray Moulding = £150,000

Pedestrian Impact on Cost = £10,000

4. Headlamps

Workscope
Headlamps designed as Pedestrian Impact friendly.

Notes
The Headlamps can be designed with breakaway mountings (part of the main moulding) and with deformable Polycarbonate lenses and reflector boxes.

Current design trend is to use polycarbonate lenses therefore there would be no requirement to change lens material for pedestrian impact legislation. The current Mondeo has PC lenses.

The deformable lamp structure would be accommodated by the design of flexible or breakaway mounting lugs/brackets. If this was identified as a requirement at the beginning of a project there would be negligible on-cost to the lamp.

However if a breakaway mounting system is adopted a repair kit would need to be designed and tooled. So the piece price and the tooling costs would be treated as After Market sales costs.

Piece Part Costs
Headlamp System = £35 (single pocket type) to £100 (Xenon type)

Pedestrian Impact On-Cost = £0

Tooling Costs
Headlamp System = £2.5 Million

Pedestrian Impact On-Cost = £0

Repair Kit Piece Part Costs
Repair Kit = £00

Pedestrian Impact On-Cost = £00

Repair Kit Tooling Costs
Repair Kit Tooling = £00,000

Pedestrian Impact On-Cost = £00,000

This section of the report covers the areas of the vehicle for Body in White.

Relative to the Freelander report the tooling costs have been increased by 5 – 10% and the piece price costs reduced between 10 – 13%, as the Mondeo vehicle volume per year has been based on 180,000 / year.

The On-Cost figures show the estimated cost effect of the Pedestrian Protection legislation on a New Vehicle Design (not for modifying an existing vehicle).

5. Head Lamp bracket moved forward.

Workscope
Head Lamp bracket moved forward by 35mm.

Notes
The head lamp one piece pressed steel panel would require all the fixing positions to have crushable mounts, the mount may need depressions with cut away portions into the steel work or dog legged fixing flanges, on impact the mounts would collapse giving a crushable zone area. The number of tooling operations would increase from three to four ops, and so there are separate LH & RH tools sets.
This type of panel manufacture with deformable mounts would be required to support and hold a glass lens with a plastic headlamp casing, but as we are suggesting the use of a deformable Polycarbonate lens and reflector boxes, this steel head lamp panel costs are not required.

Piece Part	**Costs LH & RH are**	**+ £ 0.00p**
Press Tooling	**Costs LH & RH are**	**+ £ 00,000**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

6. Energy Absorbing Crash Cans.

Workscope
Folded steel Crash Cans are required between the front long members and the introduction of a pressed steel Front Bumper Beam. This new set up to replace the Hydroformed Front Bumper Beam.

Notes
The steel folded front crash cans consist of two parts, a three sided inner and a closing outer panel, the parts have out turned flanges at the rear which are spot welded to the longmembers and out turned flanges at the front and bolted to the Front Bumper Beam for easy repair. The parts are to be designed symmetrical from LH to RH sides of the vehicle, the three sided part to be produced in three operations and the closer in a combined crash form and flange tool. The fixture to hold, locate and support both the LH and RH assemblies in one jig prior to the spot welding taking place.

Piece Part	**Costs LH & RH are + £ 2.05p**
Press Tooling	**Costs LH & RH are + £ 84,000**
Assembly piece part	**Costs one assy are + £ 0.80p**
Assembly Tooling	**Costs one fixture are + £ 11,200**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

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7. Pressed Main Bumper Beam.

Workscope

To produce a two piece pressed steel Front Bumper Beam which will carry a steel pressed front crush beam and the plastic front Bumper.

Notes

The front Bumper Beam will consist of a pressed steel front section with spot weld flanges and a closing panel, the fixing bolts will be offered from the front of the Bumper Beam through to the LH & RH crash can weld nuts. The pressed front section to be produced in three operations and the closer in a combined crash form and flange tool. The fixture to hold, locate and support the pressed steel Main Bumper Beam and the steel front crushable Beam, this assembly to be spot welded first and then the fixture to support and locate the closing panel which is then spot welded, baffles and reinforcements are also included into this assembly prior to this operation. As this part replaces the current hydroformed part it is not an on-cost classed as pedestrian protection.

Piece Part	**Costs LH & RH**	**are + £ 0.00**
Press Tooling	**Costs LH & RH**	**are + £ 0.00**
Assembly piece part	**Costs one assy**	**are + £ 0.00**
Assembly Tooling	**Costs one fixture**	**are + £ 0.00**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

8. Pressed Crush Beam with initiators to Front Bumper(Alternative to item 2)

Workscope

Bumper Beam to have pressed depressions.

Notes

Bumper Beam to have pressed depressions into the top and bottom panel surfaces to act as crush initiators; this will require three press tooling operations. This will be a new pressed steel panel and become an assembly with the current front beam; a new fixture is required to locate and spot weld the two together.

Pressed Piece Part	**Costs one compt**	**are + £ 2.80p**
Press Tooling	**Costs one compt**	**are + £ 160,000**
Assembly piece part	**Costs one assy**	**are + £ 1.12p**
Assembly Tooling	**Costs one fixture**	**are + £ 7,500**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

9. Bracket Bonnet Latch.

Workscope

The bracket Bonnet Latch mounting to have crushable fixing mounts to the Bonnet inner Panel.

Notes

The Latch and striker bracket to the Bonnet inner Panel require crushable mounts, this will increase the number of press tool operations from three ops to four ops

Pressed Piece Part	**Costs one compt**	**are + £ 0.25p**
Press Tooling	**Costs one compt**	**are + £ 33,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

10. Bonnet Inner Panel extended.

Workscope
Bonnet inner panel extended by 35mm to match Bonnet outer and the front bumper position.

Notes
The front Bonnet inner panel area will extend forward and therefore a percentage of 5% extra costs for the sheet steel and size of the pressed tooling set has been considered for this current exercise. The number of press tool - operations considered were three, now four ops running in a 500 to 800 ton press, auto sheet load and unload and manual load auto unload of the part there after.

Pressed Piece Part	**Costs one compt are + £ 0.35p**
Press Tooling	**Costs one compt are + £ 18,000**
Assembly piece part	**Costs are as below in section 12**
Assembly Tooling	**Costs are as below in section 12**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

11. Bonnet Outer Panel extended.

Workscope
Bonnet outer panel extended by 35mm to match the front bumper position.

Notes
The front Bonnet outer panel area will extend foreword and therefore a percentage of 5% extra costs for the sheet steel and size of the pressed tooling set has been considered for this current exercise. The number of press tool - operations considered is four ops running in a 500 / 800 ton press, auto sheet load and unload and auto load auto unload of the part there after.

The Hemming operation of the outer flange to the inner panel [the clinch flange] for this exercise to be performed on a free standing Hemming fixture, the fixture will increase in size, therefore a percentage of 2% extra costs for the final assembly has been considered for the current exercise.

Pressed Piece Part	**Costs one compt are + £ 0.40p**
Press Tooling	**Costs one compt are + £ 20,000**
Assembly piece part	**Costs one assy are + £ 0.30p**
Assembly Tooling	**Costs one fixture are + £ 4,900**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

12. Modify Front Fender Outers at front & top edge.

Workscope
The front Fender LH & RH to move foreword to meet the new position of the headlamp and to increase in height to suit Bonnet level.

Notes
The increase in the front Fender costs for LH & RH components has been based on an increase of costs by 5% for each hand. For this exercise it is assumed that each front Fender Outer is produced on its own set of tools for each hand, six press operations per hand, running in a 1000 ton press, the piece and tooling prices have then been calculated.

Pressed Piece Part	**Costs two compt are**	**+ £ 0.49p**
Press Tooling	**Costs two compt are**	**+ £ 58,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

13. Brake & Fluid Reservoirs & pipes, reposition bracket with crushable mounts.

Workscope
Brake & Fluid Reservoir container to be lowered repositioned and redesigned with crushable mounts.

Notes
This steel pressed component tooling operations would increase from two to three ops to produce the crushable mount zones, the press tools would run in a 100 ton press. The assembly cost of the bracket to the body in white will not be modified.

Pressed Piece Part	**Costs one compt are**	**+ £ 0.22p**
Press Tooling	**Costs one compt are**	**+ £ 23,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications. Panel & Tool development programmes,

14. Air Filter and Fuse Box with crushable mounts or structures.

Workscope
There are 2 possible options:

1. Air Filter and Fuse Box containers to be lowered repositioned and redesigned with crushable mounts.
2. Air filter and Fuse Box to have crushable structures

Notes
For crushable mounts the steel pressed component tooling operations would increase from two to three ops to produce the crushable mount zones, the press tools would run in a 100 ton press. The assembly costs for these brackets to the body in white would not be modified.

The crushable brackets would not be required if the Air Filter and Fuse Box plastic components where manufactured using a softer material and incorporated collapsible mounts in the plastic component, on impact this type of construction would deform out of the way. This is the preferred solution therefore the piece price and tooling costs can be removed from the report.

Air Filter steel bracket

Pressed Piece Part	**Costs one compt are**	**+ £ 0.00p**
Press Tooling	**Costs one compt are**	**+ £ 00,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

Fuse box steel bracket

Pressed Piece Part	**Costs one compt are**	**+ £ 0.00p**
Press Tooling	**Costs one compt are**	**+ £ 00,000**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

15. Engine position – Engine mounts – Modifications required. [See Appendix A]

Workscope
The Engine bay package would require a great deal of re – engineering, this will effect Panel and assembly tooling Manufacturing production line processes and development costing.

Notes
The potential impact on panel and tooling costs have not been included – refer to Appendix A

16. Front Fender mounting brackets.

Workscope
New deformable Front Fender fixing brackets required between the Shot Gun pressed panel and the LH & RH Front Fenders.

Notes
These new steel formed and flanged brackets to have cut away areas in the side mounts which are fixed to the shot guns, these new mounts are crushable on impact. The front and the rear brackets are produced in a set of tools with LH & RH parts being manufactured together in a 200 ton press with four operations.
No fixtures are required.

Pressed Piece Part	**Costs**	**compt are + £ 3.52p**
Press Tooling	**Costs**	**compt are + £ 169,000**
Assembly piece part	**Costs**	**assy are + £ 0.00p**
Assembly Tooling	**Costs**	**fixture are + £ 00,000**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

17. Shot Gun LH & RH Upper Wheel Arch Longmember Beam.

Workscope
The Shot Gun component is to be redesigned with an up standing flange, this flange is for securing the crushable mounting brackets which will support the front fenders.

Notes

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The component would have been produced in three operations, but for this report it will be increased to four operations in single LH & RH tools running in a 400 ton press. The cavity that is left will require a suitable material to fill the gap and seal off any engine bay fumes, this could be produced from either steel or plastic depending what strength is required from an FEA tensional stiffness calculation.

The shot gun component LH & RH will require an assembly fixture to hold and locate the front fender fixing brackets two off per side for spot welding to take place, the costs given include LH & RH assemblies.

Pressed Piece Part	**Costs**	**compt are + £ 0.70p**
Press Tooling	**Costs**	**compt are + £ 98,000**
Assembly piece part	**Costs**	**assy are + £ 1.74p**
Assembly Tooling	**Costs**	**fixture are + £ 9,000**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

18. Modify Firewall / Engine bay Bulkhead – add crush zone.

Workscope
The Engine bay Bulkhead to be modified by adding a crush zone into the front vertical face, the rear bonnet seal is fixed to this top surface.

Notes
This steel pressed component tooling operations would increase from three to four ops to produce the crushable zone in the vertical face, the press tools to run in a 300 ton press line. Any components welded to this surface may need to be repositioned; the changes to the surface should not affect the assembly of this part to the firewall assembly complete.

Pressed Piece Part	**Costs one compt are + £ 0.24p**
Press Tooling	**Costs one compt are + £ 37,000**
Assembly piece part	**Costs £ nil**
Assembly Tooling	**Costs £ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

19. Bonnet Hinge fixed with breakaway bolts or bracket with crushable mounts.

Workscope
The Bonnet hinges to have built in crushable zones either breakaway bolts or deformable mounts to the Bonnet assembly.

Notes
For this exercise it has been assumed the deformable mount route, with the upper half of the hinge steel leaf to be formed with crushable flange fixing points bolted to the Bonnet assembly.

This steel pressed component tooling operations would increase from two to three ops to produce the crushable zone in the vertical face; the press tools would produce LH & RH parts together and run in a 300 to 500 ton press. The assembly of the two half leafs with the changed form should not alter the production process at the supplies for the completed hinge.

Pressed Piece Part	**Costs two compt are**	**+ £ 1.13p**
Press Tooling	**Costs two compt are**	**+ £ 25,500**
Assembly piece part	**Costs**	**£ nil**
Assembly Tooling	**Costs**	**£ nil**

The above costs do not take into consideration – Panel manufacturing feasibility, tool & assembly process modifications, Panel & Tool development programmes.

Summary of Costs

Ref no	Report Section	PART DESCRIPTION	New Items	Compt & Assy Tool type	Additional Manufacture piece cost / Vehicle	Additional Tooling / Assy costs per Programme
1	FIGURE 1.7 FIGURE 1.8	FRONT BUMPER FACIA INCREASE DEPTH BY 28mm.		plastic	£3.00	£40,000
2	FIGURE 1.2	FRONT BUMPER ENERGY ABSORBING FOAM MATERIAL FOR LOW SPEED IMPACT		foam	£2.00	£2,000
3	FIGURE 1.9	FRONT UNDERTRAY UNDER TRAY TO SUPPORT FRONT LOWER SPOILER		plastic	£1.50	£10,000
4	1.1.2	HEADLAMPS - DESIGNED AS PEDESTRIAN IMPACT FRIENDLY REPAIR KIT WILL BE REQUIRED - NO COSTS FOR THIS REPORT	 #	plastic plastic	 £0.00	 £0
5	1.1.2	FRONT HEAD LAMP - MOVED FOREWORD - NO COSTS FOR THIS REPORT - AFTER SALES. HEAD LAMP BRKT MODIFIED WITH CRUSHABLE FIXINGS-REQUIRED IF CLASS LENS ISUSED		pressed assy	£0.00	£0
6	FIGURE 1.1	ENERGY ABSORBING CRUSH CANS PRESSED SHEET METAL INNER AND OUTER LH & RH CRUSH CANS	#	pressed assy	£2.05 £0.80	£84,000 £11,200
7	FIGURE 1.3	PRESSED MAIN BUMPER BEAM TWO PIECE SHEET METAL PRESSED BEAM REQUIRED	#	pressed assy	£0.00 £0.00	£0 £0
8	FIGURE 1.4	PRESSED CRUSH BEAM TO FRONT BUMPER - ADD CRUSH INITIATION DEPRESSIONS. ADD FORM TOOL TO PRESS IN THE DEPRESSIONS.	#	pressed assy	£2.80 £1.12	£160,000 £7,500
9	FIGURE 1.10	BRACKET BONNET LATCH CUT OUTS TO BE ADDED TO PRODUCE A CRUSHABLE ZONE AREA		pressed assy	£0.25	£33,000
10	FIGURE 1.11	BONNET INNER PANEL - [SHEET METAL PRESSING] RAISE BONNET BY 35mm		pressed assy	£0.35	£18,000
11	FIGURE 1.12 FIGURE 1.13	BONNET OUTER PANEL - [SHEET METAL PRESSING] RAISE BONNET BY 35mm		pressed assy	£0.40 £0.30	£20,000 £4,900
12	FIGURE 1.15	MODIFY FRONT FENDER OUTERS LH & RH. REPOSITION FRONT EDGE TO HEAD LAMP - INCREASE HEIGHT OF TOP SURFACE.		pressed assy	£0.49	£58,000
13	FIGURE 1.17	BRAKE & FLUID RESERVOIRS & PIPES - CRUSHABLE BRAKE RESVR BRKT. FLUID RESERVOIRS & PIPES - CRUSHABLE FLUID RESVR BRKT.		pressed assy	£0.22	£23,000
14	FIGURE 1.17	AIR FILTER , CRUSHABLE PLASTIC HOUSING - ENGINE TOP COVER TO BE REMOVED. FUSE BOX - CRUSHABLE PLASTIC HOUSING - NO COSTS FOR THIS REPORT.		plastic plastic	£0.00 £0.00	£0 £0
15	FIGURE 1.17 FIGURE 1.14	ENGINE POSITION - ENGINE MOUNT - MODIFICATIONS. **[SEE DOCUMENT]** OR RAISE BONNET 35 - THIS COST IS IN ITEM				
16	FIGURE 1.19 FIGURE 1.20	FRONT FENDER MOUNTING BRACKETS - LH & RH 2 OFF PER SIDE. DEFORMABLE WING EDGE BRACKETS REQUIRED	#	pressed assy	£3.52	£169,000
17	FIGURE 1.20 FIGURE 1.18	SHOT GUN LH & RH UPPER WHEEL ARCH LONG MEMBER BEAM MODIFY PART WITH AN UP STAND FLANGE TO MOUNT FENDER BRACKETS		pressed assy	£0.70 £1.74	£98,000 £9,000
18	1.1.3.3 FIGURE 1.21	BASE OF THE WINDSCREEN [FIREWALL SECTION] THE MODDEO ALREADY HAS A C-SHAPED PANEL THE SAME AS THE HONDA CIVIC.		pressed assy		
19	FIGURE 1.22	MODIFY FIREWALL / ENGINE BAY BULKHEAD, ADD SWAGE FORM TOOL SWAGES TO BE ADDED TO FORM CRUSH ZONE.		pressed assy	£0.24	£37,000
20	FIGURE 1.23 FIGURE 1.24	BONNET HINGE - TO BE FIXED WITH BREAK AWAY BOLTS - SHEAR BOLTS SPECIALS. NEW BRKT MOUNT HINGE FIXING TO BONNET WITH CRUSHABLE INITIATORS.		pressed assy	£1.13	£25,500
			TOTAL COSTS		**£22.61**	**£810,100**
			With Foam Bumper Excludes 8		**£18.69**	**£642,600**
			With Pressed Beam Excludes 2		**£20.61**	**£808,100**

The above tooling costs can be spread over the model life (5 Years), hence divide the above by the number of years.

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Notes for Consideration on Pedestrian Protection Legislation effects on Vehicle Design

To compliment the Piece and Tooling Costs details the following notes on the effects of Pedestrian Protection Legislation on Vehicle Design should also be considered. It should also be noted that the Piece and Tooling Costs do not include any Costings for any additional Design, Analysis and Testing.

Weight – Weight increases will occur due to additional components, deeper bumper, Lower Spoiler, higher Bonnet and longer vehicles. Any weight increase will have a negative effect on Emissions and Fuel Consumption Performance, as noted below.

Styling – Affects the Front End style on hood, bumpers, etc. Any concern that it will give a "chunkier" feel to vehicles and all will look similar is not really the case as Honda has successfully achieved the requirements with well styled vehicles that meet the current requirements. Vehicles will also be longer and have higher front ends but a capable design team should be able to accommodate this within any new style.

Package – It could be difficult to package Engines to give additional clearances (see attached notes). But designing systems as Pedestrian Impact friendly should be achievable especially working with the Supplier base. Forward vision Angle, Front Approach Angle, Kerb Strike Requirements, Airflow and Cooling performance can all be affected to their detriment.

Aerodynamics – The requirements to have a flatter Front end form will effect the Aerodynamic performance and potentially effect emissions, fuel consumption performance and vehicle NVH. The effects would be studied using CAE analysis and any issues resolved during the design process.

Emissions and Fuel Consumption – The combination of the weight increases and the Aerodynamic effects will have a negative impact on the vehicle's Emissions and Fuel Consumption Performance, which may require modifications to the Engine and Powertrain Systems. Furthermore, these changes are likely to have an effect on Vehicle Performance, Ride and Handling, High Speed Stability, Steering and Braking. Another issue to consider is the issue of effectively a softer Front end on the Airbag Sensor Calibration. The Calibration will need to take this into consideration.

Durability, Reparability and Serviceability (Insurance Ratings) – The requirement for breakaway or deformable Parts and Systems effectively weakens them. This will have a knock-on effect to the Vehicle Durability, its reparability (Thatcham) and its serviceability. Accurate Analysis for these items will be necessary to develop a compromise solution between all vehicle requirements.

Vehicle Target Setting – As stated the requirements for Pedestrian Protection legislation can affect various areas of the Vehicle Attributes. When the vehicle targets are set at the beginning of the program consideration should be given to this.

Material Selection – When materials are selected Pedestrian Protection requirements should be considered. The use of new Energy Absorbing materials will be considered in the future to aid in meeting the requirements (e.g., Pedestrian Protection Shock Absorbing Liquid Packages, etc)

Fixing Selection – When Fixings are selected Pedestrian Protection requirements should be considered. Also the position and direction of the Fixings can be designed at an early stage to have no detrimental effects. (e.g., do not have any hardpoints or sharp points facing in a forward or upward direction)

Manufacturing Feasibility – The theory of solutions to meet the requirements should be backed up with approval from the OEM and Supplier Manufacturing Engineers. Often Panel Design, stampings and assembly Production tooling Manufacturing and Production on line and off line process methods are limited, (due to many factors) and may not be able to manufacture or assemble the required designs.

Additional Engineering Design Work – In theory there should be limited additional Engineering Design as these parts and Systems will be designed anyway on a new vehicle. However it should be considered that most “new” vehicles contain a large percentage of Carry-Over Parts and Systems. These Carry-Over items, if they effect Pedestrian Protection requirements, will have to be redesigned and replaced. The phasing in period for the legislation should allow for this. The Pedestrian Protection requirements should be considered and designed for during the early stages of the Design process. The use of Deformable or Breakaway systems may cause some additional work but examples of these systems are available to use as a basis for any new Designs.

Any parts that have to be redesigned to meet the legislation can potentially be carried over to use on other vehicles which will ultimately reduce their piece costs (but could increase the tooling cost due to the volume increase). It is very difficult to adjust the figures to reflect this without more detailed involvement in the actual designs and knowing what vehicle ranges are involved. However likely candidates to be able to be carried over are brackets, wiper system, headlights (styling permitting) and Underbody BIW. Therefore for this report we can make a statement by advising a percentage decrease in costs by some 15% for the wipers and the headlamp piece prices and tooling costs. These costs have been reduced in this report.

Additional Analysis Work – In theory the only additional Analysis work required is for Pedestrian Impact. Aerodynamic, Cooling and Vehicle Crash Testing will be done anyway on a new vehicle although some additional iterations may be required if the Pedestrian Impact requirements cause any changes.

Additional Test Work – In theory the only additional Test work required is for Pedestrian Impact. Aerodynamic, Cooling and Vehicle Crash Testing will be done anyway on a new vehicle although some additional iterations may be required if the Pedestrian Impact requirements cause any changes.

Active Pedestrian Impact Systems – If it is found that a new vehicle design cannot be packaged to give sufficient Engine Clearance to the Bonnet then an Active Pedestrian Impact System can be considered. This can take the form of the new developments in Pop-up Bonnets, which raise in the event of an impact with a Pedestrian to give additional clearance, or external Airbags. These systems are complimented with additional Sensors on the front of the vehicle to determine a Pedestrian Impact is taking place before activating the systems.
However these systems are new developments and will add significant cost and weight to a vehicle. So they are likely to only be considered in the higher vehicle specification ranges where the cost can be absorbed and where for package reasons the legislation cannot be met within the vehicle design.

11.2.5 Pop-up bonnets

The costs for pop-up bonnets shown in Table 11.1 were provided by a vehicle manufacturer who was committed to having a pop-up bonnet system on a vehicle, in order to comply with the phase one requirements. The application costs are for testing of the system and for tooling of the system parts. These costs are to be applied through division amongst the vehicles produced in one year and are based on production of about 5,000 vehicles per year.

The costs produced in this section are to be taken as costs for a new vehicle as opposed to costs for modifications to an existing vehicle. As such, it may be considered that any suggested changes may form part of the normal model-replacement cycle. The result of this is that some features mentioned will have no associated pedestrian protection on-cost. For example the vehicle manufacturer concerned suggested that the new bonnet, that would be required for a pop-up bonnet system, would not be expected to be significantly higher in cost than for a ‘non-pedestrian compliant’ new model bonnet design. Therefore neither the system nor the application costs include a contribution for the bonnet itself, but just for the deployable feature. It should be noted that there is likely to be one-off extra costs around the dates when all vehicles produced have to comply with either phase one (2012) or phase two (2015) of the EC Directive.

Whilst the costs in Table 11.1 from the vehicle manufacturer are assumed to have been given with the greatest available level of accuracy because they were then close to producing a completely integrated system, it is not possible to say that they are final or verified in any way. This statement reflects the position with the development of pop-up bonnet systems with no complete system released on a vehicle as of 2004. Therefore the costs are estimated costs for a vehicle with a deployable bonnet. With any process that is incomplete, there may be outstanding issues, the resolution for which could have as yet unidentified and significant extra cost implications.

Table 11.1: Costs for a pop-up bonnet system (from a vehicle manufacturer)

	Annual sales quantity	**Cost (€)**
System cost (including actuators)	about 5,000 vehicles per year	145.44 per vehicle
Application cost (other than development)	about 5,000 vehicles per year	1,100,000
Development cost (to manufacturer)		4,600,000

12 Review of manufacturing costs

Section 11 has established costs for producing systems on the Landrover Freelander and the Ford Mondeo, for protecting pedestrians, that would address the proposed requirements of Section 10.4.1. This section of the report presents the conversion of the system costs from Section 11 into a single cost covering the integration of the pedestrian protection systems into the European vehicle fleet. The relative ease with which the systems from Section 11 are incorporated into the European fleet will vary across the vehicle segments. To address this, it is necessary to consider the change in manufacturing costs when incorporating these systems into a range of vehicles representative of the segments within the European fleet. However, as explained in Section 1.1, further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of “at least the same level of protection” of the Directive. Since TRL’s original proposals (Lawrence *et al.* 2004a) did not find any support from the experts in the area, they are no longer pursued and therefore this report only considers the costs and benefits of the present proposal. Therefore, the cost data previously obtained have been adapted to provide, to the extent possible, fleet costs for the present proposal.

It was necessary to obtain a breakdown of the European vehicle fleet and this was found from the UK Motor Industry Directory produced by the Society of Motor Manufacturers and Traders (SMMT) (2003). These data provided the number of new registrations in six European countries, divided into different segments: mini, supermini, lower medium, upper medium, executive, luxury saloon, specialist sports, dual purpose and multi-purpose vehicles. For this fleet cost exercise, the mini and supermini segments were grouped together and called supermini, while executive and luxury saloons were grouped together and called executive cars. Dual purpose included both small and large off-roaders, but these were divided into separate segments for this exercise. Similarly, the multi-purpose vehicle segment included both small MPV and MPV, and was, therefore, divided as such.

To account for the varying difficulty of including pedestrian protection features within these segments, cars chosen to be representative of each segment were investigated. The vehicles were assessed to determine what combination of the modifications identified for the Ford Mondeo and Landrover Freelander would be needed, on a new vehicle of that segment, to meet the EC proposal for phase two of the EU Directive.

From the vehicles studied, a list was formulated of the pedestrian protection features that would be needed to make a vehicle of that segment meet phase two of the EC Directive. This list of protection features, or systems, was then compared with the systems and associated costs from Section 11 to give a cost for each segment.

The costs obtained from Menard Engineering Limited in Sections 11.2.2 and 11.2.4 were in GB pounds. The values in Euro in the following sections have also been reconverted to take into account the change in the exchange rate from GB pounds to Euros since the Lawrence *et al.* (2004a) feasibility study.

12.1 Adapting cost estimates for the EC proposal

As explained above, the EC test proposals based on the draft GTR, for which fleet costs are now required, are different in some respects from those for which the costs were originally obtained. The EC proposal would confine the upper legform to bonnet leading edge test to a monitoring test only with target rather than mandatory protection. Also, the changes to the high bumper definition in the draft GTR will increase the proportion of off-road type vehicles that can be tested with the upper legform, hence these vehicles will not require the bolt-on spoiler solution that was assumed to be needed to meet the proposals in Section 10.4.1. To account for this, the costs obtained have been reviewed to remove those costs that are no longer applicable. These are the costs attributable to providing additional pedestrian protection in the bonnet leading edge region and the optional cost for a bolt-on spoiler. This is based on the assumption that no costs will be apportioned by the manufacturer during the design process for the bonnet leading edge, with respect to protecting pedestrians and other road users. However, it is possible that protection in this region will improve in line with development by each manufacturer.

The process by which this review of costs was carried out involved consideration of each vehicle model investigated for the 2004 feasibility study (Lawrence *et al.*, 2004a). For that study, modifications had been proposed for typical cars from each vehicle segment. These modifications were then equated with case study costs for a Ford Mondeo and Landrover Freelander. The process of removing requirements to pass the bonnet leading edge test was relatively simple as costs specific to those modifications could be set to zero.

During this review process it became apparent that several of the bonnet leading edge design modifications provided in the Lawrence *et al.* 2004 feasibility study review had already been assigned a zero cost, as determined by Menard Engineering Limited. Therefore, the costs associated with individual part modifications had little consequence with respect to the overall pedestrian protection 'on-costs'. However, in addition to individual part modifications, the costs attributed to numerical simulation and validation also needed to be revised and these did show significant cost decreases.

The current EC proposal has a slightly lower tibia acceleration limit in the main test area than was used for the costing exercise, so the crush depth will be greater and therefore the costs may be slightly higher than those estimated. This possible change in cost could not be obtained by selecting from the cost data available, so no adjustment was made. The current proposal also has a lower headform test speed but with lower criteria, which on balance will reduce the crush depth required so that the costs may be lower than those estimated. Again, this change in cost could not be obtained by selecting from the cost data available, so no adjustment was made.

12.2 Cost for a typical vehicle

Whilst some of the system costs provided in Section 11 could be transferred directly, some had to be adjusted. Typical adjustments were for smaller or larger quantities of material, the size of parts to be cut or pressed and therefore tooling costs, whether any existing parts already contributed or could be re-used, and the perceived level of difficulty of incorporating the required modification in to the vehicle. In this way, the cost produced for each pedestrian protection feature was either kept or adjusted for each particular vehicle segment. In every case, this adjustment was based on the justification for the system costs as received from Menard Engineering Limited. In adapting these individual costs to produce European sector costs, some subjective judgments had to be made.

The two vehicles selected for the detailed cost study by Menard were selected because, between them, they had examples of every type of modification needed to make the fleet comply, with the exception of pop-up bonnets for which the costs were obtained separately. To obtain an appropriate, representative, generic cost for each vehicle sector, the costs of individual features were taken as necessary from either vehicle. For example, although the Mondeo costs did not include a modified wiper spindle, the cost of the Freelander wiper spindle was added to the costs for the Mondeo, along with other adjustments to make a representative, generic large family car segment cost.

The segment costs derived from the manufacturing and tooling costs above will not include the product development cost, therefore an additional allowance was made for this. The additional product development costs can be attributed to Finite Element Analysis (FEA) and validation testing. The FEA costs were to cover the extra numerical simulation time that would be required to tailor the stiffness of the individual components and behaviour of the impact regions, and finally to check that the pedestrian protection performance was adequate to meet the proposed requirements. The validation testing costs were to cover the additional physical testing that would be required, by the manufacturer, to confirm that their vehicle would be approved.

The tooling, assembly, FEA and testing costs provided by Menard Engineering Limited were in the form of one cost, as opposed to a cost per vehicle. Therefore, adjustment of these costs was necessary as the tooling costs for each part could only be given as a cost per vehicle with knowledge of both the typical production run length and number of vehicles produced per year, for that particular segment of the European fleet. A typical number of vehicles produced per model within a vehicle segment in one year were found by taking the mean of the figures given for various models; these data were from vehicle manufacturers in France, Germany, Italy, Spain, Sweden and the United Kingdom (Society of Motor Manufacturers and Traders Limited, 2003). With the figure for years in production and number of vehicles produced each year, the tooling or assembly line outlay could be spread over the number of those vehicles that might typically be produced within Europe. This cost per vehicle was then added together with the piece cost per vehicle. The outcome from the investigation of cars was, therefore, to arrive at a cost for making one theoretical, representative vehicle for each of the vehicle segments, meeting the proposed requirements for phase two of the EC Directive. This cost was then factored into the breakdown of the European fleet by segment.

Manufacturers did not provide costs for brake assist systems (BAS). It was thought that this was because BAS are not fitted as discrete systems since much of the hardware is shared with anti-locking braking systems and the ECU. Since these other systems are there to improve occupant and vehicle protection and fuel consumption, etc. then the costs could reasonably be attributed more widely than to vulnerable road user protection alone. Therefore it has been assumed that BAS have negligible additional cost.

12.2.1 Supermini

It was assumed that the costs required to modify the Ford Mondeo should first be reduced slightly, for this vehicle segment, to take account of it being smaller; therefore a smaller quantity of materials and tooling costs would be necessary to make the same modifications on a smaller size of vehicle. As the supermini segment tends to have exposed wipers, the full costs of the Freelander wiper modifications have then been added. Next, the overall cost has been increased as thought necessary to take account of the extra difficulty with packaging in small cars. No account has been taken of the fact that pedestrian changes are likely to have a more significant effect on the styling of small cars. The estimated increase in cost associated with features for the protection of vulnerable road users for the supermini segment is €45.98 per vehicle.

12.2.2 Small family car

Again, it has been assumed that the costs required to modify the Ford Mondeo should first be reduced, but by a smaller margin than for the supermini, to take account of it being smaller. As the small family car segment tends to have exposed wipers, the full costs of the Freelander wiper modifications have then been added. Next, adjustments were made to reduce the overall cost slightly because packaging issues are thought to be less of a problem in mid-sized cars. The estimated increase in cost associated with features for the protection of vulnerable road users for the small family car segment is €27.76.

It is possible that a pop-up bonnet solution may be more practical for small family car variants with large engines. For a variant such as this, the cost of the pop-up bonnet will have to be on top of all the other modifications, even if it removes the necessity for some of them. Therefore, the estimated cost will be €117.50.

12.2.3 Large family car

The Ford Mondeo costs were taken directly to provide an initial cost for a large family car. The costs that were provided introduced the option for inserting either energy absorbing foam between the bumper beam and the bumper facia, or using a pressed front bumper beam with an additional pressed section in front containing crush initiation folds. The latter of these two options was chosen for the cost for this segment.

In the description of the modifications required for the Ford Mondeo to meet the proposed requirements, the justification for not modifying the wiper system is that it is thought already adequate. This is not expected to be a realistic situation for the entire large family car segment and it was felt that some allowance for this feature should be made. Therefore, some of the costs for modifying the Landrover Freelander wiper system were factored into the costs for the large family car segment. The resulting estimated increase in cost, through the inclusion of features for protecting pedestrians for the large family car segment, is €36.93.

It is also possible that, for large family car variants with large engines, a pop-up bonnet solution may be more practical. For a variant such as this, the cost of the pop-up bonnet will have to be on top of all the other modifications, even if it removes the necessity for some of them. Therefore, the estimated cost will be €134.85.

12.2.4 Executive car

Again, it has been assumed that the costs required to modify the Ford Mondeo should first be increased by a small margin to take account of it being bigger. Whilst it is possible to imagine that some executive cars will have no problems with packaging issues conflicting with the provision of features for the protection of pedestrians, it is thought likely that the combination of large wheels, large engine and streamlined shape will often cause this to be a serious problem. Therefore, the cost for providing protection for pedestrians is expected to be slightly greater than that for a vehicle from the large family car segment and is estimated to be €37.64.

It is possible, for executive cars, that a pop-up bonnet solution may be more practical for some models. For this type of vehicle it is likely that all engine variants of a model will either have a pop-up bonnet or not. If the pop-up bonnet is extended to the side reference lines, it can be made to remove the need for a crushable wing edge and the need to modify many other under-bonnet features will be removed. Therefore, although the pop-up bonnet system will be expensive, savings will be made elsewhere. Taking this into account, the estimated cost will be €129.55.

12.2.5 Sports cars

The costs for this type came from those for the Ford Mondeo. The amortized tooling costs will be far higher for sports cars because they are produced in small numbers. These costs have been increased assuming that an average of about 5,000 vehicles per model will be produced each year. For this vehicle segment, the difficulty of passing the headform requirement is very variable, depending on the size and position of the engine and the overall size of the vehicle. If it is assumed that all sports cars can be made to pass without the use of pop-up bonnets, then it is estimated that the additional cost will be €85.77.

With sports cars, as with executive cars, it is possible that a pop-up bonnet solution may be more practical for some models. For this type of vehicle, it is likely that all engine variants of a model will either have a pop-up bonnet or not. If the pop-up bonnet is extended to the side reference lines, it can be made to remove the need for a crushable wing edge and the need to modify many other under-bonnet features will be removed. Therefore, although the pop-up bonnet system will be expensive, savings will be made elsewhere. Taking this into account, the estimated cost will be €397.40. The main reason why the pop-up bonnet solution would cost significantly more for the sports car segment than for executive cars is that whilst the development costs are approximately equal for either segment, this cost is shared over a smaller number of units for sports cars.

12.2.6 Small MPV

In many ways, small MPVs are very similar to small family cars and are sometimes based on them, as is the case of the Ford Focus C-Max, which is an adaptation of the Focus car. However, the treatment of the bonnet locking platform and the upper longitudinal rail was more variable. While certain areas, such as the wing edge, may be more difficult than in cars, other areas such as the clearance over the engine may prove easier. Taking these considerations into account, the estimated increase in cost per vehicle for pedestrian protection features is €30.80 for the small MPV segment.

12.2.7 Large MPV

Large MPVs can either be likened to vans or off-roaders. For this exercise, a combination of features from the Mondeo and the Freelander were used, with adjustments to take account of the perceived difficulty for this style of vehicle. In some, the A-pillars are effectively extended to form the upper longitudinal rail and therefore lie very close to the underside of the bonnet and in others the longitudinal is cranked giving a large clearance. Whilst some extra cost has been attributed to the solutions for these problems in these estimates, it is also possible that they could be designed out at the initial design stage. Taking all of these points together, the estimated cost per new vehicle for pedestrian protection features for the MPV segment is €34.53.

12.2.8 Small off-roader

The costs for producing a small off-roader were taken initially from the costs given for modifications to the Landrover Freelander. Again these costs contain an option for using energy-absorbing foam between the bumper beam and bumper facia or alternatively using a pressed section with crush initiators. For this exercise, the option of using a pressed section was selected.

The Landrover Freelander has a clamshell bonnet design. This feature was thought to make the solutions for the bonnet region and wing edges easier and cheaper than would have been the case for a conventional bonnet design. As the costs for this segment of vehicle should represent all the vehicles contained within it, some of the costs for the wing edge modifications from the Ford Mondeo were also apportioned to the small off-roader segment.

A bolt-on spoiler for which costs were obtained was needed to meet the current Directive phase two requirement because for these vehicles the bumper height would call for the lower legform test. This is because this type of vehicle typically has a lower bumper reference line slightly lower than the 500 mm transition. The draft GTR has introduced an optional zone below 500 mm and if the lower bumper reference line falls in this zone the manufacturer can elect to use either the lower or upper legform. It is assumed that the manufacturer would normally elect for the upper legform test to retain off-road ability without the need for a bolt-on spoiler. However, whilst it is not a necessity, it is thought that a bolt-on spoiler would aid with the force distribution during an impact with a pedestrian leg and hopefully reduce the likelihood of a knee injury occurring. For the purpose of obtaining costs from the investigation of the Landrover Freelander, the full cost of producing a bolt-on spoiler was derived. If these costs are included, the estimated increase in cost per vehicle is €99.56. Without the costs attributable to bolt-on spoilers, the estimated pedestrian protection cost is €51.16, for the small off-roader vehicle segment.

It should be noted that the costs for the bumper have been calculated on the basis of meeting the proposed lower legform acceleration criterion (190 g) and not the draft GTR upper legform high bumper criteria (7.5 kN & 510 Nm).

12.2.9 Large off-roader

The large off-roader segment was thought to present many of the same issues as the small off-roader segment, with slightly increased materials and tooling costs. These potential cost increases were considered alongside reduced packaging issues.

Again, a bolt-on spoiler is not required to pass the EC proposal for phase two of the EC Directive. The estimated pedestrian protection cost for the large off-roader vehicle segment with no bolt-on spoiler is €47.41.

If the cost of producing a bolt-on spoiler is included, the estimated increase for the large off-roader segment is €96.70.

12.3 Breakdown of the European fleet

The additional cost per vehicle for a representative, generic vehicle of each segment has been estimated above in Section 12.2. To consider the costs for each segment across the EU fleet, it was necessary to obtain the breakdown of new registrations by vehicle segments for the 25 member states of the EU.

The breakdown of new registrations into vehicle segments was given for only six countries from the EU by the SMMT (Society of Motor Manufacturers and Traders Limited, 2003). For the other 19 countries, equivalent data could not be found but the total number of new registrations recorded in each, for the year 2003, for 17 countries, was available from ACEA. These figures are presented in Table 12.1. Figures on the number of new registrations for Cyprus or Malta were not available and so were estimated from their population and estimated vehicle ownership.

To derive an estimate of the breakdown of vehicles into the seven segments identified above for the 19 countries not covered by the SMMT, the distribution of new registrations by segment was likened to that of a similar country where it was available. The country selected as similar was chosen on the basis of geography and GDP (Gross Domestic Product) per capita. The estimated distribution of segments for each of the European member states is shown in Table 12.1. The way that vehicles are categorised does vary from country to country, hence in some cases zeros appear in the table when one type has been included under another type in that country. Simple addition of the number of new registrations per segment from each country considered gives a total figure. The total (i.e. EU-25) new registrations in Europe for each segment are also shown at the bottom of Table 12.1.

12.4 Costs for different combinations of solutions

If it is assumed that vehicles will continue to be produced in these numbers with the same distribution by segment, the yearly cost for pedestrian protection in future years, when phase two has come into force, can be calculated. The cost can be calculated for each segment using the representative, generic cost per vehicle for each segment (Section 12.2), multiplied by the number of vehicles produced in that segment, given in Table 12.1. The segment costs have then been summed to produce the total yearly pedestrian protection costs shown in Table 12.2. Note that these costs are for all cars; no distinction has been made at this stage to account for cars outside the scope of the current Directive (i.e. cars of maximum mass >2.5 tonnes).

Costs for various different combinations of solutions are presented in the following sections. These costs are calculated by replacing the standard cost given in Section 12.2 with the alternative cost given under a segment, where one is available. Whilst none of the following combinations is expected to match the real fleet distribution of solutions, it is thought that the real cost is likely to lie within the range of figures in Table 12.2. Of these, it is thought that the cost for having pop-up bonnets fitted to all sports cars and executive cars, but with no bolt-on spoilers fitted to the off-roader segment, is likely to be the most appropriate for the fleet, despite it almost certainly not representing the real distribution of solutions.

12.4.1 Whole fleet protected without the use of deployable systems

A total cost, assuming that no deployable solutions or bolt-on spoilers are used in any of the vehicle segments, was produced using the method described above. Although unlikely, it was thought this cost may be of interest. A total annual fleet (i.e. new registrations) cost for providing pedestrian protection for this option will be €575 million.

Table 12.1: Breakdown of the European (EU-25) new passenger car registrations by country and vehicle segment

Country	Supermini	Small family car	Large family car	Executive car	Sports car	Off-roader	MPV	Total new registrations
Austria	86,776	89,993	88,153	9,806	358	25,036	0	300,121
Belgium	170,816	156,664	64,608	35,107	4,928	13,915	12,758	458,796
Cyprus	5,921	5,142	2,254	112	446	1,128	435	15,438
Czech Republic	58,670	50,954	22,341	1,107	4,417	11,177	4,316	152,981
Denmark	27,782	28,812	28,223	3,139	115	8,015	0	96,085
Estonia	5,984	5,197	2,278	113	450	1,140	440	15,602
Finland	42,567	44,145	43,243	4,810	175	12,281	0	147,222
France	748,068	686,094	282,945	153,748	21,583	60,938	55,871	2,009,246
Germany	1,100,558	973,897	637,665	157,293	75,895	173,716	117,914	3,236,938
Greece	98,674	85,698	37,574	1,862	7,428	18,798	7,258	257,293
Hungary	79,933	69,422	30,438	1,508	6,017	15,228	5,880	208,426
Ireland	49,417	43,730	28,632	7,063	3,408	7,800	5,295	145,345
Italy	1,122,084	434,597	232,195	86,647	14,782	107,341	251,980	2,249,626
Latvia	3,342	2,902	1,272	63	252	637	246	8,713
Lithuania	2,893	2,512	1,102	55	218	551	213	7,543
Luxembourg	16,240	14,895	6,143	3,338	469	1,323	1,213	43,620
Malta	4,285	3,116	1,503	243	0	0	121	9,268
Netherlands	182,004	166,926	68,840	37,407	5,251	14,826	13,593	488,848
Poland	137,462	119,385	52,344	2,594	10,348	26,187	10,111	358,432
Portugal	87,745	63,809	30,776	4,982	0	0	2,481	189,792
Slovakia	22,912	19,899	8,724	432	1,725	4,365	1,685	59,742
Slovenia	27,530	20,020	9,656	1,563	0	0	778	59,548
Spain	689,831	267,180	142,748	53,269	9,088	65,991	154,911	1,383,017
Sweden	75,524	78,324	76,723	8,534	311	21,789	0	261,206
United Kingdom	876,876	775,958	508,063	125,324	60,470	138,409	93,949	2,579,050
Total	5,723,892	4,209,271	2,408,443	700,119	228,132	730,592	741,448	14,741,898

12.4.2 Deployable bonnet

In Section 12.2, the option of using a pop-up bonnet system was introduced for the small family car, the large family car, the executive car and sports car segments. The costs for this option have been estimated to be significantly greater than those for providing solutions without resorting to the pop-up bonnet option. Therefore, should vehicle manufacturers choose pop-up bonnet systems, the total annual fleet cost for providing pedestrian protection will increase.

At least one vehicle with a pop-up bonnet is already available and it is expected that other vehicles within the specialist sports segment using pop-up bonnets will be available soon. It is thought that the sports cars, executive cars and hot hatchback models are the most likely to opt for pop-up bonnet systems but these systems will not be universally adopted throughout any of the segments. To give some estimates of the costs of using this more expensive solution, various combinations have been calculated, however for simplicity these have been applied to whole segments. For example, the cost for pop-up bonnets being fitted to all sports and executive cars may be equivalent, approximately, to all sports cars, some executive cars and some hot hatchback models. These combinations and their costs are given in Table 12.2.

12.4.3 Attribution of the costs for bolt-on spoilers

It is thought that the addition of a spoiler to dual-purpose vehicles for use on roads would significantly increase fuel economy and stability through better management of the air flow underneath the vehicle. Therefore, it is possible that the cost of providing a removable spoiler for off-road vehicles may be recovered by this and should not be attributed to pedestrian protection. Even a small increase in fuel economy when considered over the lifetime of the vehicle would produce large financial savings for the owner. Additionally, greater stability may prevent accidents from occurring and has the potential to save lives of both occupants and vulnerable road users. With consideration given to both or either of these features, it may be that the addition of a deployable or detachable spoiler provides its own justification, for use on roads.

To investigate this, the costs for the small and large off-roader vehicle segments with the spoiler costs included were estimated and were presented in Sections 12.2.8 and 12.2.9. These revised off-roader costs were used in the re-calculation to determine the complete European vehicle fleet costs, re-calculated for the case where bolt-on spoilers are used. The effect of this was to increase the annual cost (for new registrations) to €611 million.

Table 12.2: Annual new registration costs for the EU for different combinations of solutions to meet the EC proposal

Spoiler option	Pop-up bonnet option	Cost (€ million)
No costs for fitting a spoiler to the off-roader segment attributed to pedestrian protection	No pop-up bonnets	575
	Pop-up bonnets fitted to all sports cars	646
	Pop-up bonnets fitted to all sports cars and executive cars	711
Bolt-on spoilers fitted to all of the off-roader segment and the costs attributed to pedestrian protection	No pop-up bonnets	611
	Pop-up bonnets fitted to all sports cars	682
	Pop-up bonnets fitted to all sports cars and executive cars	746

Note: The cost in the shaded row is thought likely to be the most appropriate for the fleet, despite it almost certainly not representing the real distribution of solutions.

13 Cost-benefit analysis

13.1 Introduction to cost-benefit

The intention of this section is to quantify the relative costs and benefits of vulnerable road user protection, with particular emphasis on the effects of the proposal that has been made by the EC for replacing the requirements of phase two of EC Directive 2003/102/EC (European Parliament and Council of the European Union, 2003). Vulnerable road users are those liable to be impacted in road accidents without having the benefit of a protective vehicle structure around them. This applies mainly to pedestrians and pedal cyclists, and, to a lesser extent, motorcyclists. In this study only benefits to pedestrians and pedal cyclists have been considered. Nevertheless, there will be some added benefit for motorcyclists.

The Directive requires, in its Article 5, that alternative measures shall be “at least equivalent in terms of actual effectiveness” to the requirements of the second phase of the Directive. This cost-benefit study includes estimates of the effectiveness of the proposed alternative measures relative to the current phase two requirements. These estimates are therefore the principal findings of this section.

Three ‘options’ for protecting vulnerable road users by secondary safety means (i.e. designing cars to minimise injury on impact) are considered:

> The first option considered is that currently specified in phase two of EC Directive 2003/102/EC (European Parliament and Council of the European Union, 2003) and discussed in Section 10. Estimates of the benefits that might have been obtained have been made for this option for comparison purposes; however, as it is not considered to be feasible, no costs have been determined for this option.
>
> The second option is the protection that would have been offered by the first proposal that was made by industry for replacing phase two. That was to maintain the current phase one test procedures with the addition of brake assist systems to provide additional benefits. This option will be considered as the ‘**Industry proposal**’ in the following comparisons.
>
> As was described in Sections 1.1 and 4, progress since the first feasibility study (Lawrence *et al.*, 2004a) has lead to a draft global technical regulation, or GTR. It is understood that the EC (DG Enterprise and Industry) intends to propose a package of measures, the secondary safety element of which would harmonise with the draft GTR, although the intended scope of vehicles covered would be wider than the scope of the current draft of the GTR. This ‘**EC proposal**’ is therefore the third option considered here.

In addition, the use of brake assist systems (BAS) to reduce or eliminate injury by reducing impact speed or by avoiding impact is considered. No costs have been provided for brake assist systems, so they are taken here as having negligible cost, since much of the hardware is shared with anti-locking braking systems and as these systems also improve occupant and vehicle protection the costs could reasonably be attributed more widely than to vulnerable road user protection alone.

Both the industry proposal and the EC proposal involve mandating BAS to provide additional benefits. These options are therefore shown with the benefits of BAS included as well as with only their secondary safety benefits. Since the EC proposal based on the GTR is the primary proposal ‘on the table’ at this time, the options highlighted for comparison in the tables are the current phase two (without BAS) and the EC proposal with BAS.

All options take as a baseline (i.e. zero benefits) the standard of protection provided by cars that have been designed with virtually no consideration given to the protection of vulnerable road users. This therefore applies to the majority of current car designs, as those designed with significant consideration of vulnerable road users are currently the exception. Nevertheless, car manufacturers have been aware of the likely introduction of pedestrian protection measures for a number of years now, so many designs in recent years will at least have made some progress towards providing pedestrian protection. Also, the detailed accident data used provide an effective calculation baseline corresponding to the vehicles involved in those accident cases, which again will mostly be vehicles designed without significant pedestrian protection. The baseline for the BAS part of the calculations is therefore comparable, in that it is assumed that no cars were then fitted with BAS.

In vehicle terms the scope of the EC Directive 2003/102/EC applies to M1 (passenger cars) and N1 (vans) derived from M1, in both cases for vehicles of less than 2½ tonnes. In practice it is difficult to identify those hit by car-derived vans in the accident statistics, so only cars and taxis are considered in this analysis. However, vehicle sales data have been obtained on a similar basis, so the effect of this exclusion on the cost to benefit ratio will be minimal. As the EC is considering extending the scope to vehicles with a maximum mass greater than 2½ tonnes, approximate corrections have been applied to benefits and vehicle costs where necessary to correct for the vehicles not included under the other options.

In geographical terms the scope of the study is to obtain costs and benefits for the recently enlarged European Union, i.e. the EU-25. For some member states only very limited or no data were available, so where necessary estimates have been made to fill the gaps.

This study uses detailed accident data to make estimates of the proportion of casualties that might have been prevented had the vehicles met the standard of secondary safety required by the test procedures being considered here. The primary source of this data has been the GIDAS database; GIDAS data has been kindly made available for this project by the GIDAS Steering Committee, with the assistance of the car manufacturer’s association, ACEA. This has been supplemented by fatality data from a database assembled by the IHRA Pedestrian Safety Working Group.

While data for the EU-25 have been used to get the correct fatality numbers and vehicle sales, in most other cases data from British sources has been used to get the correct proportions. This is more easily available to the authors and is more familiar to them, and in general it is of high quality. Searching for comparable data from other countries would have been time consuming and in many cases would only have been available from a few countries to a comparable standard. Using British data has also improved consistency, in that for example most of the vehicle costs were provided in UK pounds, as are the casualty costs, so the calculated cost to benefit ratio would not be subject to fluctuations as exchange rates vary. In terms of casualty injury severities it is also an advantage to be using the same definitions of seriously and slightly injured casualties for accident data as for casualty costs.

There have been a number of previous benefit studies and full cost-benefit studies looking at the effect of pedestrian test proposals, particularly of the EEVC test procedures. Lawrence *et al.* (1993) carried out a cost-benefit study looking at earlier EEVC test proposals developed by EEVC WG10. The Motor Industry Research Association (MIRA) was commissioned by the EC to carry out another cost-benefit study (Davies and Clemo, 1997; Davies, 1998). Some of these studies have also estimated benefits to pedal cyclists. The European Transport Safety Council’s (ETSC) estimate (2000) included pedestrians and pedal cyclists, and included allowances for under-reporting of accidents. The authors also carried out a study to look at the benefits from implementation of test procedures being developed by the International Harmonized Research Activities (IHRA) pedestrian safety working group. A summary of this study was included in a conference paper by the IHRA working group (Mizuno and Ishikawa, 2001), and full details are in the working group’s report (IHRA Pedestrian Safety Working Group, 2001). Most recently, Lawrence *et al.* (2002) studied costs and benefits to compare the EEVC WG17 test procedures with those of a proposed Negotiated Agreement between the EC and ACEA, which was a precursor to the very similar requirements of phase one of the Directive, 2003/102/EC (European Parliament and Council of the European Union, 2003).

The feasibility benefit study, in all three reports, has a similar methodology to the study by the authors for the IHRA working group (Mizuno and Ishikawa, 2001; IHRA Pedestrian Safety Working Group, 2001) and the study of the protection offered by the Negotiated Agreement (Lawrence *et al.*, 2002). The principle differences from the latter study are:

- The current study is a full costs and benefits study, with estimates of cost to benefit ratios.
- The options primarily being considered are different, though the ‘EEVC’ or current phase two option is in common.

- The current study includes benefit for pedal cyclists.
- The current study allows for under-reporting of accidents in national statistics.
- The current study also makes estimates for the benefits of BAS.
- Allowances are made for the manufacturers' margin in the current study. Manufacturers typically aim to achieve test results that are about 80 percent of the acceptance criteria, so that they have reasonable confidence of achieving passes in the test. They also need to have a little extra crush depth for the same reason.

Car-to-pedestrian impacts are extraordinarily complex events, with the outcome dependent on many factors. These factors include impact speed, shape of car, pedestrian age and size, pedestrian trajectory, stiffness of impacting parts of car, and the strength of impacted parts of the pedestrian. Some of the variables involved, such as injury risk distributions, are poorly understood at the present time. The same is true of many of the factors concerned with the way BAS works in the real world. The purpose of this calculation is to estimate the benefits obtained with the options in a way that best reflects the potential real-world situations.

The benefit calculation uses historical accident data to estimate the effect on future accidents that would be expected to occur from implementation of one of the current test proposals. In looking at historical data the estimate obtained is of casualties that would not have been injured at that severity had the cars that hit them met the standards required by the test proposals. Though not strictly accurate, in what follows these will normally be referred to as casualties 'saved'.

As was explained in Section 1.1, this report is a consolidation and update of two previous studies. A cost-benefit analysis formed a significant part of the original report (Lawrence *et al.*, 2004a). That cost-benefit analysis used only IHRA data for the required detailed accident data. The estimation of the benefits of BAS was very limited, in part because the detailed data necessary were not available to the authors. The extension study (Hardy and Lawrence, 2005) was almost entirely devoted to improving the cost-benefit estimates. This was achieved by working closely with the Technical University of Dresden (TUD) to produce estimates by methods that were as far as possible accepted by all parties. The principal change for that study was that GIDAS data were made available and were used for both the secondary safety and BAS calculations (though additional IHRA fatality data was used for the secondary safety calculation). A number of further changes have now been made as part of the current update study. The principal change this time was that additional GIDAS data were made available that have allowed the benefits of BAS in non-frontal accidents (typically front corner or glancing impacts) to be estimated.

13.2 Discussions with ACEA and their contractor

The background to the feasibility extension study (Hardy and Lawrence, 2005) and the current study was explained in Section 1.1. In brief, at a Monitoring Committee meeting in 2004, when the original feasibility report (Lawrence *et al.*, 2004a) was presented, the Technical University of Dresden (TUD) also made a presentation (Hannawald and Kauer 2004a) on their estimates of the benefits of phases one and two and the benefits of brake assist, a study that they had carried out as a contractor for ACEA. The estimates of benefits obtained by these two studies were very different and these conflicting estimates made it difficult to come to any decision on what the final form of the second stage should be. It was therefore agreed that both parties would work together to agree as far as possible common data, methodology, etc. so as to bring the two estimates much closer together. The data from the German In-Depth Accident Study (GIDAS) that had been used by TUD were made available to the authors also. This cooperative effort was largely successful in bringing the estimates closer together. When the current update study started ACEA were again contacted and the GIDAS Steering Committee has kindly provided additional data.

Following the Monitoring Committee meeting in 2004, TUD (with the permission of ACEA) supplied the authors with a copy of their more detailed report (Hannawald and Kauer 2004b). This was studied and a number of comments and suggestions were made to TUD; the main ones were:

- The first comment concerned TUD's basic approach of using conservative estimates of benefits. At the time it was thought that it was TUD's intention to do this so that the main estimates of relative effectiveness were conservative, so that the conclusions were more robust. In this case it would have been necessary for the secondary safety benefit estimates to be optimistic rather than conservative / pessimistic. However, from subsequent discussion it was learnt that it had been their intention to be conservative / pessimistic for both primary and secondary benefits, as a matter of principle, not to produce a robust conclusion. This remains a difference between the two studies, as the current authors think that the most accurate final estimates will be achieved by trying to use the most realistic estimates throughout, as it would be difficult to get equal degrees of conservatism on both sides when comparing benefits.
- Concerns were expressed about the specific method of the BAS calculation, where logistic injury risk curves were used to convert the with-BAS calculated impact velocities into casualties saved. It was thought that these curves might not adequately reflect the complexity of the data.
- The assumption that 'saved' injuries would be reduced in severity by one AIS level was considered to be too pessimistic. The authors' preference was to assume that fatal injuries (AIS 5 or 6 in TUD's analysis) would become serious injuries and serious injuries 'saved' would become slight injuries.
- It was considered that it was too pessimistic to assume no benefit in the lower protection zones.
- TUD had not limited the impact speed at which casualties could be 'saved'. It was thought this was too optimistic, as a tested area with good secondary safety would 'bottom out' at high speeds, so few high-speed impact injuries would be prevented.
- TUD had not taken account of the difference of test speed between phase one and phase two. Limiting casualties saved by impact velocity provides a mechanism to take account of differing test speeds.
- TUD had not taken account of the different legform acceptance criteria between phase one and phase two.

TUD then supplied data from the 712 case dataset that they had used. This included injury and case fields. The fields supplied were sufficient for the authors to use in their analysis, for both the BAS and secondary safety estimates.

TUD and ACEA were supplied with a copy of the authors' database analysis program, which had been written and further modified for a series of benefit studies. Although TUD didn't use the program themselves it should have helped them to develop their own analysis software to include the improvements suggested.

In this process there were detailed discussions about both parties' benefit analyses. Another topic discussed was BAS and the accident data used to estimate the benefits of BAS; this part of the discussions is dealt with in this report in Section 9.4.1.1.

Based on the TUD report, the opportunities offered by the GIDAS data and the discussions with TUD and ACEA, the authors made a number of changes to their benefit calculations. These calculations were then reported (Hardy and Lawrence, 2005).

The main remaining differences between TUD's and the authors' calculations for relative effectiveness were then:

- The authors considered that the TUD sample of 35 'fatalities' (MAIS 5-6) was too small to make adequate estimates of benefits for fatalities. They therefore used additional fatality data from the IHRA database; this is discussed in Section 13.4.3. This difference in samples accounts for the large difference between the two studies in the relative effectiveness of the ACEA proposal with BAS for fatalities.

- The authors preferred to calculate the casualties saved by BAS using a banded injury risk distribution (this is described in Section 13.4.7). TUD provided a copy of their logistic injury risk function calculation. The authors found that the software used didn't always find the best fit solution for the logistic curve. Also multiple cases at the same speed had less weight than if they had been at distinct speeds. It was found that the banded injury risk distribution worked well and therefore the authors continued to use it. However, it is now considered that the basic method is quite robust, and that fairly similar results would be obtained whether the logistic function or the banded distribution is used.
- TUD use conservative estimates of benefits whereas the authors try to find the most realistic estimates. This was discussed above.
- The authors have serious concerns about the quality of the accident data used to estimate the BAS benefit in terms of impact speed reductions, see Section 9.4.1.1, and therefore prefer that estimates for BAS are regarded as 'indicative'.
- The authors estimated the BAS benefits for BAS thresholds of 6.0 m/s^2 (as used by TUD) and for 4.0 m/s^2 (thought to a more realistic estimate); final estimates (Hardy and Lawrence, 2005) were based on the mean of these two sets of BAS benefits.
- TUD increase the 'equivalent car speed' (the car speed that is assumed to be equivalent to the chosen sub-system test speed) for the bonnet top to reflect a 'k' value (ratio of head impact speed to car impact speed) of 0.8. The authors assume a 'k' value of 1.0 (so the test speed is the same as the equivalent car speed). This is discussed in Sections 3.2.3.3 and 13.4.5.
- The authors increase the 'transition speed' (the speed up to which the test procedures are assumed to provide protection) by 5 km/h above the 'equivalent car speed' to take account of the manufacturers' allowance on crush depth, see Section 13.4.5 and especially Figure 13.4.

As mentioned above, when the current update study started, ACEA were again contacted and the GIDAS Steering Committee kindly provided additional data. Permission was also given for the original sample to be used again for the updated study. The additional data were from two samples. One was of frontal car to pedestrian accidents with 137 cases, which could be added to the original 712 case sample. The other sample contained 275 cases of non-frontal car to pedestrian accidents. The latter sample allowed the benefits of BAS in non-frontal accidents to be included in the estimates; this led to the largest single change between the current estimates and those reported previously. Advice was also received that a BAS threshold of 4 m/s^2 would be a realistic value to use in the calculation. Some of the discussions held are reflected elsewhere in this cost-benefit section and elsewhere in the report, though they are not specifically attributed.

13.3 Overall methodology of cost-benefit study

In discussing the methodology it can be useful to work back from the final result. In a cost-benefit calculation the main result would typically be a cost to benefit ratio, which can be used to decide whether the benefits would justify the costs, in this case the benefits in casualties saved against the costs of making cars safer. This therefore requires that both costs and benefits be quantified in financial terms. In this study, however, the principal result is probably the relative effectiveness of the various options considered. In order to get a single result for each option the casualties saved at different severities need to be combined, which is most easily done as a financial benefit.

In this study costs have already been presented in Sections 11 and 12, with costs for different vehicle options. See in particular Table 12.2. In this section they will be converted to consumer costs, which are the costs seen by the end purchaser of the car.

The financial benefits are obtained by estimating the number of casualties that might be saved, and then multiplying by a 'casualty cost'.

The estimate of the casualties saved in turn consists of two factors, the numbers of vulnerable road users currently being killed and seriously injured, and the estimate of the proportions of casualties that could in the future be saved, with safer car fronts and BAS.

The estimates of the proportions of current casualties that could be 'saved' by secondary safety measures are derived from a chain of estimates, starting with all the vulnerable road users fatally or seriously injured. A proportion of these will be injured by vehicles within the scope of the test procedures, mainly by cars. Of these, a proportion will be injured by the impact type that the test procedures are simulating, namely a frontal impact. Of these, a proportion will be injured within the impact speed range covered by the test procedures. Of these, a proportion of injuries will be caused by the tested area of the vehicle rather than by untested areas on the car (A pillars, etc.) or by the ground. Finally, some weak individuals will still be injured if the parts of the car that they hit are too stiff, so only those strong enough to be saved are included. This process is shown in Figure 13.1. Some of these stages can be combined, depending on the data available.

1: VRU casualties with fatal or serious injuries, all vehicles involved
⇓
2: Of those VRU casualties, - proportion struck by 'cars'
⇓
3: Of those VRU casualties, - proportion struck by car *fronts*
⇓
4: Of those VRU casualties, - proportion struck within the speed range
⇓
5: Of those VRU casualties, - proportion with injuries due to tested areas
⇓
6: Of those VRU casualties, - proportion strong enough not to be injured
⇓
7: Hence, proportion of all VRU casualties that could be 'saved'

Figure 13.1. Proportion of vulnerable road user (VRU) casualties potentially saved by safer car fronts

The stages can be split into two groups (Group A: lines 2 and 3; and Group B: lines 4, 5 and 6). Group A can be obtained from national statistics. Group B can be obtained by analysing an accident database that contains detailed injury information. Crucially it needs to have information on the location of the car or non-car contacts that caused each injury. Although it is instructive to separate the three lines shown in Group B, in practice these are combined in the analysis program to obtain the proportion of those hit by car fronts that could be 'saved'. A computer program has been developed, over a number of benefit studies, which considers each casualty in turn and, within that casualty, each injury in turn that has to be 'saved' in order to reduce the severity of the casualty (fatal to serious or serious to slight).

The calculations are split into a number of parallel strands, such as for fatalities and serious casualties, pedestrians and pedal cyclists, and for the different test proposals. Data are available for pedal cycle casualties only for the Group A stages above; therefore, as will be explained later, estimates for the Group B stages for pedal cyclists will be derived from those for pedestrians.

In terms of discrimination between the different options for secondary safety, Group B allows the calculation to account for differences in test speed, in different (mandatory) test areas and in different protection criteria in the impact tests.

The BAS part of the calculation shares the stages shown in Group A above, in that estimates are made for the proportions of casualties 'saved' of those hit by car fronts, and in a similar way for those hit by other areas of the car. The calculation for BAS is described in more detail later. However, it should be noted here that there is some interaction between the secondary safety and BAS calculations. This is because some casualties would potentially be saved with secondary safety alone and with BAS alone, so it is necessary to avoid counting them as saved twice over. As it is BAS which is being used to complement the secondary safety of car frontals, all casualties that can be saved by safer car fronts are included as a secondary safety benefit. The remaining casualties then form the input to part of the BAS calculation, to determine how many extra casualties would be saved by BAS.

13.4 Calculations

13.4.1 Vulnerable road user casualties in the European Union

These benefits will be estimated for fatalities and for serious casualties. Whereas the definition of a fatality is fairly consistent internationally, there is no generally accepted definition of what constitutes a serious casualty. The test procedures are intended to prevent most fractures, joint injuries and internal injuries, including brain injuries, i.e. most AIS 2+ injuries. This corresponds well to the definitions of serious casualties used by the UN Economic Commission for Europe (UNECE) and by the UK. Estimates made here of the proportion of serious casualties saved will therefore correspond to these definitions. The numbers of current EU serious casualties to these definitions will also be estimated, to avoid the problems of variable definitions and reporting rates in the statistics available from the countries of the EU. Finally, the estimates of financial benefits will use UK casualty costs; the UK serious casualty cost will correspond to the UK serious casualty definition.

Estimates of the potential changes in slight casualties due to cars passing the secondary safety test procedures are not made in this study. These injuries would typically be bruises, cuts and abrasions, and the test procedures are not designed and are not expected to reduce the frequency of them. The same is true of slight casualties hit at lower speeds due to the fitment of BAS; however where BAS would enable the car to stop before reaching the pedestrian the saving of a slightly injured casualty is assumed.

Data on pedestrian and pedal cycle fatalities by country are available from the International Road Traffic and Accident Database (IRTAD) (Brühning and Berns, 1998) and the Community database on Accidents on the Roads in Europe (CARE) database. It was possible to download the required data for most of the EU-25 countries from one or the other of these organisations' websites. For the remaining countries data were available of fatalities of all road user types. Missing pedestrian and pedal cyclist data were estimated by using proportions from countries of similar geography and / or economic position. The fatality data that were obtained and estimated are shown in Table 13.1. The data are for the latest available year for each country; in most cases this was 2003. These data have already been standardised by IRTAD or CARE to the generally accepted death within 30 days definition of fatality.

Serious casualties in the EU were not taken from the international databases because of varying definitions and reporting rates. It was considered that more reliable estimates could be obtained by multiplying the number of pedestrian and pedal cyclist fatalities in the EU by the GB ratio of pedestrian serious casualties to fatalities. However, it was also realised that this ratio varied widely with pedestrian age, and GB has a high proportion of child casualties. The estimates of EU serious casualties were therefore obtained by estimating separately over a number of age bands and then summing them, to give age-weighted estimates of seriously injured casualties. Estimates of EU slight casualties were similarly obtained. These estimates for pedestrians and pedal cyclists are given in the top row of Table 13.2.

However, these numbers were still estimates of the 'official' casualty numbers that would have been reported in national statistics. Various studies have shown that casualties are under-reported. This effect can be split into casualties not being reported to the police, the police not recording reported casualties in the national statistics and the wrong severity class being attributed to casualties.

Jacobs *et al. (*2000) reviewed a number of studies on under-reporting. Even in the developed world some countries have high under-reporting rates of fatalities (for all road user types). In Italy the numbers obtained from death certificates were 26 percent higher than those from police statistics. Others values from a variety of studies were Spain 3 percent, Switzerland 2 percent, Western Australia 5 percent, USA 2 percent, Germany 5-9 percent. In their estimates Jacobs *et al.* uprated fatalities in highly motorised countries (HMC) by 2 to 5 percent, in addition to any 30-day adjustments. Accordingly, the fatality estimates for the EU-25 have been increased in the current study by the middle of that range, 3.5 percent.

Table 13.1: Pedestrian and pedal cyclist fatalities by country for the European Union (EU-25)
Data obtained from the IRTAD and CARE websites, in most cases data are for 2003. Pedestrian and pedal cyclist fatalities for countries marked * were estimated from figures for all road users.

Country	Pedestrians	Pedal cyclists	Country	Pedestrians	Pedal cyclists
Austria	132	56	Latvia *	111	62
Belgium	132	108	Lithuania *	147	83
Cyprus *	18	4	Luxembourg	7	1
Czech Republic	290	159	Malta *	3	1
Denmark	49	47	Netherlands	97	188
Estonia *	34	19	Poland	1,878	647
Finland	59	39	Portugal	280	63
France	626	201	Slovakia *	129	71
Germany	812	616	Slovenia	38	14
Greece	279	14	Spain	787	78
Hungary	299	178	Sweden	55	35
Ireland	64	11	United Kingdom	802	116
Italy	762	322	Total	7,890	3,132

Table 13.2: Estimates of European Union (EU-25) pedestrian and pedal cyclist casualties, by severity, without and with an allowance for under-reporting

	Pedestrians			Pedal cyclists		
	Fatalities	**Serious**	**Slight**	**Fatalities**	**Serious**	**Slight**
Without allowing for under-reporting	7,890	68,016	237,752	3,132	46,286	264,476
With under-reporting adjustment	8,166	160,504	332,199	3,242	109,226	369,539

Simpson (1996) gave adjustment factors for Great Britain for pedestrians (serious 2.28 and slight 1.35) and pedal cyclists (serious 5.73 and slight 2.35). Seriously injured casualties have a higher under-reporting rate than slightly injured casualties because many seriously injured are wrongly recorded as being slightly injured. Pedal cyclist adjustment factors are higher mainly because many single vehicle accidents (i.e. pedal cycle only) are unreported. Therefore, for the current study looking at accidents involving cars, it was more realistic to use lower adjustment factors for pedal cyclists and therefore the pedestrian adjustment factors were also used for pedal cyclists.

Since the seriously injured casualties in the EU-25 are estimated from fatalities, both the 1.035 and 2.28 factors were applied to the seriously injured casualty estimates, and both the 1.035 and 1.35 factors to the slightly injured casualty estimates. The final estimates of fatalities and seriously injured casualties are shown in the bottom row of Table 13.2.

13.4.2 *Proportions hit by car fronts*

The proportions of fatally and seriously injured pedestrians and pedal cyclists that were hit by cars and car fronts were obtained from the national statistics of Great Britain, for accident years 1997-2001. See Table 13.3. Casualties hit by taxis were included, but it was not possible to identify those hit by car-derived vans (these vehicles are covered by the test proposals). The statistics record the first point of contact, so casualties were included for which this was 'front'. The proportions hit by car fronts are used in the further analysis; the proportions for cars are given here for information, as they allow the proportions of casualties hit by cars that are 'saved' to be estimated.

Table 13.3: Proportions of pedestrians and pedal cyclists by severity that were hit by cars and car fronts in Great Britain

		Fatal	**Serious**	**Slight**
Proportions hit by cars	Pedestrians	0.71	0.83	0.84
	Pedal Cyclists	0.55	0.81	0.87
Proportions hit by car fronts	Pedestrians	0.60	0.56	0.50
	Pedal Cyclists	0.44	0.45	0.44

Since this update has included, for the first time, estimates for the benefits of BAS in non-frontal impacts, where little or no compensating benefit would be expected from safer car fronts, the final estimates of relative effectiveness have become quite sensitive to the proportions of vulnerable road users hit by the fronts of cars. A strong case could be made for taking this proportion from that of the GIDAS dataset used for the next stage of the calculation, so as to better match the definition of 'frontal' that is used by them. They use Collision Deformation Characteristic (CDC) which is a measure of the estimated direction of force in the impact. This is recorded in terms of clock directions relative to the car. Only 12 o'clock is considered to be 'frontal'. On balance, it was decided to maintain the source used previously, GB data, for the main results. However, a sensitivity check was made to show what the effect would be of using the GIDAS proportions, see Section 13.6.

The proportions of pedal cyclists that are *not* hit by cars, thereby reducing the values given in Table 13.3, will include those injured in single vehicle (pedal cycle only) accidents. These are only a small proportion of the total in the national data, but it is known that this category has a very high under-reporting rate. If this under-reporting were allowed for the proportions of pedal cyclists hit by cars would be lower than the figures given. However, these figures are appropriate for purpose of the later analysis, because the estimates of pedal cyclist casualties with an under-reporting adjustment, shown in Table 13.2, also exclude most of those casualties not reported in single pedal cycle accidents.

Note that the proportions hit by cars and car fronts, shown in Table 13.3, take no account of any limitations on the scope of the test procedures, so the proportions of casualties injured by vehicles that are covered by the current phase two requirements, for instance, would be slightly less than the proportions given.

The proportion of cars that are covered by the scope of the current Directive (i.e. a maximum mass of 2.5 tonnes) is not accurately known, but based on the limited data available a value of 97.5 percent has been assumed. This is then applied later in the calculation to the estimates for the current phase two and for phase one plus BAS. For the EC proposal the corresponding proportion is assumed to be 100 percent. Two further assumptions have then been made for the calculation. Firstly, the accident risk of the cars excluded from the scope was assumed to be the same as the included cars, and secondly the injury risk in accidents of the excluded cars was assumed to be the same as the included cars. These assumptions are unlikely to be correct, though they may be inaccurate in opposite directions and thus partially cancel. However, as only a small proportion of cars are outside the scope, such inaccuracies will have limited influence on the final results. The limited scope potentially needs to be considered when estimating consumer costs for a year's production of cars, but as this estimate was only made for the EC proposal the adjustment was not necessary.

13.4.3 Detailed accident datasets

As was stated in Section 13.2, some stages of the calculation (those of Group B in Figure 13.1) require the use of an accident database that contains detailed injury information. Crucially, the calculation needs information on the location of the car or non-car contacts that caused each injury. Other fields of information required are the severity of each injury, using the Abbreviated Injury Scale (AIS), and the estimated accident impact speed.

The brake assist systems calculation requires further fields concerning the braking behaviour of the vehicle prior to impact and estimates of the potential braking that might have been available with BAS.

Two databases were available for the secondary safety calculation, from GIDAS and IHRA, but only the GIDAS database was suitable for the BAS calculation.

The German In-Depth Accident Study (GIDAS) was started in 1999. Accidents in Hanover and Dresden, and surrounding rural areas are investigated. It is jointly overseen by BASt (Bundesanstalt für Straßenwesen or Federal Highway Research Institute) and FAT (Forschungsvereinigung Automobiltechnik e.V. or German Association for Research into Automobile Technology). FAT is a department of the German automotive industry organisation Verband der Automobilindustrie (VDA). Accidents are investigated by teams at the Medical University of Hannover (MUH) and the Technical University of Dresden (TUD). The MUH team has been operating for over 25 years.

The International Harmonized Research Activities (IHRA) pedestrian accident dataset was created a few years ago when the IHRA Pedestrian Safety Working Group gathered much of what was at the time the most recent in-depth on-the-spot pedestrian accident data available for Germany, Japan, USA and Australia. However, at the time of a study by the authors for IHRA the Australian data were not available. Moreover, for the IHRA study considerable efforts had to be made to obtain extra data on fatalities and to convert the dataset into a relational database structure. Therefore, the authors' version of the dataset didn't and still doesn't include the Australian data. This dataset contains data on 1535 casualties, of which 155 were fatalities, 732 were serious casualties and 648 were slight casualties. By country the split is Germany 782 casualties, Japan 242 casualties and USA 511 casualties. The useable dataset tends to be a little smaller than this as some information is missing or uses 'unknown' codes. The accident cases are all of pedestrians hit by the fronts of cars. Among other information, the dataset has impact speeds, casualty ages and, for the injuries suffered, AIS, body region and area of the vehicle causing the injury. Further information on the IHRA pedestrian accident dataset is available from a conference paper (Mizuno and Ishikawa, 2001) and a full report by the working group (IHRA Pedestrian Safety Working Group, 2001). Further references to the IHRA pedestrian accident dataset here refer to the more detailed dataset as developed by the authors.

The original feasibility study (Lawrence *et al*., 2004a) used the IHRA pedestrian accident dataset as this was immediately available to the authors. This produced estimates that were quite divergent with those produced at about the same time by TUD under contract to ACEA. Later in 2004 the authors worked with TUD to reduce this divergence as far as possible. One of the factors that was identified as contributing to this divergence was the use of different accident datasets. A sample of 712 accident cases from the GIDAS dataset was kindly made available for this study by the GIDAS Steering Committee. The advantages that justified using this dataset were firstly that European data were more relevant when producing estimates for Europe, and secondly that the cases were on average more recent than those in the IHRA dataset (see the appropriate rows in Table 13.4). Removing the cases least relevant to Europe (i.e. the American cases) from the IHRA dataset would have widened the difference in mean accident year. The accident year, or more specifically the age of the design of the cars involved and the mix of car types, is relevant because as designs evolve the way that they interact with pedestrians can change, due to factors such as how streamlined they are. This cost-benefit study is using historical data to inform decisions about future legislation, so it is clearly preferable to use recent data, other factors being equal. It was therefore decided to use the GIDAS data provided as the primary data source for this study.

Table 13.4: Comparison of accident years of samples of GIDAS and IHRA accident data

Sample	Start year	End year	Mean accident year
712 case GIDAS sample of pedestrians hit by cars, frontal	1991	2002	1996
137 additional GIDAS cases of pedestrians hit by cars, frontal	2001	2005	2003
849 case GIDAS combined, pedestrians hit by cars, frontal	1991	2005	1997 est.
275 case sample of pedestrians hit by cars, non-frontal	1999	2005	2001
1535 case IHRA, all Germany, US & Japan	1985	1998	1993
61 case IHRA fatalities (Germany & Japan)	1985	1997	1991

One disadvantage of the GIDAS data provided was that information on whether the casualty died or not was not available. TUD practice has therefore been followed and MAIS 5-6 used as a substitute measure of fatality (MAIS is Maximum Abbreviated Injury Scale, the highest severity injury sustained by a casualty). Checks on the IHRA database showed that this gave a good match in terms of the numbers of casualties, though some MAIS 5 casualties survived and some casualties with a lower MAIS severity died. For this reason, references in the text to fatalities will often be shown in quotes (i.e. 'fatalities').

As the benefit calculation estimates separately for fatalities and serious casualties, the number of fatalities included in the dataset becomes crucial to obtaining reliable estimates of the benefits. The useable IHRA fatality sample (within the 712 case sample) was not particularly large for the purpose but the GIDAS fatality sample was only 30 percent of the size, with only 34 useable casualties. Of these only one 'fatality' was potentially 'saved', and this saving was reduced further still by the injury risk part of the calculation. When the GIDAS dataset was substituted for the IHRA dataset the proportion of 'fatalities' 'saved' was reduced by 83 percent for the current phase two and 66 percent for the then (September 2004) proposal. For seriously injured casualties the reductions were 10 percent and 3 percent respectively. Clearly this was a very large reduction in the proportion of 'fatalities' saved.

Using GIDAS data also nearly closed up the differences in 'fatalities' saved between the different proposals. Since the only potentially 'saved' 'fatality' is 'saved' by all test proposals the only differences are those caused by injury risk due to the different acceptance criteria. Differences of test speed and tested area have no *apparent* effect on fatalities when using the GIDAS dataset. This is a significant problem as this study is attempting to quantify the differences in protection provided by the different proposals. It is reasonable to expect that these differences would have an effect on casualties in the 'real world'. Therefore it was decided to expand the number of fatal cases by adding additional cases from the IHRA dataset. TUD and ACEA did not agree with this decision.

MAIS 5-6 'fatalities' from the IHRA dataset were used for comparability with the GIDAS dataset, rather than true fatalities. It was decided that a total of about 100 'fatalities' would be a reasonable sample. As the American cars in the IHRA dataset were likely to be the most dissimilar to European cars they were discarded. By comparing the two datasets a number of German cases were identified that appeared in both datasets (GIDAS data contain MUH cases from before GIDAS was formed). These were discarded from the IHRA 'fatalities' dataset. This left 63 'fatalities' from the IHRA dataset, giving a total of 98 'fatalities' when combined with those in the GIDAS 712 case dataset. This combined 'fatality' dataset was considered to be a reasonable compromise. On the one hand it would be preferable to have a still larger ‘fatality’ sample, and on the other it would be preferable to have more recent data with a highest content of European cars.

These were the data samples used in the extension study that was reported in 2005 (Hardy and Lawrence, 2005).

For the current 2006 update study, ACEA was again approached about obtaining GIDAS data. The GIDAS Steering Committee not only gave permission for the 712 case sample to be used again but they provided two further samples. These were a further 137 cases of car front to pedestrian accidents (i.e. the collision deformation characteristic (CDC) was 12 o’clock) and 275 cases of car to pedestrian accidents that were not frontal.

The IHRA ‘fatality’ cases used, and in particular at those that could be ‘saved’ by one or more test options, were re-examined. It was noted that three casualties were from the same accident, and hence were impacted at the same speed. This meant that these casualties were not independent cases. It seemed more reasonable to use a sample of independent cases so two of the casualties were removed from the data used. Otherwise, the IHRA ‘fatality’ sample used this time is as was used previously.

The combined 849 case GIDAS frontal sample contains 41 ‘fatalities’. The IHRA sample is now 61 cases, giving a total of 102 ‘fatalities’. This combined ‘fatality’ sample, by the country collecting the data, is 58 casualties from Germany (of which 41 GIDAS and 17 IHRA) and 44 casualties from Japan.

The cumulative impact speed distributions of the samples by severity are shown in Figure 13.2. The GIDAS and IHRA ‘fatality’ samples are shown separately. It can be seen that the impact speeds of the GIDAS fatalities tend to be at higher speeds than those of the IHRA data. As the IHRA data contains a proportion of German cases this difference might be greater still if split by country. It can also be seen that the IHRA distribution is coarser than the GIDAS distribution, because many more of the impact speed estimates are at multiples of 5 km/h. This is a significant disadvantage when using the data for the current purpose.

As the use of the IHRA ‘fatality’ data has been criticised by ACEA and TUD, a sensitivity analysis is presented in Section 13.6 to show what the effect would be of not using this IHRA ‘fatality’ data.

13.4.4 Injury risks

The differences between the current phase two requirements and the EC proposal need, as far as possible, to be converted into a method for estimating the likely benefits. A previous study by the authors (Lawrence *et al.*, 2002) was able to compare test procedures with different test speeds, so discrimination between the test procedures was primarily on the basis of speed. However, some of the changes proposed by the EC are increases in the acceptance criteria. Another major set of changes proposed was with the lower protection zones.

It was decided to use an injury risk method to discriminate between the test procedure options. Most acceptance criteria are correlated with a risk of injury. If a test point gives a certain reading then this can be used to estimate the risk of injury to someone contacting the same point at an equivalent speed. There is normally an injury risk curve from which injury risk can be read off against the test output. For the legform tibia acceleration and knee bending angle criteria the injury risk curves of Matsui (2003) were used, see Figure 3.8. The shear displacement criterion wasn’t considered as cars meeting the bending angle and tibia acceleration criteria rarely fail on shear displacement. For each acceptance criteria it was assumed that the average test output would be at the manufacturers’ target value, which is normally set at 80 percent of the acceptance criteria. Therefore, for each acceptance criteria the injury risk was obtained for an output at 80 percent of the acceptance criteria. For the upper legform, force and bending moment injury risk curves by Rodmell and Lawrence (1998) were used; these also appear in the European Enhanced Vehicle-safety Committee report (2002a). For the headform, an injury risk curve by Mertz (1993) was used. The injury risks obtained are shown in Table 13.5. Those injury risks used in the analysis are shown in bold; for the lower legform and upper legform tests the criterion with the higher injury risk was taken in each case.

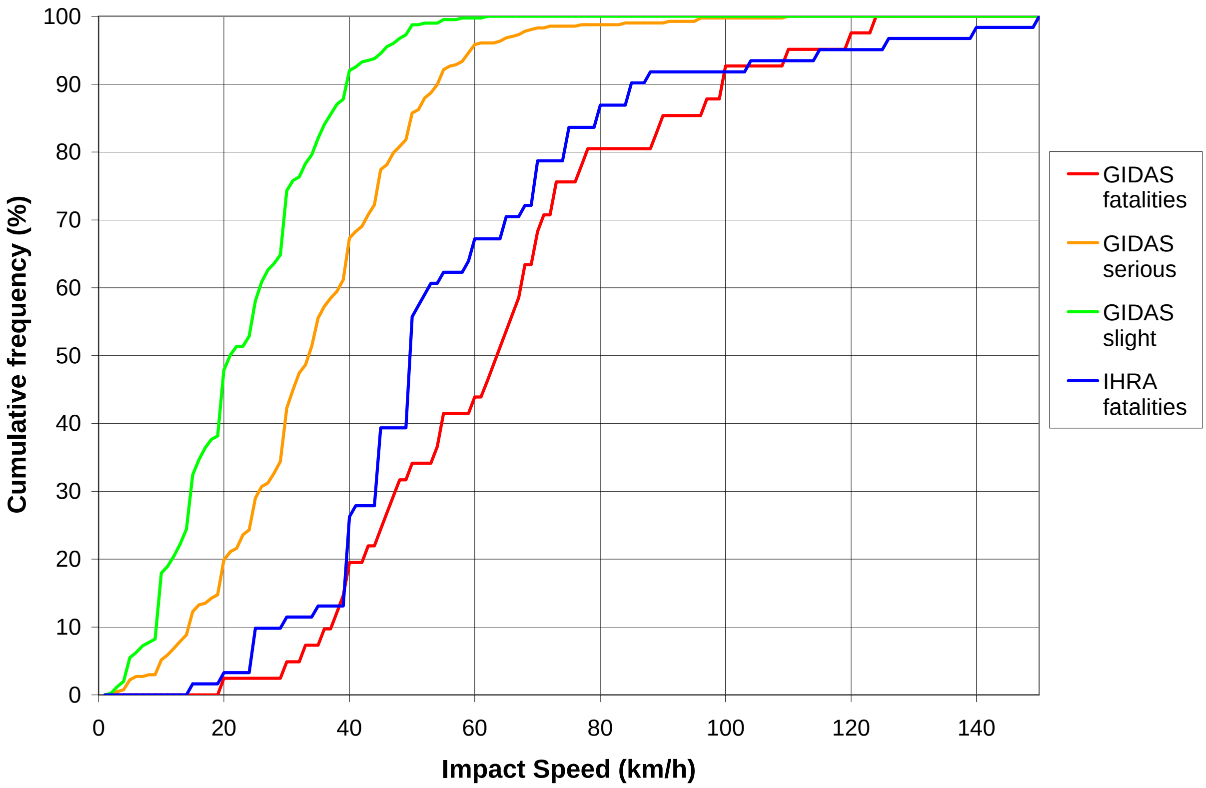


Figure 13.2. Cumulative impact speed distributions, for the car front to pedestrian accident data used from the GIDAS and IHRA databases, by casualty severity

Table 13.5: Injury causing parameters, acceptance criteria proposed and injury risks used in the analysis based on manufacturer's targets at 80 percent of the acceptance criteria

Impactor and parameter	Acceptance criterion / injury risk				
	Current phase two	**Industry proposal: main area**	**Industry proposal: lower protection area**	**EC proposal: main area**	**EC proposal: lower protection area**
Lower legform, knee bending angle	15° / 5.4%	21° / 13.5%		19° / 10.2%	19° / 10.2%
Lower legform, tibia acceleration	150 g / **9.0%**	200 g / **22.4%**		170 g / **13.1%**	250 g / **48.3%**
Upper legform, sum of forces	5 kN / 10.3%	not tested		not tested	
Upper legform, bending moment	300 Nm / **11.8%**				
Headform, HPC	1000 / **7.0%**	1000 / **7.0%**	2000 / **63.8%**	1000 / **7.0%**	1700 / **42.3%**

It was assumed that a non-mandatory upper legform test would have no benefits other than preventing this area becoming less safe than before, so this was treated as a no test area.

No allowance was made for the reduced upper legform test energies or the reduced energy cap, as this would have added even more complexity to the calculation. Likewise, deploying systems such as pop-up bonnets were not considered; for calculation purposes they were taken as being no different to non-deploying systems. There were several other differences that it was not practical to evaluate, including: change of headform mass, change of child to adult test areas transition wrap around distance (WAD) and the level of protection provided by the high bumper test (the lower legform test was assumed for all bumpers).

13.4.5 Methodology for proportions hit at survivable speeds

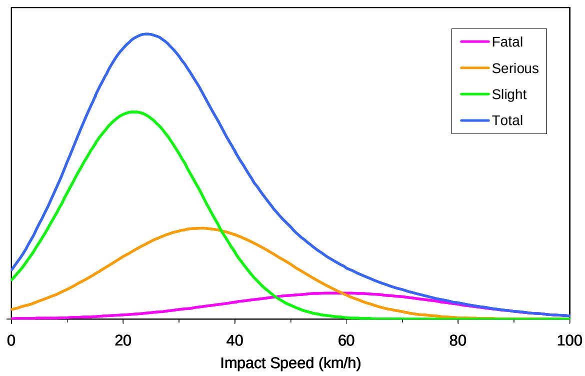
The test proposals are designed to provide protection up to a certain speed or speeds. At very high pedestrian impact speeds little difference would be expected, as the car would be crushed beyond the depth to which it would be crushed in the approval tests, and the pedestrian kinematics and head impact locations would be different. The impact speeds of different phases of pedestrian impacts in relation to the initial speed of the car are reflected in the sub-system test speed, which may not be the same as the car impact speed. For the purpose of the calculation, what matters is the ‘equivalent car speed’, not the test speed. Clearly, there will be a range of speeds over which the test procedures may or may not provide protection in each individual accident. However, a basis is required for estimating the average benefit over the whole range of accident cases.

The ratio of head impact speed to vehicle speed, sometimes called the ‘k’ value, has been subject to debate over a number of years. The authors’ opinion is that an average value of about 1.0 is correct for the shorter pedestrians likely to hit their head on the bonnet top of typical European cars with short bonnets. This issue is discussed in more detail in Section 3.2.3.3. A ‘k’ of 1.0 has therefore been used in this study, i.e. the equivalent car speed is taken as being equal to the headform test speed. The TUD analysis has a value of ‘k’ of 0.8, giving a higher vehicle impact speed. A number of studies have supported a lower value but often they use computer models that are not sufficiently biofidelic (in the authors’ opinion). The choice of ‘k’ might be expected to have a limited effect on relative effectiveness estimates, *provided the sample size is adequate*, as the same value is used for all three test proposals. The sensitivity of the analysis to the ‘k’ value is investigated in Section 13.6. For the bumper the leg impact speed is the same as the vehicle speed so the equivalent car speed is 40 km/h, which is the lower legform test speed for all proposals. The equivalent car speed is also 40 km/h for the bonnet leading edge test.

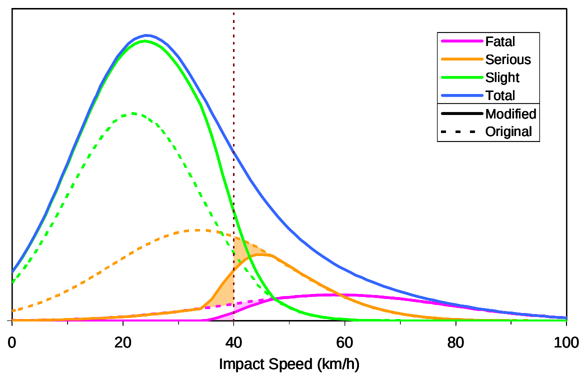
In some previous studies, including the 2004 feasibility study (Lawrence *et al*., 2004a), two very different methods were used to calculate the proportion of injured casualties hit at speeds at which the test procedure could protect them: a) A simplified assumption that those casualties prevented above the equivalent car impact speed will match those casualties not prevented below. b) An assumption that the safety measures will shift the distribution of the relative proportions of fatalities, seriously injured casualties and slightly injured casualties upward in impact speed. The first assumption was used by the authors (Lawrence *et al*., 1993), and the second by MIRA (Davies and Clemo, 1997). However, the speed-shift method requires an impact speed to be chosen, on the basis of sub-system test results, at which the baseline cars would just pass the protection criteria of the proposed tests. When the authors had used this method previously this speed had been taken from the early MIRA study. However, ACEA advised the authors that they considered that this speed was out-of-date for current cars. The method is also relatively inflexible when attempting to discriminate between test procedures with different speeds in different test areas. This current update study therefore uses only the ‘equivalent car impact speed’ method.

The equivalent car impact speed method is illustrated in Figure 13.3. Figure 13.3a is an idealised ‘current’ speed and severity distribution created to show the methods; it does not correspond to any real data set. However, it can be seen that few accidents occur at high speeds, and higher severity accidents are less frequent and peak at higher speeds. At very low speeds most accidents result in slight injury and at very high speeds virtually all are fatal.

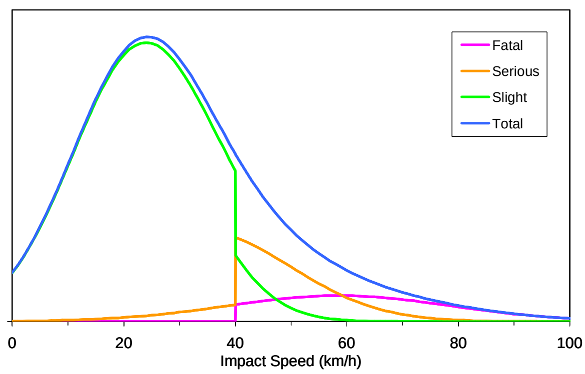
Figure 13.3b shows how this speed distribution is likely to be modified with implementation of the pedestrian protection Directive. Note that for clarity only cases that involve the front of cars, where the injuries have been caused in the original scenario by parts of the car that will be tested, are considered here. For the casualty to be ‘saved’ the impact also has to be at a survivable speed, and the impact forces must not exceed the strength of the pedestrian. Since these forces will also be a function of speed, there will be a rapid reduction in the numbers of fatally and seriously injured casualties below the equivalent car speed. However, some weak or unlucky casualties will still be injured at speeds below the equivalent car speed and some strong or lucky casualties will be 'saved' at speeds above the equivalent car speed. These are shown shaded in Figure 13.3b. Note that no benefit has been assumed for slight casualties as the test procedures are not designed to prevent such minor injuries. Also, note that fatalities 'saved' are assumed to still be seriously injured and serious casualties 'saved' to still be slightly injured.



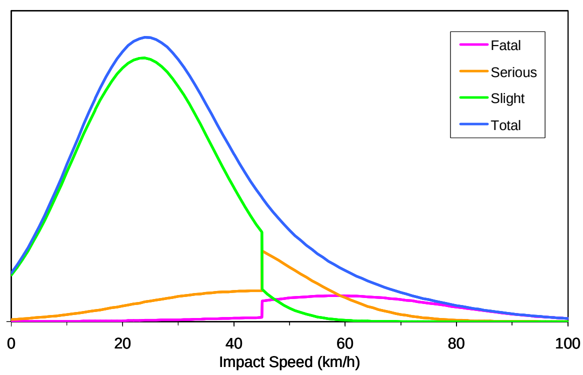
a. Example speed distribution



b. 'Uninjured up to the equivalent car speed' actual assumption



c. 'Uninjured up to the equivalent car speed' – previous calculation method



d. 'Uninjured up to the equivalent car speed' – current calculation method using injury risks

Figure 13.3. Example speed distributions: before pedestrian protection, assumed distribution with pedestrian protection and 'uninjured up to the equivalent car speed' calculation methods

Figure 13.3b shows how this speed distribution is likely to be modified with implementation of the pedestrian protection Directive. Note that for clarity only cases that involve the front of cars, where the injuries have been caused in the original scenario by parts of the car that will be tested, are considered here. For the casualty to be 'saved' the impact also has to be at a survivable speed, and the impact forces must not exceed the strength of the pedestrian. Since these forces will also be a function of speed, there will be a rapid reduction in the numbers of fatally and seriously injured casualties below the equivalent car speed. However, some weak or unlucky casualties will still be injured at speeds below the equivalent car speed and some strong or lucky casualties will be 'saved' at speeds above the equivalent car speed. These are shown shaded in Figure 13.3b. Note that no benefit has been assumed for slight casualties as the test procedures are not designed to prevent such minor injuries. Also, note that fatalities 'saved' are assumed to still be seriously injured and serious casualties 'saved' to still be slightly injured.

In the previous two studies the assumption used for the 'uninjured up to the equivalent car speed' calculation method corresponded to that shown in Figure 13.3c. All fatalities and seriously injured casualties hit at speeds up to the equivalent car speed of the test procedure are taken to be 'saved', provided the injuries were caused by areas of the car that will be tested by the test procedures. However, it isn't reasonable to assume that most fatalities could be converted to slight injuries or none. It is more likely that they would still be seriously injured. Similarly, it is more likely that existing serious casualties will still be slightly injured. The effect of these assumptions can be seen, with the serious distribution following the original fatality distribution at speeds below the equivalent car speed and the slight distribution increasing to maintain the original total distribution. However, the abrupt transition at the equivalent car speed was only a working assumption, made for ease of calculation.

It was explained in Section 13.4.4 that the current study needed to use injury risks to calculate the difference between the benefits of the current and proposed phase two requirements. The calculation method is shown in Figures 13.4 and 13.3d. The proportion of fatalities and seriously injured casualties saved at lower speeds is for ease of calculation taken to be fixed at all speeds below a 'transition speed', although the proportions will be different for the three different test procedure options. At higher speeds the assumption is again of no casualties saved. However, since the risk of injury in the calculation was no longer taken to be zero at speeds below the equivalent car speed, some method was needed to get back the casualties 'saved' in compensation at speeds above the equivalent car speed. It was therefore decided to increase the transition speed for calculation purposes. Some test runs of the database analysis program were performed to obtain a speed addition that was equivalent to the previous method, of assuming for calculation purposes a zero injury risk below the equivalent car speed. It was found that an addition of 5 km/h achieved this. This addition can be justified in real-world terms as car manufacturers would provide an additional measure of protection to be sure of meeting the requirements. Therefore cars will have some additional crush depth to prevent bottoming out in impact testing if the vehicle should prove slightly softer than expected. Also, some parts of the car will have more crush depth than others, so some of those hit at higher speeds will survive without injury, particularly if they are tougher than average.

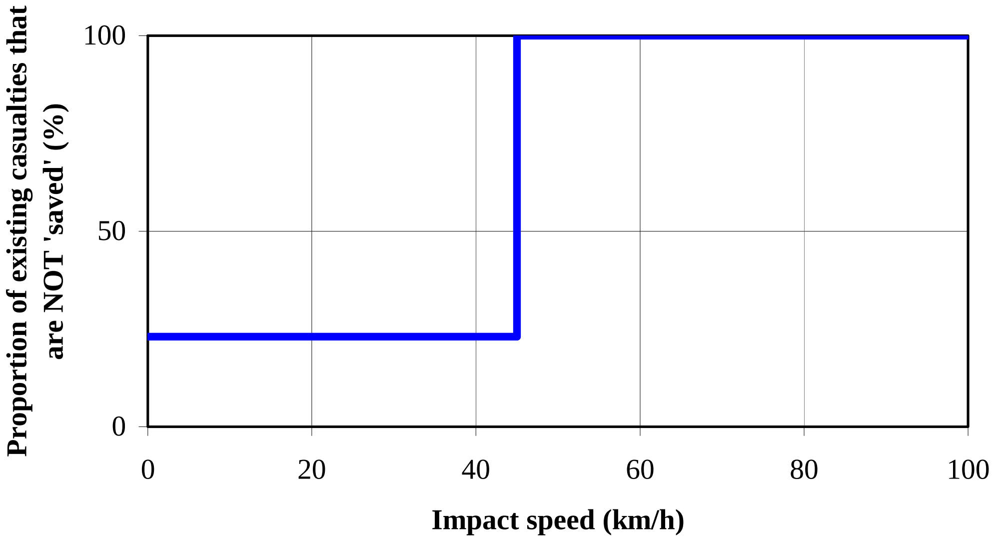


Figure 13.4. Injury risk against impact speed model used in benefit calculation for 40 km/h equivalent car speed

The injury risk up to the transition speed varies according to the part of the car contacted and the test proposal

Note that the calculation uses the same transition speed for both fatalities and seriously injured casualties. This is probably quite a pessimistic assumption for fatalities, although one effect of the test requirements will be that crush depths will be designed in, so that there may be a more abrupt transition by impact speed between low severity injuries and high severity injuries than there is with most current cars.

13.4.6 Obtaining proportions hit by test area and at survivable speeds

Although it is instructive to separate the three lines of Group B shown in Figure 13.1, in practice these are combined in the analysis program to obtain the proportion of those hit by car fronts that could be 'saved'. A computer program has been developed, over a number of benefit studies, which considers each casualty in turn and, within that casualty, each injury in turn that has to be 'saved' in order to reduce the severity of the casualty (fatal to serious or serious to slight).

Preventing some injuries to a pedestrian with multiple injuries will not necessarily benefit the pedestrian, or the benefit may be of limited value. It is assumed that impact with an improved car will not affect the likelihood of injury from areas of the car outside the area tested by the test procedures nor from later impact with the road or the exterior environment generally. Injuries currently occurring from contact with non-tested areas and the ground will therefore continue to occur. If the pedestrian should receive a fatal injury from ground contact then the result will be the same, however much improved the car is. For casualties with multiple serious injuries there will be some benefit from preventing individual injuries, but it will not be proportional to the number prevented. To maximise the benefit it would be necessary to prevent all serious injuries, so that the casualty is uninjured or only slightly injured. When a monetary value (casualty cost) is put on a seriously injured casualty, obtaining that benefit requires that the casualty is no longer defined as serious. Even then, if the casualty is still slightly injured, the benefit is offset by the residual slight casualty cost.

For seriously injured casualties it was therefore assumed that the serious casualty could be potentially 'saved' if all of the AIS 2 to 4 injuries were caused by contact with tested areas of the car. For 'fatalities' it was, in the same way, assumed that the 'fatality' could be potentially 'saved' if all of the AIS 5 and 6 injuries were caused by contact with tested areas of the car.

The tested areas under the test proposals match well the descriptions of contact areas in the IHRA pedestrian accident dataset. The 'Front Bumper' and 'Front Panel' together were considered as being tested by the legform. It was assumed for the purpose of these calculations that all cars would be subject to the legform test, as the alternative upper legform test applies to relatively few vehicles with high bumpers. The 'Leading Edge of Bonnet and Wing' area was considered as being tested by the upper legform. The 'Bonnet and Wing' area was considered as being tested by the headforms. Casualties for whom there was an injury of the severity being considered, where the injury source was unknown or where non-contact injury was recorded, were not included in the analysis. All other contact areas were taken to be non-tested areas.

The GIDAS dataset includes a number of bonnet top areas: bonnet front third, bonnet middle third, bonnet rear third, rear edge of bonnet, wing, and bonnet unspecified, whereas in the IHRA dataset the bonnet top is a single area. After discussion with TUD, the authors broadly copied TUD's treatment of these areas. TUD assumed that the one third lower protection zone would correspond to the wing and rear edge of the bonnet, as these tend to be the difficult areas to make safe. An appropriate percentage (85 percent) of these two areas (wing and rear edge of the bonnet) was therefore taken as being in the lower protection zone. The front third of the bonnet (note this does not include the bonnet leading edge) was assumed to be at less than 1000 mm wrap around distance and therefore not part of the tested area. Other specified areas (i.e. middle and rear thirds) were assumed to be wholly within the higher protection zone. The 'bonnet unspecified' in the GIDAS dataset was treated the same as was the combined bonnet in the IHRA dataset.

Areas just inside the nominated relaxation or lower protection zones have to be safer than the central parts of the zone, because they are still effectively involved in tests where the impact point is just outside the zone and a step change in stiffness is not be possible. It is therefore not practical to make full use of the concession over the full width or area allowed. It was therefore assumed that the *effective* width or area of the relaxation zone would in each case be five percent of the car's width narrower or the bonnet's area smaller than the defined percentage.

Consideration was given as to whether the injuries to a given casualty would tend to be all in the lower protection zone or all in the higher protection zone. Some tendency for them to be grouped would be expected. Three options were to assume lining up of the lower protection zones across all car regions, assume lining up only within the bonnet top or assume lining up only within the bonnet sub-divisions. The middle option seemed to be the best compromise. Strictly, there is a fourth option, to assume no lining up even within a bonnet sub-region; however this was rejected, as frequently multiple injuries will arise from one contact. This part of the analysis was handled by considering the least safe sub-regions first, those with the highest proportion of lower protection zone. The first relevant bonnet top injury then determined the result for the whole of the bonnet top.

A way was developed of analysing the accident data using a random number function to determine which zone (main or relaxed) the casualty contacted. Multiple passes (10,000) were made through the database to smooth out the effects of the random variation. This improves the consistency of the analysis, which is desirable when comparisons are being made between different proposals that provide benefits of similar magnitude.

In Section 13.4.4 and particularly Figure 13.4 the assumption was made that not all casualties would have an injury prevented as there would still be a remaining injury risk from impact with a protected area. However, most casualties have more than one injury so an estimate has to be made for the whole casualty. If injury risks were taken for a number of injuries then the chance of the casualty being considered to be ‘saved’ in the calculation might be quite small. However, in practice many of the factors that determine whether a casualty would be injured would apply across the whole body, such as age, fitness, health, vehicle impact speed, vehicle type. Therefore the preferred assumption was that the casualty would have a fixed ‘strength’ that could be compared with the injury risk taken from Table 13.5. If the ‘strength’ of the casualty was more than the injury risk for that contact then that injury was considered to be ‘saved’, otherwise they were considered as still being injured. However, each case needs to be considered for the full range of possible casualty ‘strength’ from zero to 100 percent. As there are only a few injury risk values in Table 13.5, the full range of casualty ‘strength’ can be evaluated by setting the ‘strength’ to a value within each interval in turn and weighting the result by the size of that interval.

The dataset was analysed on a casualty-by-casualty basis to obtain a combined proportion of those casualties hit up to the equivalent car speed and injured by tested areas. The analysis then automatically took into account any interaction between the two effects, such as the possibility that fewer head to bonnet top impacts occurred at higher speeds because the windscreen was hit instead.

Summary of the calculation within the analysis program:

> For each test option, severity (fatal or serious), ‘strength’ value, pass through the database and casualty:
>
> > Each injury considered would be ‘saved’ only if:
> >
> > > Injury was caused by a tested area,
> > >
> > > Case impact speed was less than or equal to the transition speed (i.e. equivalent car speed plus 5 km/h), and
> > >
> > > Casualty ‘strength’ was greater than injury risk (with higher and lower protection zones determined randomly in required proportion)
> >
> > Each casualty would be ‘saved’ only if all injuries of severity matching the casualty severity were ‘saved’ (AIS 5-6 injuries for MAIS 5-6 casualties, AIS 2-4 injuries for MAIS 2-4 casualties).

13.4.7 Brake assist systems

In Section 9.4.1.1 the reliability of the BAS data was discussed. Despite these concerns the data were used ‘as if correct’ in the calculation. The results concerning BAS should therefore be regarded as ‘indicative’. The possible effects of systematic errors in these data are considered in Section 13.6.

From discussions with TUD, it was ascertained how the impact speed with BAS fitment calculation was performed by TUD, as a case-by-case calculation. The results obtained were quite close to those reported by TUD, but it was not possible to get exactly the same number of impacts prevented (57 cases obtained instead of TUD's 56, from the original 712 case sample).

One accident was found to have a much lower assumed deceleration with BAS than the estimated actual deceleration, because the road surface condition was unknown. Other cases were found where there was insufficient information for an accurate calculation or one of the required fields was unknown. In total 11 frontal cases were discarded from the combined 849 case frontal sample used in the case-by-case BAS calculation, and 7 cases from the 275 case non-frontal sample. These were still used for the secondary safety calculation and the injury risk by impact velocity distribution that is used in the BAS benefit calculation.

The essence of the TUD method of obtaining the benefit of BAS can be split into three stages:

1. On a case-by-case basis, estimate what the impact speed would have been had BAS been fitted. Where there was no braking or where the braking was less than the assumed BAS threshold this would be the same as the estimated actual impact velocity. Where the BAS activation threshold was exceeded this would normally be a lower velocity or the impact may be avoided.
2. Produce a distribution of injury risk by velocity from the accident data. This is done for fatalities, and for fatalities plus seriously injured casualties, so that at any speed the risk of serious injury is the difference between the two injury risks. As well as the risk for the original accident data, these distributions are obtained for the expected injury risk distribution after the introduction of each set of test proposals. This allows for the interaction between the BAS benefit and the secondary safety benefit, as the overall benefit will be less than the sum of both individually.
3. Apply the set of impact velocities with BAS fitted to the injury distributions and sum over all cases, to give the number of casualties. The reduction in the number of casualties, compared with the original number or with the number for the secondary safety alone, is then the additional BAS benefit.

In the first stage above, after further consultation with TUD, it was established that this case-by case calculation made the following simplifying assumptions:

a) That, where braking had occurred, there was a constant braking deceleration phase before impact. Without BAS this was at the mean deceleration estimated by the accident investigators. With BAS, this was at the deceleration that they estimated would be possible in a BAS equipped vehicle, provided that the BAS threshold had been reached. If the BAS threshold was not reached this would be at the mean braking deceleration obtained, so there would be no BAS benefit. The braking distance of this phase would be the braking length estimated by the accident investigators.

b) Before the constant braking phase the deceleration would rise linearly to the constant level over 0.3 s. This assumed rise time was the same with and without BAS.

The case-by-case BAS calculation, where the assumed BAS threshold was reached, currently:

i) Uses impact speed, mean braking deceleration and braking length to estimate an intermediate speed, assuming constant deceleration.

ii) Uses this intermediate speed, mean braking deceleration and an assumed rise time to estimate the initial speed before braking commenced, assuming a linear rise. The distance covered in this phase is also estimated. This rise time is typically 0.3 s but this can be varied, for all cases together, if required. (Distance covered and variable rise time were added for the 2006 report.)

iii) Uses this initial speed, the expected with-BAS mean braking deceleration and an assumed rise time to estimate the intermediate speed at the beginning of the constant braking phase, assuming a linear rise. The distance covered in this phase is also estimated. This rise time is typically 0.3 s but this can be varied, for all cases together, if required. (Distance covered and variable rise time were added for the 2006 report.)

iv) Uses the distances covered in the rise times above to adjust the constant deceleration braking length. (Added for the 2006 report.)

v) Uses this intermediate speed, adjusted braking distance and the with-BAS deceleration to estimate the with-BAS impact speed.

The authors were content to use the TUD method for the first stage, apart from the refinements mentioned, and also for the third stage apart from the way impact avoided cases were dealt with. However, for the second stage TUD matched the injury distributions to a logistic curve. This is a two parameter ‘S’-shaped curve and it was thought that it might not reflect the complexity of the injury risk against velocity distribution; this could potentially affect the interaction between the secondary and BAS benefits, possibly over-estimating the combined benefits. In addition, TUD was constraining the logistic solution to ensure that the correct numbers of casualties were obtained if the without-BAS impact speeds were used in the calculation. It was found that the software used could obtain ‘solutions’ to the logistic curve that were not the best fit solutions.

For these reasons it was decided to use a banded injury risk distribution. The severity and impact speed data were banded into 10 km/h wide bands, of 1-10, 11-20, 21-30 km/h, etc. to obtain the injury risk for each band. (Both the GIDAS and IHRA databases contain only integer values for impact speed.) These distributions are shown in Figure 13.5, for current cars (no secondary safety by design), for the current phase two, for phase one and for the EC proposal. (These are for the final accident data used and so just illustrate the principle of the injury risk distribution, at this stage of the step-by-step discussion.) In each case the data point is taken at the average impact speed of the data points within the band, rather than at the band centre.

When the injury risks were obtained for each casualty they were obtained by interpolating between data points by impact speed. In the case of casualties impacted at speeds below the lowest speed data point the injury risk was obtained by extrapolation from the first two data points. In cases where the impact would have been avoided with BAS the injury risk was taken to be zero. It can be seen that the injury risk can vary wildly at high speeds where there are very few casualties in the accident databases. This can of course lead to large errors in the injury risk calculated for individual casualties; however, because there are so few casualties at these speeds the contribution they make to the total injury risk is very small, especially as most of these errors will tend to be cancelled by errors in the opposite direction for other casualties.

As a check on the validity of this banded injury risk distribution method the numbers of casualties obtained for the without-BAS case were found by using the method. This gave casualty numbers that were quite close to the original numbers, especially for seriously injured casualties. These were then factored to obtain exactly the original numbers and the same factors were used for the corresponding with-BAS case.

Though this method may be less elegant than the constrained logistic method of TUD, it is still preferred here for the reasons given above. However, it is now thought that this general method of using an injury risk distribution to estimate the additional benefits of BAS is quite robust, so that fairly similar results would be obtained whether the logistic function or the banded distribution is used.

The results obtained gave a higher benefit for BAS than a comparable estimate quoted by TUD; both were calculated for BAS without secondary safety, using the original 712 case sample from the GIDAS dataset, a 6 m/s² BAS threshold and the GIDAS car frontal casualties of all pedestrian casualties proportion. Estimated benefits of a reduction in numbers of casualties of 5.8 percent of all pedestrian fatalities and 5.7 percent of all pedestrian seriously injured casualties were obtained, compared with the TUD estimates of 5.2 percent for both severities. The difference in benefits could be because here the injury risk was taken as being zero when the impact was avoided with BAS, rather than it being due to the use of the banded distribution method.

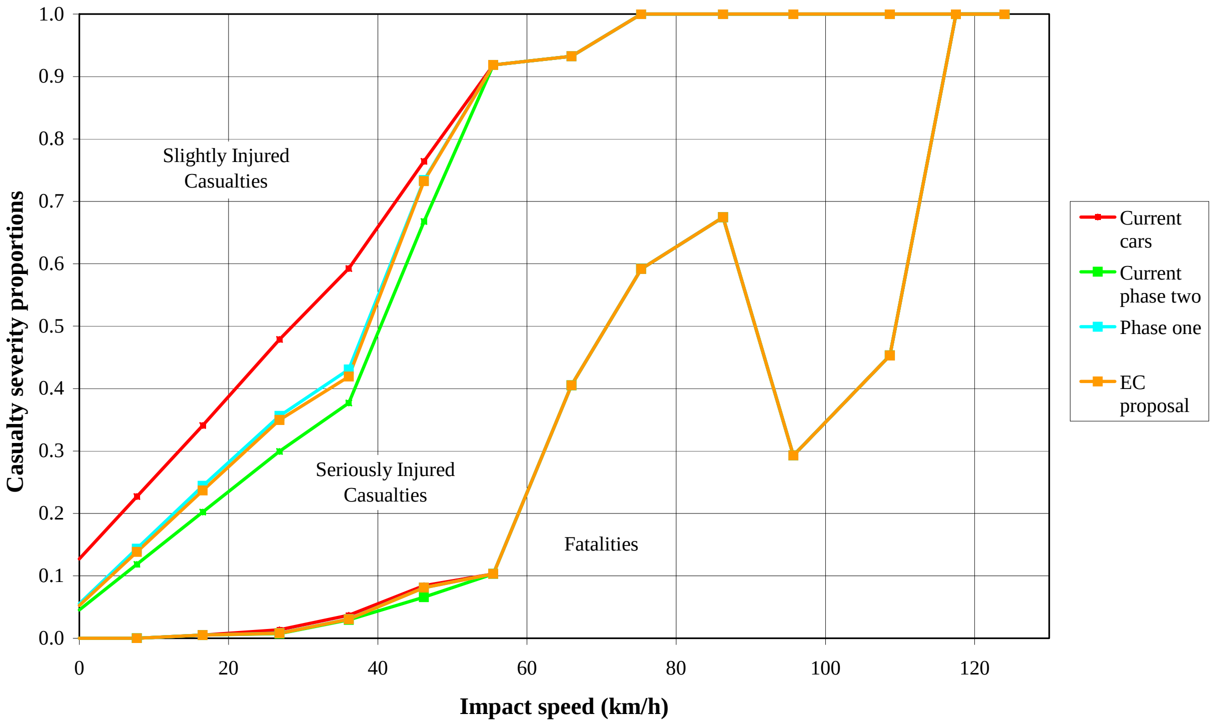


Figure 13.5. Injury severity risk by impact speed using banded data

For the 2005 extension study the authors decided that the BAS threshold deceleration (the deceleration necessary to trigger a BAS) of 6.0 m/s² (the 'conservative' value used by TUD) was probably too high for a most realistic estimate, but given the uncertainty on this issue it was decided to take the mean of estimates obtained using thresholds of 6.0 and 4.0 m/s². For this current 2006 update, advice has been received from ACEA that a BAS threshold of 4.0 m/s² would be a reasonable assumption; therefore a single estimate of 4.0 m/s² has been used.

The BAS calculation for the non-frontal cases was carried out in the same way as for the frontal cases.

13.4.8 Combining secondary safety and BAS, and pedal cyclist contribution

The proportions of casualties saved by the secondary safety options were obtained as described above. For each option a velocity distribution was obtained of the casualties that would remain after those estimated to be saved were removed. This velocity distribution was then used in the banded BAS calculation described above, to avoid double counting casualties that could be saved by secondary safety and by BAS. The two estimates of proportions saved could then be added together. The proportion saved by BAS in non-frontal accident was similarly obtained, except that no secondary safety benefit was assumed so the banded BAS calculation used the original velocity distribution for the non-frontal dataset.

For the pedal cyclist strand of the calculation, there was no comparable database to use to estimate the survivable speed and tested area term or terms. In an earlier benefit study van Kampen (1994) had considered how to allow for pedal cyclists. With their greater height and speed pedal cyclists will have a lower proportion of accidents in which they could be 'saved'. Also, they would get less benefit when hit at their front or rear, but would be most similar to pedestrians when hit side on. He therefore considered that pedal cyclists would be saved at half the rate of pedestrians. Therefore, for this current study the rate of saved pedal cyclists will be taken to be half of the rate for pedestrians, for both secondary safety and BAS. It isn't clear from van Kampen's report as to when this factor was applied, whether to all pedal cyclist casualties, or only to those hit by the fronts of cars. For this study the factor has been applied to those hit by the fronts of cars, which gives the lower estimates. For the

BAS benefit in non-frontal accidents involving pedal cyclists it was considered that a lower factor would be more appropriate, because the pedal cycle velocity vector would mean that less of the closing speed could be influenced by BAS. In this case, therefore, a factor of a third was used.

13.5 Results

13.5.1 Proportional reductions in casualties

The proportions of casualties hit by the fronts of cars, given in Table 13.3, were combined with the proportions saved that were obtained from the secondary safety and the BAS calculations for frontal accidents. At this stage, also, the proportion of cars covered by the scope of each option was factored in. This gives the proportions of current casualties that would be 'saved' for each injury severity; these are shown in Table 13.6. The contribution of BAS in non-frontal accidents was also included, having been obtained in a similar way using the proportions hit by other parts of cars, which were also obtained from the GB national data. As was explained in Section 13.4.1, it was assumed that slight casualties are 'saved' only in those accidents where BAS allows the car to stop before reaching the pedestrian.

Table 13.6: Estimated proportions of all vulnerable road user casualties that would be 'saved' to a lower injury severity, that would be obtained by implementation of the various options

Road user type	BAS fitment	Current phase two			Industry proposal			EC proposal		
		Fatal	Serious	Slight	Fatal	Serious	Slight	Fatal	Serious	Slight
Pedestrians	no BAS	0.067	0.161	0	0.036	0.110	0	0.039	0.120	0
	BAS fitted	n/a	n/a	n/a	0.111	0.213	0.202	0.116	0.225	0.207
Pedal cyclists	no BAS	0.024	0.064	0	0.013	0.044	0	0.014	0.048	0
	BAS fitted	n/a	n/a	n/a	0.053	0.100	0.088	0.056	0.106	0.090

However, as noted earlier, it isn't reasonable to assume that most fatalities could be converted to slight injuries or none. It is more likely that they would still be seriously injured. Therefore, an adjustment was also made to the proportions saved by secondary safety, reducing the numbers of seriously injured casualties saved to reflect the fatalities which are saved, to estimate the proportional reduction in serious casualties. (The proportion of fatalities saved is unchanged). The slightly injured casualties saved were similarly adjusted to reflect the serious injured casualties that are saved; in some cases it is estimated that there will be a net increase in slight casualties. The estimated proportional reductions in vulnerable road user casualties thus obtained are given in Table 13.7.

It can be seen that the secondary safety contribution to the benefits to be obtained from the EC proposal is to save about 4 percent of all pedestrian fatalities and 12 percent of all seriously injured pedestrian casualties. The BAS contribution is not shown separately in Table 13.7 but it can easily be derived by subtraction as being about 8 percent of all pedestrian fatalities, 10 percent of all seriously injured pedestrian casualties and 16 percent of all slightly injured pedestrian casualties.

In Table 13.8, estimates of effectiveness of the various options, relative to the current phase two without BAS, are given. On these estimates, both proposals with BAS match the current phase two benefits. Estimates are given later that combine both severities. The estimates for pedal cyclists are higher than those for pedestrians, despite assuming a smaller fraction of the proportion of pedestrians saved in non-frontal (of the car) accidents, because there is a higher proportion of non-frontal accidents and therefore the benefits of BAS in non-frontal accidents have a greater influence.

Table 13.7: Estimated proportional reductions in numbers of vulnerable road user casualties, by severity, that would be obtained by implementation of the various options

Road user type	BAS fitment	Current phase two			Industry proposal			EC proposal		
		Fatal	Serious	Slight	Fatal	Serious	Slight	Fatal	Serious	Slight
Pedestrians	no BAS	0.067	0.158	-0.078	0.036	0.108	-0.053	0.039	0.118	-0.058
	BAS fitted	n/a	n/a	n/a	0.111	0.208	0.099	0.116	0.219	0.099
Pedal cyclists	no BAS	0.024	0.064	-0.019	0.013	0.043	-0.013	0.014	0.047	-0.014
	BAS fitted	n/a	n/a	n/a	0.053	0.098	0.059	0.056	0.104	0.059

Negative proportions imply an increase in slight casualties (due to serious casualties saved being reduced in severity to slightly injured).

Table 13.8: Estimated effectiveness of each option, relative to the current phase two requirements without fitment of BAS

Road user type	BAS fitment	Current phase two		Industry proposal		EC proposal	
		Fatal (%)	Serious (%)	Fatal (%)	Serious (%)	Fatal (%)	Serious (%)
Pedestrians	no BAS	100	100	53	68	58	75
	BAS fitted	n/a	n/a	166	132	173	139
Pedal cyclists	no BAS	100	100	53	68	58	74
	BAS fitted	n/a	n/a	218	155	228	164

13.5.2 Numbers of casualties 'saved'

The proportions in Table 13.7 can now be multiplied by the numbers of current casualties estimated for the European Union, see Table 13.2 (bottom row), to predict the reduction in the numbers of casualties that could be obtained with each of the options, see Table 13.9. These are the annual savings that might be expected if cars complying with the option below formed 100 percent of the car fleet (ignoring issues of scope). Alternatively, if a steady state is assumed, it is the savings that would accrue over the lifetime of one year's new car registrations. These estimates are for all casualties saved, whether currently reported or not.

13.5.3 Financial benefits of casualties 'saved'

Casualty costs were obtained for Great Britain (Department for Transport, 2005) at June 2004 prices. These were used because GB casualty costs are obtained using the 'willingness to pay' methodology that was recommended by the COST action 313 working group (Alfaro *et al.*, 1994). Many other countries do not use the recommended method, or may only use it only for fatalities. These GB casualty costs were converted to casualty costs in Euro, using the EU's June 2006 exchange rate £0.6847 = €1 (£1 = € 1.460). These casualty costs and, for information, their breakdown into their component parts is shown in Table 13.10. This is the same exchange rate as that used to convert vehicle costs from sterling to Euro.

Table 13.9: Estimated annual reduction in numbers of vulnerable road user casualties in the European Union (EU-25), by severity, that would be obtained by implementation of the various options

Road user type	BAS fitment	Current phase two			Industry proposal			EC proposal		
		Fatal	Serious	Slight	Fatal	Serious	Slight	Fatal	Serious	Slight
Pedestrians	no BAS	547	25,308	-25,855	292	17,296	-17,588	320	18,893	-19,213
	BAS fitted	n/a	n/a	n/a	906	33,330	32,950	947	35,197	32,765
Pedal cyclists	no BAS	79	6,937	-7,017	42	4,731	-4,773	46	5,168	-5,214
	BAS fitted	n/a	n/a	n/a	173	10,731	21,640	181	11,353	21,844
Vulnerable road users	no BAS	626	32,246	-32,872	334	22,027	-22,361	366	24,060	-24,427
	BAS fitted	n/a	n/a	n/a	1,079	44,061	54,590	1,128	46,550	54,609

Negative numbers imply an increase in slight casualties (due to serious casualties saved being reduced in severity to slightly injured).

Table 13.10. Average value of prevention per casualty by severity and element of cost
Values for Great Britain (Department for Transport, 2005) converted to Euro

Injury Severity	Lost output	Medical and ambulance	Human costs	Total
Fatal	€695,081	€1,193	€1,325,687	€2,021,999
Serious	€26,780	€16,223	€184,209	€227,199
Slight	€2,830	€1,201	€13,485	€17,513

Note that because some elements of accident values are not quantified, total accident values may be regarded as minimum estimates.

The above costs are for reported casualties. Unreported casualties tend to have less severe injuries. Using the above costs directly would therefore over estimate the financial benefit. Hopkin and Simpson (1995) describe in detail how the casualty costs are calculated. Human costs were obtained using willingness to pay methodology for a range of different severities within the serious and slight classifications. The other components of the casualty cost (see Table 13.10) are also obtained for a range of severity. For the current study, lower, and therefore more appropriate casualty costs for the unreported casualties, were obtained by taking the costs for the least severe category within both the serious and slight classifications. The total 'unreported' casualty costs were then adjusted to reflect changes in the published casualty costs since the Hopkin and Simpson report. Finally, working casualty costs were estimated that reflected the balance of reported and unreported casualties that were used as the current casualties in the calculation; these are shown in Table 13.11.

Table 13.11: Casualty costs used in this study, adjusted to reflect the inclusion of non-reported casualties

Fatal	Serious	Slight
€2,021,999	€125,153	€13,588

Financial benefits were now estimated for each option by multiplying the reductions in casualties in Table 13.9 with the corresponding casualty cost from Table 13.11, and summing together the amounts for the three casualty severities. These estimates are shown in Table 13.12.

Table 13.12: Estimated annual financial benefit to vulnerable road users in the European Union (EU-25), by severity, that would be obtained by implementation of the various options

Road user type	BAS fitment	Current phase two (€ million)	Industry proposal (€ million)	EC proposal (€ million)
Pedestrians	no BAS	3,922	2,515	2,750
	BAS fitted	n/a	6,451	6,766
Pedal cyclists	no BAS	933	613	670
	BAS fitted	n/a	1,987	2,084
Vulnerable road users	no BAS	4,855	3,128	3,420
	BAS fitted	n/a	8,438	8,849

As well as giving the financial benefits the use of casualty costs provides a convenient way of combining the benefits of saving casualties of all severities. Hence a single relative effectiveness value can be obtained for each proposal, see Table 13.13.

Table 13.13: Estimated financial effectiveness of each option, relative to the current phase two requirements without fitment of BAS

BAS fitment	Current phase two (%)	Industry proposal (%)	EC proposal (%)
no BAS	100	64	70
BAS fitted	n/a	174	182

13.5.4 Costs of protecting vulnerable road users

In Table 12.2 the costs of various options for providing protection for vulnerable road users to the standard of the EC proposal were shown. These costs are production costs; i.e. they are the costs to the motor manufacturers.

Most of the benefits of safer cars are obtained by members of the public, as a reduced human cost element. Much of the benefit of a reduction in lost output will also be obtained by the public. When comparing with the costs of achieving this improved safety, therefore, the best comparison is obtained by looking at the cost to members of the public. The manufacturer would typically take a 5 to 10 percent profit. The dealer's margin (including their profit) would be about 10 percent. VAT would typically be about 15 percent. Taking the middle of the range for profit gives a combined mark-up of 36 percent. This was then rounded up to 40 percent to cover a possible increase in delivery charges (due to vehicles with pedestrian protection possibly being longer). The consumer costs for the EC proposal in Table 13.14 were thereby obtained by marking up the costs in Table 12.2

by 40 percent. Reductions in these consumer costs to reflect a reduced scope can potentially be factored in at this point, but for the EC proposal the scope is assumed to be 100 percent anyway.

Table 13.14 also shows cost to benefit ratios for the vehicle fleet, including fitting pop-up bonnets and bolt-on spoilers, based on the EC proposal. These are estimated using the benefits (which include the BAS benefit) from Table 13.12. The cost to benefit ratio in Table 13.15 is estimated using the preferred solution (shown shaded) in Table 13.14. Estimates of the benefit per car, over its lifetime, are also given for each option. BAS were considered to have a low cost, given that most of the hardware is needed anyway for ABS; also there are additional benefits to car occupants from having it. The cost of BAS was therefore taken as zero for calculation purposes. This approximation will have led to an over-estimate of the benefit to cost ratio.

Table 13.14: Consumer costs and cost to benefit ratios for the EC proposal for the different combinations of solutions for car types

Spoiler option	Pop-up bonnet option	Consumer cost (€ million)	Cost to benefit ratio
No costs for fitting a spoiler to the off-roader segment attributed to pedestrian protection	No pop-up bonnets	805	1 : 11.0
	Pop-up bonnets fitted to all sports cars	905	1 : 9.8
	Pop-up bonnets fitted to all sports cars and executive cars	995	1 : 8.9
Bolt-on spoilers fitted to all of the off-roader segment and the costs attributed to pedestrian protection	No pop-up bonnets	855	1 : 10.3
	Pop-up bonnets fitted to all sports cars	955	1 : 9.3
	Pop-up bonnets fitted to all sports cars and executive cars	1045	1 : 8.5

Notes: The consumer cost and the cost-benefit ratio in the shaded cells is thought likely to be the most appropriate for the fleet, despite it almost certainly not representing the real distribution of solutions.

Table 13.15: Estimated benefit to vulnerable road users, cost to benefit ratios and lifetime benefit per car sold from implementation of the various test options

	Current phase two	Industry proposal (including BAS)	EC proposal (including BAS)
Benefit (€ million)	4,855	8,438	8,849
Cost to benefit ratio	n/a	n/a	1 : 8.9
Lifetime benefit per car (€)	338	587	600

Note: The cost to benefit ratio is calculated using the consumer cost in the shaded cell in Table 13.14 above.

13.6 Sensitivity analysis

The analysis program was set up to estimate the benefits that would be obtained from making the changes to the three test zones separately, from a baseline of the current phase two. See Table 13.16. It should be noted that as saving a casualty requires that all injuries of that severity be saved, so the reduction in benefits from making all three changes together will be less than the sum of the individual changes. It can be seen that making the bonnet leading edge test non-mandatory would have very little effect on fatalities, as the analysis, based on a limited sample, indicates no effect. However, the effect of making the bonnet leading edge test non-mandatory has the largest effect on serious casualties saved. The changes to the head test zone show a particularly large reduction in savings for fatalities. It should be noted that this would have been a much smaller reduction without the addition of the IHRA fatality cases. See the sensitivity analysis on this below.

Table 13.16: Examination of proposed passive protection changes within the EC proposal, by test zone, compared with the current phase two benefits

		Fatalities reduction		Serious casualties reduction		Financial effectiveness	
		(no.)	**(%)**	**(no.)**	**(%)**	**(€ million)**	**(%)**
Current phase two requirements		626	100	32,246	100	4,855	100
After changes made to:	Bumper test zone	605	96.6	30,333	94.1	4,599	94.7
	Head test zone	378	60.4	30,904	95.8	4,207	86.7
	BLE test zone	626	100	26,620	82.6	4,228	87.1

It was mentioned earlier that the addition of benefits from BAS in non-frontal impacts had a very large effect, but that this did depend on the source of the estimates for the proportions of casualties in frontal and non-frontal accidents of all those in accidents with cars. The earlier estimates used proportions from GB national data. However, the original GIDAS sample of 712 car frontal pedestrian cases is known to have been obtained from a sample of 826 cases hit by cars. The split by severity is also known. Corresponding proportions for pedal cyclists were not known, but pro rata estimates were made based on GIDAS and GB pedestrian proportions and GB pedal cyclists proportions. The resulting estimates for the relative effectiveness of the different test options are compared in Table 13.17 with the corresponding estimates from Table 13.13 using the GB frontal proportions.

Table 13.17: Comparison of estimates of the relative financial effectiveness of each option that are obtained using GIDAS proportions for frontal and non-frontal of all car to pedestrian (estimated pro rata for pedal cyclists) and proportions from GB national data

Data used for frontal proportion	Current phase two (%)	Industry proposal (including BAS) (%)	EC proposal (including BAS) (%)
GIDAS	100	153	161
GB national data	100	174	182

The use in this study of additional fatalities from the IHRA dataset is an aspect of the calculation that ACEA and TUD do not agree with. The extra casualties are used to increase the sample size but there are clearly differences between the two fatality datasets, such as impact speed, see the distributions in Figure 13.2. Estimates of relative effectiveness obtained using only GIDAS data are compared in Table 13.18 with the estimates of relative effectiveness from Table 13.8. It can be seen that with GIDAS data the estimated benefits to fatalities from passive protection are quite small compared with the benefits of BAS. Small changes to the benefits for serious casualties will be because of the assumption that fatalities 'saved' become seriously injured. The benefit results are sensitive to the dataset used primarily because of the different headform test speeds, so the presence or absence of 'saveable' casualties in the vehicle speed range where one test option provides protection but another does not, will, with these small GIDAS and IHRA fatality samples, have a disproportionate effect. One option for a future analysis might be to attempt some kind of smoothing process on the data from both datasets, so that the velocity distribution bears a greater resemblance to what might be expected, and clusters and gaps are avoided. The GIDAS dataset has a gap in the crucial speed range; further analysis might show whether the IHRA data in that speed range are a cluster or are part of a plausible speed distribution.

Table 13.18: Comparison of estimates of the relative effectiveness of each option for pedestrians that are obtained both by using only GIDAS data (i.e. no IHRA fatalities) and by using GIDAS data supplemented with IHRA fatality data

Data used	BAS fitment	Current phase two		Industry proposal		EC proposal	
		Fatal (%)	Serious (%)	Fatal (%)	Serious (%)	Fatal (%)	Serious (%)
GIDAS only	no BAS	100	100	85	68	93	74
	BAS fitted	n/a	n/a	611	130	632	138
GIDAS + IHRA	no BAS	100	100	53	68	58	75
	BAS fitted	n/a	n/a	166	132	173	139

As was explained in Sections 3.2.3.3 and 13.4.5, the value of ‘k’ (ratio of head impact speed to vehicle speed) is the subject of much debate, and whereas the authors assumed that ‘k’ = 1.0 there is support among some experts for ‘k’ = 0.8. In the cost-benefit calculation this value affects the vehicle impact speed range where protection can be provided. Therefore a sensitivity check has been performed, see Table 13.19, comparing the relative effectiveness estimates obtained used ‘k’ = 0.8 with those previously obtained for ‘k’ = 1.0 (from Table 13.8). Using ‘k’ = 0.8 means that the estimated benefits are increased, particularly for fatalities, so the contribution of BAS to the relative effectiveness decreases. The difference is fairly small for serious casualties mainly because most were already within the speed range that was assumed to be protected (see Figure 13.2), though without the manufacturer’s margin of 5 km/h (see Section 13.4.5) more additional benefits would have been estimated by changing ‘k’ to 0.8. The analysis was also repeated for the combination of no IHRA fatalities and ‘k’ = 0.8. These results are not presented but they showed that changing ‘k’ made no difference to the fatalities when using only GIDAS data. Note that for fatalities the limited sample sizes (both with and without the IHRA data) mean that the benefits predicted are very sensitive to the vehicle impact speeds of the few fatalities that could potentially be ‘saved’.

Table 13.19: Comparison of estimates of the relative effectiveness of each option for pedestrians that are obtained with the headform ‘k’ value set to 0.8 and 1.0

‘k’ value	BAS fitment	Current phase two		Industry proposal		EC proposal	
		Fatal (%)	Serious (%)	Fatal (%)	Serious (%)	Fatal (%)	Serious (%)
0.8	no BAS	100	100	66	70	72	76
	BAS fitted	n/a	n/a	150	131	158	138
1.0	no BAS	100	100	53	68	58	75
	BAS fitted	n/a	n/a	166	132	173	139

Clearly, changing the assumed 'k' will affect all test options in a roughly similar way. However, some would argue that if 'k' = 0.8 then the current phase two should have been set at 32 km/h for a vehicle speed of 40 km/h. Had this been the case then the benefits with 'k' = 0.8 would have been the same as those that have been calculated for 40 km/h and 'k' = 1.0. To illustrate this, relative effectiveness has also been calculated based on a comparison with these 'intended' benefits, see Table 13.20.

Table 13.20: Alternative and illustrative estimates of the relative effectiveness of each option that are obtained if the headform 'k' value is 0.8 instead of 1.0, taken relative to the current phase two with 'k' = 1.0

'k' value	BAS fitment	Current phase two		Industry proposal		EC proposal	
		Fatal (%)	Serious (%)	Fatal (%)	Serious (%)	Fatal (%)	Serious (%)
0.8	no BAS	127	103	84	72	92	78
	BAS fitted	n/a	n/a	191	135	202	142
1.0	no BAS	100	100	53	68	58	75
	BAS fitted	n/a	n/a	166	132	173	139

In Section 9.4.1.1 concerns were expressed about the data from the GIDAS database that was made available for the current study. For each accident four items of information were used in the BAS calculation (the calculation itself was discussed in more detail in Section 13.4.7):

- Estimated mean braking deceleration
- Estimated mean braking deceleration that could have been achieved had BAS been fitted and triggered
- Estimated braking distance
- Estimated impact speed

For a variety of reasons, none of these estimates will be exactly correct. If the errors in these values were all random, however, the effect of these errors on the relative effectiveness estimates would be expected to be small, as the errors would largely cancel. However, because of the methodology used to make these estimates, such as the use of look-up tables, it is also possible that there could be systematic errors in these estimates, and such errors could cause significant errors in the final results. The sensitivity of the key final result, the relative effectiveness, to such errors has therefore been examined, see Table 13.21. In each case the values of one parameter have been adjusted by a fixed percentage for all cases together. The adjustment was arbitrarily set at ±10 percent in all cases, as it was not possible to work out a realistic likely systematic error. The true level of systematic error may be much more or less than this. The first three parameters could easily be adjusted in the spreadsheet and new estimates of relative effectiveness obtained automatically. It would have been much more complicated to obtain the same estimates for impact speed, requiring manual adjustments and program changes, because it is also used in the secondary safety calculation and to generate the speed bands used in the BAS calculation.

It can be seen that the results are very sensitive to both deceleration values, as might be expected, as the potential for BAS to improve braking depends on the margin between these two values. Even so, the relative effectiveness always remains above 100 percent with this level of adjustment. By comparison, adjusting the braking distance has a much smaller effect, which again may be expected as much of the effect it has on the 'with BAS' part of the calculation is offset by the effect it has on the 'without BAS' back-calculation. Changing the impact speed seems to have a small effect on the average speed reduction of those cases that still impact (range 2.29 to 2.40 km/h), and a more direct effect on the proportion of cases where the car could stop before impact (range 11.1 to 15.5 percent).

Table 13.21: Sensitivity of estimates of relative effectiveness to adjustment of estimates for mean braking deceleration, mean braking deceleration with BAS and braking distance

Parameter	Adjustment	Current phase two (%)	Industry proposal (including BAS) (%)	EC proposal (including BAS) (%)
Mean braking deceleration	+10%	100	128	136
	-10%	100	210	219
Mean braking deceleration with BAS	+10%	100	224	233
	-10%	100	119	126
Braking distance	+10%	100	182	191
	-10%	100	167	175
Baseline	---	100	174	182

The other values that are critical to the BAS calculation are the values that are set globally for all cases, namely the BAS threshold and the braking rise times. These are important both to consider how BAS on the road compares with the simple model applied in the calculation and also to look at the potential that improved BAS may offer in the future.

The value of the BAS threshold used in the main calculation, 4.0 m/s², was advised as being a reasonable 'typical' value to take, by ACEA. (Their contractor TUD used a 'conservative' value of 6.0 m/s².) For pedal speed sensitive systems it isn't possible to calculate using accident data in a way that matches the way the system works, as the pedal rate cannot be estimated. Nevertheless, the assumption for calculation purposes, that where the threshold is exceeded a pedal rate system would have been triggered, seems to be a reasonable one. For pedal force sensitive systems the draft testing procedure specifies that the rate change should occur between 3.5 and 5.0 m/s², so 4.0 m/s² is below the middle of this range. More importantly, the calculation model assumes that in all cases where the threshold is reached the braking deceleration rises to full ABS braking. In reality this will only occur if the rate change threshold is exceeded by an adequate margin. The necessary margin to achieve this depends on the boost rate but the boost rates used in many systems are likely to be close to the minimum specified. In all cases where the threshold is exceeded there will be some benefit but the maximum BAS benefit may not be achieved until the pedal force reaches a level that corresponds to an un-boosted deceleration in excess of 6 m/s². It would be possible to improve the calculation model, at the cost of significantly increased complexity, but this would only be relevant to pedal force sensitivity systems. Therefore, as an approximate guide to the possible magnitude of this over-estimated benefit for pedal force sensitive systems, estimates of the relative effectiveness have been obtained for a BAS threshold of 5.0 m/s². These are compared with those for the baseline estimates for a 4.0 m/s² BAS threshold, in Table 13.22. It can be seen that, although the higher threshold does reduce the estimated benefits, the relative effectiveness is still well over 100 percent. Note that the change of threshold was applied to all cases, so the reduction is probably over-stated given the mix of different BAS systems on the road, as brake pedal force sensitive systems are less common than the brake pedal speed sensitive type.

The assumed rise times to reach the assumed constant braking decelerations, with and without BAS, have been set up to be independently adjustable within the spreadsheet. The rise in both cases is assumed to be linear. For the main results in Section 13.5 both were set to 0.3 s. This means that this phase of the braking has little influence on the final results, as the without-BAS back calculation to get the velocity at the start of the braking and the with-BAS forward calculation nearly cancel. When the BAS triggers there is some calculated BAS benefit in this stage as the with-BAS constant deceleration is greater so the rate of increase of deceleration also has to be greater. Nevertheless, it is only when different rise times are used with and without BAS that this phase of the braking may have more influence on the final results. In Table 13.23 estimates of relative effectiveness are compared for with-BAS braking rise times of 0.20, 0.29 and the baseline 0.30 s. The first value provides an indication of the benefits that might be obtained in the future if improved technology were able to enhance BAS by significantly shortening the rise time. It can be seen that there is a very significant increase in the benefits obtained, demonstrating both that the estimated benefits of BAS are very sensitive to the assumed rise time and that the benefits of real-world BAS will be very sensitive to how rapidly full braking can be achieved. The 0.29 s rise time represents a much more modest and therefore more easily achievable enhancement of BAS; this increases the relative effectiveness by a further 7 percent of the current phase two. These changed parameters represent idealised enhancements for calculation purposes; the possibilities for enhancements to BAS were discussed in Section 9.6.

Table 13.22: Comparison of the estimates of the relative effectiveness of each option that are obtained if the BAS threshold is assumed to be 5.0 m/s² and 4.0 m/s²

BAS threshold (m/s²)	Current phase two (%)	Industry proposal (including BAS) (%)	EC proposal (including BAS) (%)
5.0	100	158	166
4.0	100	174	182

Table 13.23: Comparison of estimates of the relative effectiveness of each option that are obtained if the with-BAS rise time is assumed to be 0.20, 0.29 s and 0.30 s

With-BAS braking rise time (s)	Current phase two (%)	Industry proposal (including BAS) (%)	EC proposal (including BAS) (%)
0.20	100	227	237
0.29	100	180	189
0.30	100	174	182

The results in Table 13.23 can also provide an indication of the possible errors that might have been obtained if the assumptions made for rise times were not sufficiently accurate. For small changes, the effect of an error in the average rise time without BAS is likely to be similar, but in the opposite direction, to the effect of an error in the average with-BAS rise time. Therefore, it is important to consider how the with and without BAS rise times will compare. Again, the real-world performance of BAS is likely to vary between the two main types of BAS. Typical rise times are not known for the brake pedal speed sensitive type of BAS but they could potentially reach maximum braking quite quickly, with a shorter rise time than in a vehicle without BAS, in which case the benefits could be greater than estimated. Also, the assumption of a 0.3 s rise time without BAS may be somewhat optimistic; if real-world rise times were closer to the 0.7 s assumed in the LAB study (see Section 9.4.1.2) then the benefit of the brake pedal speed sensitive type of BAS could be much higher than estimated. However, the brake pedal force sensitive type of BAS will normally have a longer rise time than in the without-BAS case, if the BAS is achieving an increased deceleration. This is because the presence of this type of BAS does not reduce the pedal travel required to achieve a given deceleration level; it only reduces the pedal force required. The assumption of equal rise times with and without BAS is probably a reasonable one when considering the likely mix of the two BAS types.

13.7 Discussion of cost-benefit study

It should be noted that the benefits in casualties saved shown in Table 13.7 are proportions of all pedestrians and pedal cyclists injured by all vehicle types. They are expressed in this way because the numbers of all pedestrian and pedal cyclist casualties are more easily available from national and international statistics, and can then be factored with the proportions given here to obtain estimates of casualty numbers that could be saved. However, for some purposes it may be more appropriate to have estimates of the benefits as proportions of the casualties currently injured by cars or by the fronts of cars that will be made safer. These can be obtained by effectively removing the proportion injured by cars or by the front of cars factor from the chain calculation. These proportions injured by cars and by car fronts were given in Table 13.3. Hence, the proportional reductions in those casualties hit by cars and by the fronts of cars, that would be obtained by implementation of the various options, were estimated and are shown in Table 13.24. Note that these proportions relate to all cars and all car fronts. The proportions would be slightly higher than shown for the current phase two and for phase one plus BAS options, if only cars within the scope (i.e. ≤2.5 tonnes) were considered.

Table 13.24: Estimated proportional reductions in numbers of those pedestrian and pedal cyclist casualties hit by cars and by car fronts, that would be obtained by implementation of the various options, by severity

Sample	Road user type	Current phase two		Industry proposal (including BAS)		EC proposal (including BAS)	
		Fatal	Serious	Fatal	Serious	Fatal	Serious
Those hit by cars	Pedestrians	0.095	0.189	0.157	0.249	0.164	0.263
	Pedal cyclists	0.045	0.079	0.098	0.121	0.102	0.128
Those hit by car fronts	Pedestrians	0.111	0.282	0.184	0.372	0.193	0.392
	Pedal cyclists	0.056	0.143	0.121	0.220	0.127	0.233

There are a number of factors that could lead to under or over estimations in a way that would influence the relative effectiveness estimates. It should be noted that this can occur in three main ways. Factors that over or under estimate the benefits of one secondary safety option compared with another will obviously affect the relative effectiveness. Also, factors that affect the estimated benefits of BAS will affect the relative effectiveness. Less obviously, any factors that affected the estimated benefits of the different secondary safety options in the same proportions would still affect the relative effectiveness, as the contribution of BAS to the relative effectiveness would be increased or reduced.

- As the baseline of the benefit analysis was cars designed without consideration for pedestrian safety, the estimates of benefits for all options include both the benefits of the first phase and the additional benefits of the second phase. The relative effectiveness estimates could have been expressed in relation to the *additional* benefits of phase two over phase one. Had they been expressed in this way the estimates would have been far more divergent from 100 percent. In the case of the principal estimate, of the EC proposal including BAS, the relative effectiveness would have been much higher if expressed in this way.

- Real world accidents tend to be much more variable than those considered in vehicle safety research. Many of the injuries in the accident data have been attributed to regions of the pedestrian's body that are different to the body part that was assumed when the test procedures were developed. In some cases these are not unexpected, such as chests injured by bonnet tops, but a few cases involve body regions that would not normally be expected to be injured by the part of the car concerned, such as a head injured by a bumper. As 'classic' bonnet leading edge injuries (femur and pelvis) have been greatly reduced with modern car designs a high proportion of these injuries will be to other body regions. The simplifying assumption used in the analysis is that injuries to all body regions that are caused by tested areas are potentially saved, subject to vehicle speed and injury risk considerations. However, designing the vehicle to pass a test procedure that uses a simulated body part involves tuning the stiffness, crush depth, etc. of the vehicle to that body part. The vehicle would therefore not be tuned to provide best protection for some of the other body regions. Also the injury risk curves used would not apply to a different body part. Therefore, some of these other body part injuries will not be saved in real world accidents. Other body parts may be over protected, with a lower injury risk than expected, but on balance the overall secondary safety benefits will probably be overstated on this account.
- Some of the pedestrians hit by existing cars will not have been injured and therefore will not appear in the accident data. However the injury risks curves give the proportion that would be expected to be injured of all those hit, not just of those currently injured. By applying injury risks to casualties in the accident databases the benefit study may have overstated the benefits. This can be illustrated with a simple example, ignoring complications such as impact speed, injury severity or risks to multiple body regions. If, of 100 impacted pedestrians, 90 percent are currently injured and a test procedure will ensure a 20 percent injury risk then there will be 90 current casualties of which 80 percent or 72 will be predicted (by the benefit calculation) to be 'saved' by the test procedure. However, it would be more accurate to say that 80 percent of those hit would not be injured, i.e. 80 pedestrians, of which 10 would be those uninjured with current cars and 70 would have been 'saved' (i.e. 2 fewer than estimated by the benefit calculation). In practice, the accident data available do not record those not injured so it would be difficult to avoid this inaccuracy.
- The assumption in the benefit calculation that the injury risk remains constant from the transition speed down to very low speeds will be unduly pessimistic. However, other aspects of injury risk variation by speed, such as the assumed 5 km/h manufacturers' margin, could cause errors in either direction.
- The simplifying assumption used, that whether or not injuries received (caused by tested area within survivable speed range) would be prevented, depended on a value given to the 'strength' of a casualty. This effectively means that if the 'strength' was high enough to allow the casualty to survive impact to the test area with the highest injury risk then the casualty would also survive impacts to all areas with a lower injury risk. In reality additional injuries in the accident case would reduce the probability that all injuries and hence the casualty could be 'saved'.
- The calculations have assumed that the test impactors and procedures were fully developed so as to simulate adequately that part of the pedestrian impact, with measurements corresponding to all injury modes. However, all the current impactors have limited biofidelity and measurement capability. The lower legform, for instance, monitors the risk of upper tibia fracture in a bending mode by measuring tibia acceleration rather than bending moment; also, it would not detect a high risk of femur or lower tibia fracture. It follows that vehicles developed using these impactors may not be optimised for maximum protection or may not protect against some injury modes, so that the injured saved in this calculation may be over estimated.
- It was effectively assumed in the calculation that injuries in the accident database occurred at random across the width of the bumper and bonnet leading edge, and over the surface of the

bonnet top. In practice the areas that are likely to be in the nominated relaxation zones are some of the areas that are particularly injurious on current 'unsafe' cars. Therefore, these areas will be over represented within the injuries in the accident database. It follows that the calculation will have assumed too high a proportion of injuries were in the higher safety zone and over estimated the injuries 'saved'.

- Benefits from preventing head injuries will be over-stated as the injury risk curve used is for AIS 4+ injuries rather than AIS 2+.
- Possible secondary safety benefits in non-frontal accidents were not considered due to lack of time. While, in theory, no benefit would be expected in such accidents, as the pedestrian would not be expected to be hit by the tested area, in practice benefits would have been obtained in some cases, as the use of the CDC parameter does not provide a reliable way of distinguishing these accident types. This would have reduced to some extent the large increase in benefits obtained by considering the benefits of BAS in non-frontal accidents.
- The financial benefits of preventing slight casualties may be over-stated for vulnerable road users, because the casualty cost used includes a high cost element due to whiplash type injuries to car occupants that are frequently recorded as slight injuries in the GB national data.
- As was shown in Section 13.6, the relative effectiveness was affected by a number of the decisions made:
    - Use of GB rather than GIDAS pedestrian to car frontal cases proportion of all pedestrian to car cases
    - Use of additional fatality cases from the IHRA dataset
    - Use of 'k' value of 1.0 rather than value of 0.8 supported by some experts and used in the TUD benefit study
- The benefits estimated in the BAS calculations are very sensitive to any systematic errors in the estimated actual mean braking deceleration and in the estimated maximum braking that would have been available in a BAS equipped car (see Section 13.6). There will be uncertainty with both of these estimates and the benefits in any accident case depend on the difference between these two values. While the potential benefits may be lower than estimated in the cases where braking was detected there may also be cases where braking occurred but was not detected, which would add to the benefits obtained.
- The benefits estimated to be obtained from BAS are very sensitive to the assumptions made about the shape of the deceleration time history, such as the rate of the rise to the full deceleration obtained in both the with-BAS and without-BAS calculations (see Section 13.6). The calculation used was relatively simplistic. The type of BAS that triggers on the pedal speed probably gives a response similar to or better than that assumed. However, the dual boost type may have a longer rise time than that assumed, because greater pedal travel would be required to reach the higher deceleration obtained.
- The BAS calculation assumes that the ABS deceleration is reached in all cases where the BAS threshold is exceeded. However, with the dual boost type of BAS, cases where the threshold was exceeded by a small amount would not reach the ABS deceleration.
- Driver response factors may reduce the BAS benefits, such as drivers 'backing off' when the deceleration obtained exceeds what they expected.

Some of the above factors concerning BAS were discussed in more detail in Section 9 and in particular in Section 9.4.1.1. BAS are also discussed further in Section 13.7.1.

A cost to benefit ratio was given for the EC proposal in Table 13.15. It could be seen that this estimate was very favourable to the protection of vulnerable road users. However, it should be noted that this estimate has a degree of uncertainty attached to it. The estimates of injuries saved are sensitive to some of the assumptions made about how well cars, that are designed to meet the test procedures, will protect vulnerable road users from injury. On the cost side, also, there are uncertainties about how much the protection required will cost. Indeed, there can be no exact cost for protecting vulnerable road users, as it depends on how the manufacturer makes engineering compromises between the various demands on the car design.

There are a number of factors that could lead to either under or over estimating the cost to benefit ratio. Many of those affecting benefits are in the list above, and are therefore not repeated. The following are additional factors that affect the cost-benefit ratio:

- Casualty costs reflect the wealth of those that they are obtained for. With greater wealth people are prepared to spend more to avoid injury or death, and values for lost output will also be greater. The casualty costs used were for Great Britain. These are up-rated annually according to the increase in GDP per capita. These will be approximately correct when extended to the EU-15, but with the recent expansion to the EU-25 the values used will be higher than a wealth-adjusted casualty cost would be. Moreover, with higher casualty rates per 100,000 population in the new member states, the adjusted casualty costs would be lower still if weighted by casualties rather than by population.
- The costs obtained from Table 12.2 relate to production costs only, although in this section they have been converted to consumer costs for the cost-benefit study. Menard Engineering Limited mentioned fuel economy and insurance issues, but no costs were provided for these aspects. It is debatable as to what these aspects might add to costs.
- The consumer costs would arise when a car is purchased, but the benefits may arise several years later. With a 10-year life of a car being fairly typical, the benefits would be obtained on average about 5 years later. These future benefits could be discounted back to the time of purchase, which would reduce their value at that time.
- No account has been taken of the known long-term downward trend in pedestrian casualties. This has been occurring in the EU-15 countries as a whole over at least the last three decades. It is likely that pedal cyclist casualties are behaving similarly. However, information is not to hand as to what the trend is in the EU-25; it may be with the high accident rate in the new member states that the current trend is upward. However, even if this is the case it is likely that in time the new members will conform more to the accident pattern of the older members.
- There is also a long-term upward trend in the number of cars sold, which would add to costs proportionally. On the other hand, increasing wealth (in excess of inflation) increases casualty costs and hence the benefits from saving casualties.
- The costs included did not include the cost of BAS.

Given how favourable the cost to benefit ratios are, it is very unlikely that the above factors could have made a significant difference in demonstrating that the proposed phase two protection requirements are justified financially.

In the benefit tables and the analysis used to produce them, the baseline for all the estimates was car designs that were being made a few years ago and that therefore appear in the accident data. These were cars designed with virtually no thought to pedestrian safety, and without BAS. Because of the inevitable lag between car sales and the accidents they are involved in, these baseline cars are no longer exactly the same as current cars. Some changes not intended to protect pedestrians may nevertheless be of benefit. There are increasing numbers of cars on the road with some measure of pedestrian protection and that have scored well in Euro NCAP tests. These changes in current cars will reduce the future benefits that will be obtained by any of the test proposals for phase two. This will also reduce the relative effectiveness of these proposals as a proportion of the current phase two benefit. However, the difference between these proposals in absolute terms (casualties or financial) with be roughly the same.

This report is an input into the wider discussions as to what could replace the phase two requirements of the current pedestrian protection Directive and associated EC Decision. Benefits of the EC proposal are compared with those of the current phase two. For the BAS benefit estimates in the current study, the baseline has therefore been taken to be the situation as it was when the current

Directive was first being developed. This was before BAS were fitted to new cars and, therefore, the estimates for the benefits of BAS in this study have all been for a change from a zero fitment rate to a 100 percent fitment rate.

It should be stated that all of the results given are subject to a degree of uncertainty as virtually all of the analysis is based on assumptions that are very simplistic compared with the real world. The same is true of the accident data used in the analysis. Much of the precision with which results have been transferred from the spreadsheet is therefore spurious. However, if the results had been rounded to adequately reflect the uncertainty it might have been more difficult to compare different options. As was stated in Section 9.4.1.1, though, it is considered that the accident data used for the BAS benefit calculation cannot be justified in strictly scientific terms. The uncertainties associated with the BAS data are therefore considered to be somewhat greater than with the rest of the data and analysis.

The most important result of the current study is the effectiveness estimate for the EC proposal relative to the benefits of the current phase two, see Table 13.13. The EC proposal, with BAS, gives greater benefits than the current phase two, with an estimated relative effectiveness of 182 percent of the current phase two. This implies that brake assist systems are capable of ensuring the levels of safety required and the recommendation is therefore strongly made that brake assist systems should be mandated as part of a replacement for the current phase two requirements. However, the comments above concerning the BAS benefit estimates should be taken into account.

13.7.1 Further discussion of the benefits of BAS

The benefits estimated for BAS here have been based on an idealised braking deceleration time history. The assumptions made do not correspond to the real world performance either of BAS or of drivers without BAS. Comparisons between the real world and the calculation method are complicated by there being at least two different BAS types in common use. Some consideration was given in Section 13.6 to the sensitivity effects of two parameters used in the calculation, the assumed BAS threshold and the braking deceleration rise time. The characteristics of most brake pedal force sensitive systems are probably poorer than the assumptions made in the calculation. However, it does not follow that these give lower benefits than were estimated as typical drivers without BAS may not match the assumptions made either. It seems likely that the more common brake pedal speed sensitive type will typically perform better than the assumptions made, though this is not confirmed. Overall, current BAS on average probably perform comparably to the assumptions made. It should be considered whether this is adequate or whether it is desirable for most or all systems to match the assumptions made in the calculation. However, care is needed as changing the characteristics of BAS to increase the theoretical benefits may increase the risk of unintended consequences. Further research may be required to fully understand all of the factors that are relevant in order to optimise the various systems.

Although many car models that are currently in production are fitted with BAS, it should be noted that ACEA have said that many of these would not pass the proposed test procedure that was discussed in Section 9.5. It is understood that many would have a boost ratio that was too low. Such systems would still offer benefits to vulnerable road users, but other things being equal the benefits would be lower than with systems complying with the proposed test procedure.

Many of the tables in Sections 13.5 and 13.6 give estimates for secondary safety only (the ‘no BAS’ rows) and for the combination of secondary safety and BAS (the ‘BAS fitted’ rows). If, for whatever reason, it is considered that the benefits of BAS have been over-estimated here, an alternative estimate can be obtained by interpolating between these two rows. For instance, an estimate for the combination of secondary safety with half of the estimated BAS benefits could be obtained by taking the average of the values from the two rows.

There are a number of additional benefits from brake assist systems that have not been quantified here. By reducing vehicle speeds the driver will have more time to take additional avoiding action such as steering. Similarly, the pedestrian will have more time to finish passing in front of the vehicle or to take active avoiding action. The benefits of brake assist will apply to all parts of the car, not just the tested area. More than this, the pedestrian's speed after the vehicle impact will also be reduced by BAS, so ground injuries will be reduced.

In summary, the key advantages and disadvantages of providing vulnerable road user protection by using BAS rather than by secondary safety means are:

Advantages:

- Impact speed and hence injury risk can be reduced, irrespective of what part of the car hits the vulnerable road user.
- The vulnerable road user will be thrown forwards at a lower speed and will therefore have a lower risk of ground contact injuries.
- Some impacts will be avoided and hence there will be no injury.
- The car will take longer to reach the vulnerable road user, giving more opportunity for them to avoid each other.

Disadvantages:

- Protection is dependant on the driver's braking behaviour; no benefit is obtained if the driver fails to brake before the impact.

13.7.2 Changed estimates from previous cost-benefit studies

The estimates made in cost-benefit studies such as this one can be sensitive to many factors, so that estimates can differ quite markedly from study to study. It is useful to be able to account for the reasons for these differences, if only to assist in avoiding mistakes in the calculation. The original feasibility study (Lawrence *et al*., 2004a) contained the following comparison with a previous study by the authors:

> The benefits in Euro estimated for the European Union have increased by 134 percent (i.e. a factor of 2.34 times) since the previous study (Lawrence *et al.*, 2002). It is instructive to identify the reasons, using the EEVC (i.e. current phase two) option as this is the only comparable option between the two studies. Changing from the EU-15 to the EU-25 has added 59 percent to the benefit, because of the high accident rate in many of the newly joined countries. Including pedal cyclist casualties has added 21 percent and allowing for under-reporting rates 16 percent. A modest 9 percent increase in casualty costs in UK pounds has been offset by an -8 percent change in benefits due to the movement of the exchange rate. These factors together would account for 124 percent of the increase, if it is assumed that they act independently.

Differences between Lawrence *et al*. (2004a) and the extension study (Hardy and Lawrence, 2005) are explained in the latter report.

The following changes were made between the extension study and this current update study. As the relative effectiveness of the EC proposal with BAS is the key result, its values after each change and the percentage changes, *relative to previous stage*, are given for each stage. These changes are not necessarily independent so the size of the changes may depend on the order in which these changes were applied.

Hardy and Lawrence (2005): 117 percent – starting point

1. Updating EU fatality data (from IRTAD and CARE websites), updating casualty costs, updating exchange rate: 117 percent, no change
2. Changing BAS threshold from 6 m/s² and 4 m/s² (averaged later in calculation) to single 4 m/s² value (advised by ACEA): 124 percent (+6 percent)
3. Adding extra 137 pedestrian to car front cases from the GIDAS database (this also increases the GIDAS proportion in the fatality sample): 126 percent (+2 percent)

4. Removing two 'fatalities' from the three 'fatality' case in the IHRA dataset: 131 percent (+4 percent)
5. Minor refinement to BAS calculation to allow for the change in the constant deceleration braking length between the with-BAS and without-BAS cases: 133 percent (+1 percent)
6. Addition of benefits of BAS in non-frontal accidents: 170 percent (+28 percent)
7. Adding assumption that EC proposal would cover all cars, whereas the other test options exclude roughly 2½ percent of cars that are >2.5 tonnes maximum mass: 174 percent (+3 percent)
8. Correction of a previous oversight that used slight casualty numbers without the adjustment to include non-reported accidents: 182 percent (+5 percent)

It can be seen that more than half of the total change has been from the inclusion of benefits from BAS in non-frontal accidents. These benefits were not included in the previous study as the necessary accident data were not available at the time. As has been stated previously, these non-frontal accident benefit estimates are sensitive to the data used to obtain the frontal proportions, and would have been significantly less if the frontal proportions had been taken from the GIDAS database.

13.7.3 Summary table

Table 13.25 brings together many of the most important results that were presented and discussed previously. It can be seen that the full EC proposal, including BAS and an increased scope, has a relative financial effectiveness of 182 percent of the current phase two. Potential for further benefits to be obtained by using enhanced BAS is also indicated.

Table 13.25: Summary of estimated benefits of the current phase two and the effect of proposed and possible longer term changes on these benefits

		Fatalities reduction		Serious casualties reduction		Financial effectiveness	
		(no.)	(%)	(no.)	(%)	(€ million)	(%)
Current phase two requirements		626	100	32,246	100	4,855	100
After changes made to:	Bumper test zone	605	97	30,333	94	4,599	95
	Head test zone	378	60	30,904	96	4,207	87
	BLE test zone	626	100	26,620	83	4,228	87
EC proposal for passive requirements		357	57	23,459	73	3,334	69
Additional benefits from BAS		743	119	21,927	68	5,294	109
EC proposal including BAS		1,100	176	45,386	141	8,628	178
EC proposal including increase in scope		1,128	180	46,550	144	8,849	182
Indicative future benefits with enhanced BAS	with slightly shorter rise time (0.29 s)	1,175	188	47,841	148	9,175	189
	with much shorter rise time (0.2 s)	1,514	242	57,046	177	11,509	237

14 Discussion of possibilities and other issues

There are a number of concern that should be considered before phase two of the Directive is introduced. These include:

- possible improvements to the test methods and their protection criteria
- are the costs of providing the protection justified by the potential savings in seriously and fatally injured casualties?
- is it feasible to provide the level of protection required in phase two within a functioning vehicle?
- if not, what should the test requirements be to obtain the optimum balance between feasibility and the protection of vulnerable road users?
- will the requirements be unreasonably restrictive to certain vehicle types or scales of production?

Most of these issues have been studied in depth in the preceding sections of this report.

A number of improvements to the test methods have been identified, the most significant of which are a heavier child headform impactor, revised upper legform test energies and new or reduced tolerances on test conditions. These changes will mean that the protection required will be more appropriate and it is thought that all the changes will make it easier for car manufacturers to achieve compliance.

It has been concluded that, although meeting phase two of the Directive might be feasible for some types of vehicles, overall it would be unduly restrictive and is therefore not feasible without some modifications. Therefore a number of changes to phase two of the Directive were proposed in the original feasibility study (Lawrence *et al.*, 2004a) and these changes were based on data and observations on feasibility issues provided by:

- the European car industry in a series of face-to-face meetings and in documents provided following these meetings.
- the associations of European and Japanese car manufacturers.
- a response was also received from the Korean association of car manufacturers, however they had no comments on phase two of the Directive.

In addition, current cars with good pedestrian protection were examined and the author’s experience gained over a number of years work in the field of pedestrian protection was also used to consider feasibility issues.

The draft GTR includes many of the recommendations made by Lawrence *et al.* (2004a) and the only significant difference between the GTR and the proposals by Lawrence *et al.* (2004a) is the lower headform test speed but this is compensated for, to some extent by the more demanding protection criteria in the GTR. Utilising the GTR for a revised phase two of the Directive represents an opportunity to harmonise with this draft global technical regulation and also meet the car industry’s concerns about the feasibility of meeting the present requirements. Consequently, the authors recommend that the option of using the GTR as a basis for a revised regulation should be considered and understand the Commission are considering this along with other options such as extending the scope of the legislation to include larger vehicles.

14.1 Protocol for deployable (contact or pre-contact) systems

As discussed in Sections 8 and 10, it is thought vital that the deployable systems work reliably and in an appropriate way in all combinations of pedestrian accidents. ‘Appropriate’ here may mean not operating in all high speed accidents. As already discussed, test methods and tools to assess the performance of the pedestrian accident detection system used to trigger such a device must be appropriate for the human property or properties that the technology detects and the assumptions in the algorithms that are used to determine if contact with a pedestrian has started or is about to occur. A further assessment programme is necessary to ensure that once triggered the system deploys safely, reliably and in time for all combinations of accident situation, or not operate if appropriate. Again, such a programme must be matched to the deployment system used.

Ideally all this could be achieved by requiring that the system be examined by following a well-defined evaluation programme.

However, because the first two stages of this process must be matched to the solution used and very different solutions and combinations of technologies could be used in deployable systems, it is not possible to have a clear-cut assessment method. Therefore, it is recommended that a generic protocol be developed and used to assess deployable systems.

Then, once a complete system has been shown to work as intended, the protection that it offers can be assessed by testing it in the deployed position using the tests described in phase two of the Directive, linking as necessary the timing of the deployment and pedestrian test impact. However, depending on the size, location and method of operation of the deployable system some additional rules may be needed in the phase two test methods to, for example, select appropriate test areas and test locations. This is because a vehicle with active system(s) will effectively have two or more shapes, and also gaps at the edges of the deployable system. Some guidance for marking the bonnet top test area for pop-up bonnets has been given in Section 10; however, there may be a need to develop further rules as new technologies are developed.

A prototype sensor legform has been developed as part of this study. This legform is intended for testing a bumper to leg contact sensor. The sensor legform is described in Section 7 and it is thought to be a good starting point for developing an impactor for a bumper contact switch / force type sensor system, however, it would need far more development before it could be used to approve such a trigger system.

Some guidance on what should be included in a general protocol has been provided in Section 10 and a more detailed protocol was proposed by Chinn and Holding (2003) in their guide to assessing active adaptive secondary safety systems. Car manufacturers (Organisation Internationale des Constructeurs Automobiles (OICA)) and their first tier suppliers (European Association of Automotive Suppliers (CLEPA)) have produced a ‘certification standard’ (OICA / CLEPA, 2005) for this purpose. Although marked as ‘draft’ it is understood that it was intended to be the final version at that time; the marking is intended to indicate that it will need updating for technical progress such as different sensor technologies. However, it appears to need further work to expand the standard. For example, it only requires the trigger system to be tested with the adult legform. It does not include a test to see if the system will trigger as intended with smaller pedestrians, who may need a lower trigger threshold.

Deployable systems appear to offer many advantages over conventional passive protection measures; however, it is thought that a flexible approach will be needed in the methods used to show:

- that they work reliably and in an appropriate way in all combinations of pedestrian accident,
- that they provide appropriate protection when deployed.

14.2 Small series production

Passenger cars built in small series can currently be granted derogations on a discretionary basis by the Member States, provided they were registered in their territory. However, a proposal for a Directive (Commission of the European Communities, 2003) includes a new procedure for verifying the conformity of a small series vehicle by means of simplified tests or by comparison with tests carried out on similar vehicles, without there being a need to undergo the entire type-approval procedure.

The proposal states "The concept of the European small-series procedure is based on a simplified administrative process, and not on a lowering of the safety or environmental aspects; the manufacturer may demonstrate, in a limited number of cases, compliance with the requirements of a regulatory instrument by himself producing evidence or test reports, subject to the agreement of the approval authority."

In the case of pedestrian protection it may be difficult to demonstrate compliance using the methods proposed. It may also be difficult and unduly expensive, for manufacturers that only make cars in small series, to develop a vehicle that provides in full the safety standards required for pedestrian protection. Therefore, it is recommended that some consideration be given to just requiring manufacturers who exclusively produce cars in small series to demonstrate that they have paid due care and attention to pedestrian protection, by, for example, providing sufficient crush depth and a stiffness that is approximately appropriate.

14.3 Vehicle parts not covered by phase two

The IHRA Pedestrian Safety Working Group have shown an interest in including the A-pillars and roof leading edge in the adult headform test zone. At the moment, there is no feasible method of reducing the resulting HPC to less than 1000; therefore it is currently unfair to require this of manufacturers through legislation. However, by the time of the commencement of phase two of the EC Directive, protection may be available. Therefore it is recommended that some consideration be given to introducing a review, at some time in the future, to consider the feasibility of adding a requirement to test these areas.

15 Conclusions

1. The original feasibility study and cost-benefit analysis carried out for the European Commission (Lawrence *et al.*, 2004a) has been consolidated and updated to produce this new report.

    a. The scope of this update includes taking account of the draft GTR and, as far as is possible, more recent data.

    b. The updated cost-benefit analysis compares the benefits of the current phase two requirements with those of phase one plus brake assist and what the authors understand to be the EC proposal for phase two which also includes brake assist.

    c. The Directive requires that if, as a result of the feasibility assessment, it is considered necessary to adapt the provisions of phase two, to include a combination of passive and active measures, it must achieve at least the same level of protection as the existing provisions of phase two. Further work has led to the conclusion that the present proposal for revising phase two, which includes the active measure of brake assist, achieves – and is likely to exceed by a considerable margin – the requirement of "at least the same level of protection" of the Directive. Since TRL's original proposals (Lawrence *et al*. 2004a) did not find any support from the experts in the area, they are no longer pursued and therefore this report only considers the costs and benefits of the present proposal. Accordingly, this document brings together the present levels of understanding, thus providing an evaluation of the present position vis-à-vis phase two of the Directive.

2. The original study of alternative test methods (Lawrence *et al.*, 2004a) has been updated to take into account new data and the current understanding with regard to feasibility issues and a number of recommendations have been made for revising phase two of the Directive. The main recommendations were:

    a) If the EC proposal, as defined herein, is accepted as the basis for legislation to replace phase two of the current Directive (2003/102/EC) then the following are recommended:

        (i) Those parts of the proposals by Lawrence *et al.* (2004a) that were regarded as improvements to the test procedures, rather than feasibility adjustments, should also be included in the revised test procedures.

        (ii) The bonnet leading edge test should at least be retained as a monitoring only test.

        (iii) The changes to the second phase should be kept under review with regard to real-world injuries caused by the bonnet leading edge of cars meeting phase one or phase two requirements for the bumper, once sufficient accident data are available.

    b) It is thought that it may be beneficial to have two tibia accelerometers fitted to the lower legform test tool; however, this is not recommended for phase two of the Directive, as more research is needed.

    c) It is recommended that permanent towing eyes be set back by at least 150 mm from the front face of the bumper.

    d) Although the bonnet leading edge test is aimed at protecting the adult male it could also be effective in providing some protection for smaller adults and children.

        (i) Nevertheless, given the level of criticism of this test method and the feasibility issues of meeting the protection requirements it is recommended that more work should be carried out in this area.

        (ii) It is clear that a better understanding of the bonnet leading edge contact is needed to refine or replace the current test.

(iii) In the mean time it is therefore considered more prudent to retain the current test for monitoring purposes rather than leaving a potentially significant load path with no future protection requirement.

3. The main differences between the current phase two requirements and the draft GTR have been summarised and discussed and the following observations and recommendations have been made:

   a) The most significant difference is that the draft GTR proposes a head test speed of 35 km/h whereas the current Directive’s phase two requirement is 40 km/h. However, the effect of the reduction in velocity on protection will be smaller than might be anticipated due to the manufacturers’ standard practice of exceeding regulatory protection requirements by about 20 percent.

   b) It is recommended that a definitive study be carried out to determine what range of bumper heights the lower legform impactor is appropriate for. Until this is done a well justified high bumper definition cannot be produced.

4. A number of options to extend the scope of the Directive to include larger vehicles have been identified and potential problems in using the test tools and methods, for vehicles they were not necessarily designed for, have been discussed.

   a) It has been suggested that problems in using these rules are almost certain to be found when they are used on larger vehicles.

   b) It would, therefore, be essential to undertake a study of large vehicles to develop workable new rules for the current test methods to be applied to large vehicles.

   c) Ideally, new test methods and rules should also be developed for these larger vehicles.

5. A study has been made of new technologies that might be used to avoid a pedestrian accident or mitigate its effects in terms of injuries. One technology was identified, pop-up bonnets, as already being used on certain new vehicles in order to meet phase one of the Directive. The following observations were made with regard to this system.

   a) Test of a pop-up bonnet system on a mule vehicle, showed that it deployed the bonnet as intended and was fully deployed before the predicted pedestrian head contact.

   b) Testing of the deployed system on a mule vehicle showed that it provided considerable benefit over the original vehicle and passed the phase two Directive head protection requirements in many places despite using the original vehicle bonnet which had not been optimised for this use.

   c) Testing with pedestrian dummies by Fredriksson *et al.* (2001) showed that the pop-up bonnet system tested remained in a raised position until the head impacted the bonnet. This confirmed that the lifting mechanism could support the torso of a pedestrian for the required period as opposed to sinking before the head impact occurred.

   d) Testing of a bumper with a trigger system for a pop-up bonnet show that it is important to use a trigger test tool that is appropriate for the detection system being used.

   e) It is thought that, by their nature, there is likely to be less confidence that pop-up bonnet systems will always work as intended compared with protection by vehicle deformation. Pop-up bonnets are also likely to have higher costs. Therefore, for both cost and confidence reasons it is thought that pop-up bonnets solutions would not applied to the whole fleet but instead would normally be reserved for sport or executive type vehicles where simpler vehicle deformation solutions are not practical due to restricted crush depth.

6. A study of brake assist has been carried out and the conclusions were:

   a. There is evidence that BAS will have a beneficial effect on accidents generally and pedestrian accidents specifically. However, there is still uncertainty with respect to accurately quantifying the magnitude of that benefit.

b. The evidence available suggests that it is reasonable to assume that BAS will result in a reduction in pedestrian fatalities of greater than zero and less than 12 percent. Within this estimate it is likely that the true answer will lie somewhere in the mid-range of values. However, it must be noted that with the data currently available, any estimate of benefits that aims to produce a more specific single answer within that range will carry a substantial risk of either under or over estimating the real benefits of the system in pedestrian accidents. Further accident research will be required in order to increase confidence in the results and to narrow the range of benefits that can be confidently predicted.

c. A variety of different brake assist systems are currently available and there are at least two fundamentally different operating principles. No published research was identified that compared the effectiveness of different brake assist systems with different operating principles or different activation thresholds.

d. The only BAS test procedure identified, for inclusion with the other test procedures, was that proposed by ACEA. Only two variants of the brake assist system were covered within the scope of that procedure and these were treated as being equally effective, which is not proven. The procedure only enforces a minimum standard for one aspect of performance (minimum amount of brake boost over and above demand). Performance in relation to the emergency detection criteria or the trigger thresholds was not considered for speed sensitive devices and was not worded as compulsory for force activated systems.

e. A range of values within which the trigger threshold must lie could be added to the procedure for pedal speed activated systems in order to make it more robust and the procedure for force activated systems could be re-worded to enforce the range of forces already quoted. This could be implemented almost immediately. Further research could compare the effectiveness of different brake assist systems with different operating principles in order to find optimal operating conditions. This information could potentially be used to develop an enhanced BAS test procedure that ensured a higher standard level of performance in service than exists now, thus potentially offering greater benefits than the current mix of systems. This could be implemented in a relatively short time frame.

f. In the long term, enhanced brake assist and collision mitigation systems could offer further benefits to pedestrians but these systems still require considerable research and technical development before they can be proven to be effective and reliable pedestrian protection systems.

7. The original review of technical restrictions by Lawrence *et al.* (2004a) has been updated and the most important inclusions are:

a. Sub-systems tests do not take account of an earlier contact which might in some circumstances compromise protection intended for a later contact. This may be of particular concern for pop-up bonnets which are very likely to be more poorly supported than conventional bonnets. Therefore a protocol, to determine if deployable systems work as intended, should include an assessment of the risk of earlier contacts compromising protection for later contacts.

b. The situation regarding the lateral knee joint bending stiffness has been discussed and the authors have concluded that EEVC WG17 requirement is more appropriate to represent the living human than the lower stiffness selected for the Flex-PLI legform impactor. Nevertheless, if a lower stiffness is chosen for a new regulation then this would have consequences for feasibility. A sensitivity study appears to suggest that reducing the knee stiffness would make it far more difficult for manufacturers to meet the protection requirements. Therefore before any changes to the knee bending stiffness are made it is recommended that a study of the effects on feasibility be carried out.

8. Guideline manufacturing costs for the ‘EC proposal’ have been produced by selecting slightly different combinations of costs from the earlier feasibility study and these guideline costs have been used in the updated cost-benefit study.

9. An updated cost-benefit study has been carried out and the conclusions were:

   a. The financial benefits estimated for the secondary safety elements of the Industry and EC proposals, and including consideration of BAS and for the latter proposal an increase in scope to cover heavier vehicles, as a percentage of those of the current phase two, are 174 percent and 182 percent respectively.

   b. BAS offers significant benefits to many vulnerable road users. Whereas the passive safety measures cannot protect against injuries caused by the ground or by non-tested areas, BAS can reduce the impact severity and hence injury risk for all contact areas.

   c. BAS can also provide significant benefits in non-frontal impacts. The estimated indicative financial benefits of BAS in non-frontal impacts, for the EC proposal, corresponded to 37 percent of the financial benefits of the current phase two.

   d. Current BAS cannot provide any benefits in the roughly half of pedestrian accidents where the driver was unable to brake before impact.

   e. The estimates of the effectiveness of BAS are for a change in the fitment rate of BAS from zero to 100 percent.

   f. It is recommended that if fitment of BAS becomes part of a package of changes to the phase two requirements then minimum standards for BAS should be agreed.

   g. It should be noted that the estimated benefits of brake assist systems must be regarded in the light of the uncertainties discussed, as insufficient data have as yet become available to accurately gauge their benefits for vulnerable road users. Nevertheless, brake assist systems are capable of providing valuable additional benefits for pedestrians and other road users. The recommendation is therefore strongly made that brake assist systems should be mandated as part of the package of requirements for phase two.

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IRTAD: www.bast.de/htdocs/fachthemen/irtad//english/irtadlan.htm

JASTI Co. Ltd.: http://www.jasti.co.jp

Mazda: www.mazdausa.com

Mitsubishi: http://www.mitsubishi-motors.com/corporate/about_us/technology/safety/e/abs.html

Nissan: http://www.nissan.co.uk/home/common/glossary/index.html

PSA Peugeot-Citroen: http://www.psa-peugeot-citroen.com/en/afternoon.php

Renault: www.renault.com

S•Tech Co. Ltd.: www.s-techinc.co.jp

TRW: www.trw.com

UNECE:

> **GRSP (Working Party on Passive Safety)**: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grsp/grspage.html
>
> **Informal Group on Pedestrian Safety**: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grsp/pedestrian_10.html
>
> **Flex-PLI Technical Evaluation Subgroup**: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grsp/pedestrian_FlexPLI.html