Pedestrian protection test procedures and design: Final report
(April 1992 to March 1999)

Prepared for Vehicle Standards and Engineering Division,
Department of the Environment, Transport and the Regions

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Executive Summary

Pedestrian casualties form a large proportion of road user casualties in most developed countries. Car design measures can reduce the severity of pedestrian injuries and will also benefit many pedal cyclists and a small number of motor cyclists. The EEVC Working Group 10 produced pedestrian test methods and performance criteria in 1991. Initially, impact tests using a pedestrian dummy were considered. However, some significant disadvantages of pedestrian testing using dummies for regulatory purposes became apparent and sub-systems test methods were developed instead. The test methods proposed by EEVC WG10 consist of three test procedures to assess a car’s performance. These represent the three main phases of a pedestrian impact: the bumper impact at about knee height, the bonnet leading edge impact at about upper leg/pelvis height and the head impact with the bonnet top.

In this research project the test devices and the test procedures proposed by EEVC WG10 were evaluated and improved. An assessment was made of the headform test method and the original ‘research’ child and adult headform impactors. This revealed only one minor problem with the test method regarding the aiming for the selected test site. However, the research impactors, made from bowling balls, were found to require improvements to make them suitable for use in a regulatory test. An improved definition for the aiming of the headform impactor was produced to overcome the difficulty found. The impactors and test method were found to produce repeatable results with a Coefficient of Variation of less than 1.2%. Following this, TRL produced improved research impactors, which were used to evaluate four cars using the EEVC headform pedestrian head impact test procedure. A total of 52 headform tests were performed to four popular cars, with test sites over the full test area, including the wing tops, scuttle and base of the windshield. These tests showed that the level of pedestrian protection offered by the vehicles varied considerably on the same vehicle at different locations and from vehicle to vehicle, with the best points only just failing to meet the head injury criterion and the worst exceeding the criterion by a large margin. Details of the improved research impactors were provided to the company tasked with designing and producing production versions of the head impactors. These production impactors were still based on bowling balls, but with an improved flesh. Although these headform impactors were considered satisfactory for regulative testing and had been used for a large number of tests in many test houses throughout the world, they suffered from manufacturing and minor instrumentation, handling and durability problems. To overcome these problems the use an alternative cast plastic was explored with a revised accelerometer mounting. One example of the adult impactor was manufactured and this prototype impactor was assessed. Despite showing promise in most respects the impactor failed the to meet the certification requirements and it was decided to abandon development of this design. An alternative provisional design made from aluminium was produced. New production aluminium headforms with thicker PVC flesh are currently under development.

The upper legform impactor and test methods have been assessed and some problems have been found. These have been resolved by; developing an improved dynamic certification method; resolving a problem of an unintended load path in the upper legform impactor; developing a production version of the upper legform impactor suitable for use in legislative tests. In addition the provisional acceptance criteria values have been refined by reconstructing well documented pedestrian accidents and carrying out a statistical analysis of the results, the upper legform test energy look-up graph have been improved by developing and using a mathematical simulation model and an estimate has been made of the number of cars tested under the Euro-NCAP programme that would have passed the upper legform test had the new energies and acceptance criteria been used.

The original ‘research’ legform impactors and test methods were evaluated and problems observed have been resolved. Anthropomorphic data have been used to produce new targets for the mass, centre of gravity and moment of inertia for the simplified shapes of the tibia and femur impactor sections. A prototype legform impactor has been developed and assessed and it has been shown to meet the EEVC specification. Improved shear and bending certification tests have been developed. This prototype design has been used for a large number of tests in many test houses throughout the world. The only shortcoming found with this impactor was a lack of damping of the shear spring system; this aspect had been left for a subsequent stage of development. An experimental impactor with a damped shear spring system was produced and assessed and found to provide the required shear spring damping. The initial work on designing a production version of the damped legform impactor, suitable for use in legislative tests, was undertaken. An improved dynamic certification method was developed. A statistical analysis of the results of biomechanical tests was carried out to determine the risk of tibia fracture due to acceleration forces.

A cost benefit analysis for the proposed pedestrian protection test procedures and requirements was undertaken. The costs of implementing the proposed pedestrian impact test procedures were estimated by an independent vehicle design consultancy. The benefits to be derived from implementation of the test procedures were given in terms of the monetary values placed on the reduction in fatal and serious casualties resulting from vehicle design changes. In order to compare the costs with the benefits, the effect on casualties for all the vehicles produced in one calendar year were estimated over the mean life of those vehicles. The proportional reductions of fatally and seriously injured pedestrians resulting from the
implementation of the test procedures were derived from accident studies and test results. These estimates were revised slightly following comments on the report and the final predictions were a reduction of 8 percent of all fatally injured pedestrians and 21 percent of all seriously injured pedestrians. The benefit of these savings in pedestrian casualties was compared with the costs of producing safer vehicles and the benefits to cost ratio produced from these values was 7.1 : 1. This compares with the most recent alternative estimate by others which predicted much larger costs and larger benefits giving a final best benefits to cost ratio estimate of 1 : 1.7.

An initial study to assess the pedestrian safety of one model of off-road vehicle both with and without bull bars was undertaken. The areas of the body of a adult pedestrian likely to be contacted by the top tube of the bar are the upper leg, pelvis or abdomen while for the child pedestrian it is likely to strike the chest or head. The lower parts of bull bars also appear likely to increase the risk of injury to lower parts of the pedestrian’s body. The EEVC sub-system pedestrian test methods do not include impactors to represent all the pedestrian body parts at risk. However, they were considered the best existing method for this assessment. At the time of this part of the study only the upper legform impactor was available to TRL so only this was used for the assessment. It was concluded from these tests that the safety of bull bars should be assessed by impact tests and that a code of practice for bull bars manufacturers would not be effective. It was also concluded that it may be possible to make bull bars that improve the pedestrian protection of a vehicle.

The ISO and IHRA working groups are also developing pedestrian protection test methods, the test methods produced to date are, very similar to those of the EEVC.
1 Introduction and background

As part of their target to minimise road accidents, the Department of the Environment, Transport and the Regions has supported a continuing programme of research on pedestrian protection at TRL.

Pedestrian casualties form a large proportion of road user casualties in most developed countries. Car design measures to reduce the severity of pedestrian injuries will also benefit many pedal cyclists and a small number of motor cyclists. In Great Britain in 1998, of the 3,421 road users killed 31 per cent were pedestrians or pedal cyclists and of the 40,834 road users seriously injured, again, 31 per cent were pedestrians or pedal cyclists (Department of the Environment, Transport and the Regions, 1999). European accident data show that 6,593 pedestrians and 2,302 cyclists were killed in road accidents in the year 1998, in the fifteen countries of the European Union (IRTAD, 2000) and approximately 180,000 pedestrian and cyclists were seriously injured.

Historically, funded by the DETR, TRL undertook a large proportion of the research that has led to the current pedestrian protection test methods. Between 1988 and 1991, TRL chaired a European collaborative group, the European Experimental Vehicles Committee - Working Group 10 who produced proposed test methods and performance criteria (Harris, 1991). Initially, impact tests using a pedestrian dummy were considered. However, some significant disadvantages of pedestrian testing using dummies for regulatory purposes became apparent. The repeatability of test 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 impact progress. Also, 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 pedestrian’s stature as well as the position of first contact across the vehicle’s width and the pedestrian’s motion 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. For test methods intended for legislative use, as in this case, sub-system test methods would overcome these disadvantages. Sub-systems 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 to design for and model mathematically.
- They can be more easily used in component development.
- The test severity can be adjusted (e.g. energy cap) to take account of practical design limitations.

The test methods proposed by EEVC WG10 consist of three test procedures to assess a car’s performance using separate impactors. The three impactor types are: (i) a legform impactor representing the adult lower limb to indicate lateral knee joint shear displacement, bending angle and tibia acceleration caused by the contact of the bumper area, (ii) 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, and (iii) 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. For the bumper and bonnet leading edge the impactors have been chosen to represent those statures most easily injured by these vehicle feature which accident data shows are adults. The longer and heavier legs of adults require more protection than those of children so bumpers and bonnet leading edges that are safe for adults in impacts up to the test speed will normally provide protection effective at higher speeds for children.

Following the initial proposals, these test methods were evaluated and further refined by Working Group 10. TRL, under this DETR project, made a significant contribution to this work which was reported in the final report of EEVC - WG10 (EEVC, 1994).

More recently, again under this DETR project, TRL made a significant contribution to the work of EEVC Working Group 17 whose main task was to review and update the pedestrian protection test methods that had been developed earlier by EEVC - WG10. Working Group 17 was set-up in June 1997 and reported their revisions of the pedestrian test methods to the EEVC Steering Committee in late 1998 (EEVC, 1998). As part of a regulation, these test methods with appropriate performance requirements would require cars to achieve a certain level of safety in collisions with pedestrians.

Since the WG10 test methods were first produced in 1991, the European Community (EC) has been considering their incorporation in an EC Directive to require new cars to be less aggressive in accidents with pedestrians. The final report on the test methods developed by the EEVC - WG10 was produced in late 1994 (EEVC, 1994) and following this the working group was dissolved in November 1994. The test methods, with some revisions, were incorporated in a draft EC Directive in early 1996 (European Commission, 1996). In 1998, at the International Conference of Enhanced Safety of Vehicles (ESV), the representative of the European Commission made a commitment to put before Parliament a proposal for a pedestrian protection Directive based on the recommendations of EEVC - WG17. The approved EEVC report (WG17) was delivered to the European Commission in March 1999.

1 Now the ‘European Enhanced Vehicle safety Committee’
The aim of the research project ‘Pedestrian protection test procedures and design’ was to support the development of the EEVC pedestrian test methods and the adoption of these test proposals as an EC Directive. The project also supported the efforts of the working groups developing world-wide pedestrian test procedures. This was achieved by providing UK experts to participate in the meetings of two international pedestrian working groups under the auspices of International Organization for Standardization (ISO) and International Harmonised Research Activities (IHRA). The research project ‘Pedestrian protection test procedures and design’ commenced in April 1992 and was completed in March 1999. The work in this period is summarised in this final report.

The research project included:
- The evaluation and improvement of the test procedures.
- The assessment and development of the test tools.
- The reconstruction of accidents to obtain biomechanical data for the femur and pelvis contact with the bonnet leading edge acceptance values.
- A study of the cost and benefits of improved pedestrian protection.
- An initial study of the value of using a code of practice to improve the pedestrian protection of bull bars.

2 EEVC pedestrian test procedures: research summary and discussion

With one exception (bull bars) all research carried out under this project has been related to developing and supporting the EEVC test methods. Some of the topics have been addressed at different stages within the project, as progress has been made or international activities have given rise to the need for additional phases of work. Therefore, for each main area of work the research is summarised chronologically.

As already mentioned pedestrian protection test methods were developed by the EEVC - Working Group 10. Their mandate was to develop sub-system pedestrian test methods for car fronts, up to the base of the windscreen, which were to address pedestrian accident at 40 km/h. These test methods were to be suitable for use in vehicle safety legislation. The work of WG10 was started in 1987 and a report was produced in 1991 describing the test methods that had been developed (Harris, 1991). Harris (TRL) chaired the working group from 1987 until 1991. This phase of work was partially funded by the EC under a contract with a consortium of EEVC – WG10 members, including TRL. It was originally anticipated that the work would be complete at this stage. However, despite being essentially complete some values were provisional, the test methods had not been fully assessed and production versions of the impactors did not exist. Therefore, the working group continued until 1994, chaired by Janssen (TNO), when the final report (EEVC, 1994) was produced. In this period, the test methods and test tools were evaluated and refined and this work was used as a basis for an EU draft Directive in 1996 (European Commission, 1996). Lawrence (TRL) was a member of WG10 throughout.

On the request of the EEVC Steering Committee the former members of EEVC - WG10 met again, in May 1997, to discuss technical progress and new developments with respect to the EEVC pedestrian protection test methods. Following the meeting the EEVC Steering Committee decided in June 1997 to create a new EEVC working group: EEVC - WG17 Pedestrian Safety, with two main tasks:

a) Review of the EEVC - WG10 test methods as described in their final report (EEVC, 1994) and propose possible adjustments taking into account new and existing data in the field of accident statistics, biomechanics and test results (to be completed within one year).

b) Prepare the European contribution to the IHRA working group on pedestrian safety.

Lawrence, was appointed a member of EEVC - WG17 representing the United Kingdom and remains a member to date. Working Group 17 produced its report reviewing and updating the pedestrian test methods in December 1998, the EEVC Steering Committee approved this report in late February 1999 and it was delivered to the European Commission in March 1999 (EEVC, 1998). The review by the working group covered accident statistics, biomechanics and accident reconstruction, test results and simulations, impactors, input from other organisations and improvements to the test methods. The 1998 EEVC report completed Working Group 17’s task of reviewing the test methods, however, some minor items were still provisional. Since then the Working Group has worked to resolve these final issues.

Throughout the period of this project both EEVC Working Group 10 and Working Group 17 have reviewed and improved the test methods and impactor specification. As part of this task TRL have assessed the impactors, the test methods and the certification procedures. These assessments have identified many minor problems and TRL has produced suggestions to resolve these.

For both the 1994 and 1998 reports of WG10 and WG17 respectively TRL carried out systematic and detailed reviews of the test methods in order to identify and rectify problems. Nearly all the figures and diagrams in the WG17 revisions are new or have been up-dated; most of this work was undertaken by TRL. TRL hold the master copies of all the figures and diagrams in the test methods and has offered support in transferring them into EU documents.

2.1 Headform impactors and test method

Within EEVC Working Group 10 the research laboratory responsible for developing the head impact procedures and the original research headform impactors was the Bundesanstalt für Straßenwesen (BASt).

2.1.1 Progress with headform impactors and test method up to the final report of WG10 in 1994

2.1.1.1 Assessment of the original BAS/ research

headform impactors

TRL manufactured examples of the BASt prototype adult and child head impactors using information and materials...
supplied by BASf. TRL then carried out a programme of tests to evaluate the impactors and the bonnet top test proposals. TRL, in collaboration with BASf, also carried out a limited programme of development of the head flesh in order to meet the certification requirements. The TRL report (Lawrence and Hardy, 1993a) gave the results of this work and discussed the performance of the impactors and the test method, and it is summarised below.

An examination by TRL of the BASf prototype head impactors revealed that the seismic mass of the accelerometers in the adult impactor were all more than 30 mm from the centre of the sphere and the centre of gravity of the child headform impactor was 21 mm from the centre of the sphere. The offset of the centre of gravity of the impactors from its geometric centre would make it more likely to rotate during impact. The offset of the accelerometers would cause inaccuracies in measuring resultant acceleration if the impactor rotates during the main phase of impacts. Because these two effects are undesirable, they were reported to the EEVC Working Group, who decided that production versions of the impactors should have this aberration corrected to improve the impactor’s repeatability.

In all certification tests with the impactors fitted with the prototype flesh supplied by BASf the peak resultant acceleration exceeded by a small margin the certifiable range for the adult and child. The acceleration characteristic of these impactors in this certification test is predominantly dependent on the rubber flesh. Impactors fitted with these fleshes had just passed in earlier certification tests by BASf. One flesh was returned to BASf for a comparative test where it was tested together with samples that BASf had previously been using and it was found that they all now exceeded the maximum giving similar results to those found at TRL. It was concluded from this that the fleshes suffered from age hardening. Some of the fleshes, manufactured from new rubber mixtures, did meet the certification requirement and by mixing two rubbers in various combinations the performance of the flesh could be finely adjusted.

Only the aiming of the impactor was found to require clarification. This was because for most car shapes the impact was not normal to the bonnet resulting in the first contact being offset from the line of flight of the centre of the sphere. The procedure for identifying the test area was clear and easy to follow. The selection of test sites was also easy to follow and the requirements result in a good coverage of the bonnet. The requirements for setting up and testing the car were also clear and easy to follow.

The impactors and test method produced repeatable results with a Coefficient of Variation of less than 1.2%. However the proposed EEVC - WG10 tolerance on impactor velocity and mass may cause some further variation in results particularly for car structures close to their limit of deformation.

The most significant recommendations made were:

- A suitable system of attaching the flesh to the impactor should be devised.
- The designs should be revised to position the accelerometers and the centre of gravity close to the geometric centre of the spheres.
- The test method should include an additional section to define whether the impact location should be specified as the first point of contact or the impactor axis.
- The certification method should include a requirement to take only the second and subsequent drops for certification values. A time for the flesh to recovery should also be specified between each test for both certification and impact tests.

2.1.1.2 Progress with BASf-based headform impactors

Following the above work EEVC Working Group 10 accepted the above recommendations and revised the headform specification. TRL produced a new design for the steel inserts which achieve the requirement, for the child and adult headforms, that the centre of gravity and the seismic mass of the accelerometers are both within 10 mm of the centre of the impactor sphere. TRL manufactured examples of these impactors.

The TRL headform impactors were used to evaluate four cars using the EEVC pedestrian head impact test procedure. A total of 52 headform tests were performed to four popular cars, with test sites over the full test area, including the wing tops, scuttle and base of the windscreen. The report (Lawrence and Hardy, 1994) is summarised below.

In the child headform tests the lowest HIC was 1194, for the relatively soft areas found on the Fiat Uno. The highest child HIC was in excess of 7383, for the impact directly over the very strong MacPherson strut on the Peugeot 205. For the adult headform tests the highest and lowest HIC were both recorded on the Fiat Uno. These were a HIC of 1132, for the relatively soft back of the bonnet and 7721, over the very strong hinge reinforcement and wing edge.

None of the test sites on the four cars tested complied with the pedestrian protection requirement for the HIC not to exceed 1000. However, several test sites came close to passing the requirement, particularly when the non-linear effects of the HIC calculation method is taken into account. The Fiat Uno gave the most promising results and would have been close to passing at most test sites if the heater air intake chamber had been weaker.

Because these cars have been designed with no specific pedestrian impact requirements in mind, little thought appears to have been given to reducing the number of hard under-bonnet components that lay close to the underside of the bonnet. Some under-bonnet components are unnecessarily strong or close to the bonnet. Some, like MacPherson struts and wing edges, would be difficult to make softer without more fundamental modifications. Others, like heater air intake chambers, could be made of a weaker material without requiring significant changes to the vehicle design.

For some areas of the cars tested, relatively minor modifications may well achieve the HIC requirement. For other parts more fundamental modifications would be required. However a Directive is only likely to require
pedestrian protection on new car designs. To achieve
significant benefits at an early stage, it may be desirable to
phase in the proportion of the bonnet top that has to meet
the test requirement.

The tests performed in co-operation with Rover were
reported by Rover (Giles, 1993). Of the four tests to the
Discovery with each of the headforms, one child and one
adult test passed the requirement for the HIC not to exceed
1000. Results with this vehicle and the Rover 214 were
otherwise similar to results obtained with the popular cars.
Although these test to the Rover vehicles were with the unmodified headforms the results are likely to have been
similar with the modified ones. It is encouraging to have
some tests which pass the requirement, although it is
obviously a great deal more difficult to pass at every
location within the test area. It may be significant that the
Discovery has an aluminium bonnet.

Following the above work, details of the TRL
test method which stabilise the rubber flesh and hence reduce
suffer from vibration in the accelerometer mounting.

2.1.2 Progress with headform impactors and test method
subsequent to the final report of WG10 in 1994

2.1.2.1 TNO Prototype adult headform impactor
No problems of durability where found with impactors
made from the original batch of bowling balls (Lawrence
and Hardy, 1993a). However, all the headform impactors
manufactured by Ogle and sold by TNO were made from
subsequent batches of bowling balls, which have suffered
problems with durability of the adult headform material.
These impactors suffer surface chipping when vehicle parts cut through the rubber skull cap and material splitting away around the threaded holes, used to retain the rubber skull cap and steel insert. The Ogle design also suffered from vibration in the accelerometer mounting.

The German manufacturers of the ‘bowling ball’ used as a basis for the headform were apparently not able to help with the problem of durability.

To overcome the problem of durability TNO decided to
use an alternative material, a semi-rigid polyurethane, for
the sphere. To reduce the vibration, TNO revised the
accelerometer mounting. TNO manufactured one example of this prototype design, and it gave satisfactory results in
an initial assessment by TNO. Following this TNO
requested TRL to assess its performance. The TRL report
(Thornton and Lawrence, 1996) gave the results of this
work and discussed the performance of the impactors, and
it is summarised below.

The TNO polyurethane headform was found to meet all
the EEVC - WG10 physical requirements of size, mass,
centre of gravity moment of inertia and position of accelerometers, with all values lying close to the mean
value required.

The TNO polyurethane headform was shown to give
good repeatability and showed no signs of durability
problems when used in ‘harsh’ tests. However, some
resonance was found to be present in the transverse axes
during impact.

The TRL certification tests showed that the TNO
polyurethane headform failed to meet the EEVC - WG10
certification requirement in its present form, despite it
having passed similar tests at TNO. TRL recommended
that these conflicting results be further investigated.

Subsequent to the TRL report, TNO carried out further
certification tests and obtained similar results to TRL. They
concluded that their original certification test had been
conducted before the polyurethane material had had time to
cure fully. Although the certification performance of the
headforms is predominantly dependent on the properties of
the flesh, some deformation of the sphere also occurs and it
was concluded that the cured polyurethane was too hard.

After experimenting with the polyurethane properties by
adjusting the mix TNO concluded that it was difficult to
control the hardness of the polyurethane to meet the
certification requirements with the flesh designed for the
bowling ball impactors. At this stage TNO decided to
abandon development of this design. However, it should be
noted that, following the good initial TNO assessment
results, the polyurethane headform was included in the draft

2.1.2.2 WG17 Aluminium headforms
In the second meeting of EEVC - WG17, in January 1998,
TRL proposed that aluminium be used for the headform
impactors. In the fourth meeting of WG17 in June 1998
TRL informed the group that they were considering
developing new aluminium headform impactors with thicker
PVC flesh. The new flesh material would be the same as
used for the heads of the Hybrid family of dummies and
thickness would be approximately matched to that on the
forehead of the Hybrid. The working group accepted the use
of these new materials. To assist TNO in this, TRL produced
a provisional design for an aluminium adult headform
impactor, which nominally met the EEVC physical
requirements and had improved accelerometer mountings.

TRL, in collaboration with Ogle, developed these designs to
produce production quality prototypes. It is intended that the
new aluminium headforms will be produced by FTSS in
simulation with TNO2 and marketed by FTSS. TRL have
been requested to assess these new headform impactors and
the new headform dynamic certification method proposed
by TNO when the new headforms are available.

2.2 Upper legform impactor and test method
Within EEVC Working Group 10, TRL were responsible for
developing the bonnet leading edge test procedure and the
upper legform impactor. By the end of the previous
DETRA project (PRS1/22A) in 1992 TRL had developed

2 FTSS have now taken over the commercial and manufacturing aspects
of the TNO / Ogle dummies.
the original research upper legform impactor and a first prototype impactor intended to be more suitable for use in legislative tests.

2.2.1 Progress with bonnet leading edge impactor and test method up to the final report of WG10 in 1994

In 1992, TRL carried out a programme of tests with the prototype impactor to evaluate it and the bonnet leading edge test method. Four popular European cars were tested with the impactor. The result of this work is summarised below.

The test procedure, vehicle measurement and look-up methods for direction, velocity and energy, in the draft Directive were found easy to understand and use. The following recommendations were made:

- The corner reference points should be specified as the intersection of the bonnet side and bonnet leading edge reference lines.
- The test sites should be a no closer to the corner reference point than half the impactor width (75 mm).
- The problem found in repairing one car between tests showed the need for an additional section in the draft Directive to the following effect: ‘The test house should satisfy themselves that the vehicle for the second and subsequent tests, whether repaired or not, is still representative of the type, for the purposes of the test’.

The impactor had proved to be robust. A total of 74 tests to vehicles had been performed with one test device without requiring any maintenance or repairs, apart from replacement of the foam flesh. The outer rubber skin received a small cut from headlamp glass in one test.

The recommendations in the above summary were accepted by EEVC Working Group 10 and incorporated in the test methods in their 1994 final report (EEVC, 1994).

TRL also produced improved quality graphs of the three bonnet leading edge look-up curves. The velocity graph has been refined slightly to prevent the impactor mass, calculated from velocity and energy, being less than the 9.5 kg minimum required in the impactor specification. These graphs are used in the test method to determine the impact parameters for a each shape of car tested and were also incorporated in the WG10 test methods in their 1994 final report (EEVC, 1994).

Following on from the above work minor improvements to the prototype impactor were made to produce a production version. These included the plating of steel parts, the design of a stronger clutch assembly, the use of non-asbestos clutch friction material, and a protective covering for the strain gauging. A full set of CAD drawings of the impactor were made for impactor production.

It was apparent that there was a demand for the upper legform impactor from research institutes, test houses and car manufacturers. It was concluded that it would support the development of pedestrian friendly bonnet leading edge systems and the adoption of the EEVC test methods if the impactor were made available to others. Although not part of this project, TRL started to manufacture and sell upper legform impactors in 1993 and to-date 31 impactors have been supplied. TRL, by manufacturing the impactors themselves, were able to refine further and improve the design in the light of experience gained both in manufacturing and using them at TRL and at customer test laboratories.

The test method requires several steps to determine the impact parameters for a particular car shape. This includes finding values for direction, velocity and energy, from look-up graphs. TRL produced a computer program that automates this process and eliminates the small variations obtained in manually using the look-up graphs.

The test procedure was used by BASt to test a range of cars and no problems were found with the test method nor the production version of the impactor used (Zellmer, 1994).

2.2.1.1 Development of an improved upper legform certification method

The original upper legform certification method proposed by TRL (Harris, et al., 1991) was developed towards the end of the EC contract. It consisted of striking an immovable anvil at a velocity considerably lower than that used to test a car. This is not ideal because the performance of the Confor foam used as flesh is speed dependent.

As part of the work for the EEVC Working Group 10 TRL carried out a programme of research to developed an improved upper legform certification test. Ideally the dynamic certification test should be designed to load the upper legform in a similar manner to a car impact in terms of force, speed and loading mode, while giving results of a similar order of magnitude to the pass/fail criteria of the upper legform (to car) test. The design targets set for the certification method were:

- a repeatable test;
- a test that generates bending and force in the impactor in the range of ½ to 1 times the acceptance values;
- to test at an impactor velocity of about 30 km/h and impactor mass of about 12 kg, the middle of the ranges used to test cars. It is important to use a typical velocity because the performance of the Confor foam used for the flesh is speed dependent. Also, if at a later date the Confor foam were replaced by an alternative, it would be important to match the performance at typical test velocities;
- to achieve the above without the use of energy absorbing materials on the impacted object of the certification equipment. The use of energy absorbing materials would reduce repeatability and require additional quality control procedures;
- to establish certification acceptance criteria which allow adequate tolerances for normal variations in the foam and for the certification test temperature range, while being strict enough to exclude unacceptable batches of foam and to exclude impactors which are faulty by design, manufacture or subsequent failure.

After consideration of the above certification requirements it was decided to investigate the suitability of using a stationary cylindrical pendulum as an object to be hit by the impactor. The pendulum would represent a
repeatable bonnet leading edge. Initial calculations suggested that striking a 3 kg cylinder suspended on wires would produce suitable impactor transducer outputs. Figure 1 shows the final certification test set-up.

Figure 1 Test set-up for upper legform impactor dynamic certification test

After some initial tests with a 100mm-diameter cylinder made from steel tube, a 150 mm outside diameter cylinder was made from steel tube. This diameter was chosen to represent a typical bonnet leading edge. A nominal length of 275 mm was selected as long enough not to be rotated rapidly by slightly off-centre impacts, while still allowing a sufficient wall thickness (3 mm) within the desired mass of 3 kg. Two initial tests were carried out with the upper legform impactor, set to a mass of 12 kg, striking this pendulum to establish a test velocity that achieved suitable transducer outputs. A velocity of 8 m/s was selected for all subsequent tests. This velocity was chosen as it is also an integer value in m/s and is close to the middle of the range of velocity (20 to 40 km/h depending on vehicle shape) used to test vehicles.

To establish suitable data to select values for the certification pass band it was decided to carry out certification tests at different temperatures and with flesh from different batches, to establish the range of test results likely to be found with the impactor. A plastic tent was constructed around the test area and a thermostatically controlled electric heater was used to control the temperature. Flesh from three different manufacturing batches was used, with the month and year of delivery being used to identify each batch of foam. A suitable pass band was then selected from these results.

In tests to cars the loading on the flesh will depend on the shape and stiffness of the car. Some damage to the flesh, whether visible or not, may occur. It had already been noted that the flesh becomes slightly softer with repeated testing. This effect will make it a little more difficult for a vehicle to pass if old flesh is used. To obtain some understanding of the deterioration of the flesh the certification test was repeated using the same flesh. The results showed that the flesh deteriorates slightly in the first three impacts with the bending and force increasing by about 4% and 6% respectively. This small deterioration in the energy absorbing capacity of the flesh is likely to have a minor effect on the results of tests to cars because, to pass the test, the majority of the energy will have to be absorbed by the car. For vehicle development tests this deterioration would be acceptable. However, the use of previously used flesh will make regulatory tests to vehicles a little more difficult to pass, therefore it would be advisable to fit new flesh before each test. Therefore, TRL have decided to recommend the use of new flesh for regulatory tests in their legform user notes.

Based on this work TRL produced an upper legform certification procedure suitable for inclusion in the EEVC - WG10 test methods and this was accepted by EEVC Working Group and included in the WG10 test methods in their 1994 final report (EEVC, 1994).

2.2.2 Progress with bonnet leading edge impactor and test method subsequent to the final report of WG10 in 1994

2.2.2.1 Unintended load path in the upper legform impactor

A problem of an unintended load path in the upper legform impactor was discovered by BASt. This was observed when they integrated the force readings from the load cells, and in one test it was found that the impulse obtained was not sufficient to bring the mass of the impactor behind the load cells to a halt. Although this calculation method is not completely appropriate for this impactor with non-rigid components, it showed that there was a problem. BASt further found that the problem was resolved if they tested without Confor foam flesh on the impactor or if the foam was cut down so that it only covered the front of the impactor.

To understand and resolve this problem TRL carried out a programme of research. First the BASt tests were repeated and the problem was reproduced. This work showed that, although the Confor foam is soft when compressed statically, it is stiff enough dynamically to transmit significant levels of force from the impact point at the front to parts of the impactor behind the load cells. It was found that the foam was transmitted force to the weight carrier brackets and the clutch plates. Historically, the problem was not observed in the original research impactor so it probably arose from design changes made to improve the attachment method and appearance of the foam and skin, and to strengthen the clutch plates.

The solution was simply to reduce the area of the Confor foam sheets so that there was a gap between the foam and the weight carrier brackets, the skin attachment studding and the clutch plates. Tests were carried out with different flesh cut out arrangements to find the optimum flesh shape, which removed the problem, without interfering with the impactors operation. The changes to the size and shape of the foam reduced the effectiveness of the original method of locating the outer rubber skin. This problem was resolved by the use of additional spacers on the skin attachment studding. The effect on the total impactor weight was minimal, with the reduction in the weight of the foam compensating for the weight of the spacers.

However, this fault existed on the impactor used to develop the dynamic certification procedure. Therefore the
effect of removing the load path on the dynamic certification procedure was found and a small adjustment to the dynamic certification velocity was proposed along with minor changes to the impactor specification. These changes were incorporated in the draft EC Directive (European Commission, 1996).

2.2.2.2 Acceptance criteria for the upper legform test
The damage caused to the bonnet leading edge in suitable well-documented pedestrian accidents was reconstructed with the upper legform impactor by TRL. These data were then combined with all suitable upper legform accident reconstruction data from earlier TRL studies and studies by the Japan Automobile Research Institute (JARI) (Matsui et al., 1998) (Matsui, 1998). Accident reconstruction data of this type has the advantage that the measurements can be related to the injuries of real pedestrians and includes the transfer function between a mechanical impactor and a human. Using injury risk analysis, criteria for bending moment (300Nm) and force (5kN) were proposed by TRL from the reconstruction data (Rodmell and Lawrence, 1998a). To determine the most suitable method of analysing the data to produce the above proposal, TRL first made a study of the different statistical methods available for finding injury risk curves from this type of data. The study of statistical methods was particularly important because revised criteria had also been proposed to the working group by JARI (Matsui et al., 1998) using a statistical method that required assumptions to be made of ‘safe loads’. The statistical method used by JARI could also have produced results biased by the effects of sampling. The majority of the working group accepted the revised criteria proposed by TRL of force not to exceed 5 kN and bending not to exceed 300 Nm. However, the French representative preferred to use an alternative value of 360 Nm. This he calculated from the mean of a number of static femur bending tests using a correction factor for the effects of loading rate and the difference in the distance between the femur supports in the cadaver tests and the femur tube supports in the upper legform impactor. The method used to convert from static cadaver test results to equivalent impactor values was tenuous, could not be related to the target of a 20% injury risk and made no allowance for an impactor transfer function. The working group accepted the criteria proposed by TRL by majority vote.

2.2.2.3 Computer simulation of pedestrian to bonnet leading edge impact
When a car front strikes a pedestrian, the severity of the bonnet leading edge impact is dependent on the vehicle shape and speed. The EEVC test methods are intended to represent an accident at 40 km/h. For the upper legform sub-system test to reproduce a pedestrian accident at 40 km/h it was necessary to establish the relationship between vehicle geometry and the severity of the bonnet leading edge contact. This relationship was represented by the local change in velocity of the pedestrian’s body, the direction of forces during the contact and the vehicle deformation energy. The impact angle and velocity were obtained by WG10 from a series of full-scale experimental impacts between a pedestrian dummy and a range of full size car shapes carried out by TRL (Lawrence, 1990); the energy of the impact was found from a limited number of mathematical simulations. These original simulations made use of lumped parameter dynamics software codes. The comparatively simple models used have provided adequate responses of pedestrian impacts, but concerns have surrounded the ability of these models to provide accurate predictions of upper legform test energies. Furthermore, there were limitations on how the MADYMO models had been structured to assess upper legform test energies (Lawrence and Hardy, 1998). Since these test methods were first developed, car designs have changed; many modern cars have been tested to the WG10 requirements and mathematical simulation tools have been improved. Recent accident statistics are now available along with more recent computer simulation results (still using simple lumped parameter dynamics software code) and new accident reconstructions data. Considering all of this information suggested that the energy required in the WG10 upper legform test was probably too high for the more streamlined car shapes. This problem was likely to be mainly due to the limited data available to WG10 and other simplifications in the original simulations.

Further mathematical simulations of pedestrian to car impacts were therefore carried out by TRL to produce data suitable for reconsidering the WG10 test energy requirements for the upper legform test method (Lawrence and Hardy, 1998). These simulations were made using the most powerful simulation method currently available, finite element analysis. Simulations were made of impacts between fifty-four models of cars, of various defined shapes, and a simulated pedestrian dummy. For all these car shapes, the bumper shape along with the bumper and bonnet stiffness were chosen so that the car would meet or be close to meeting the pedestrian injury criteria. In addition three simulations have been carried out to determine the effect of simulating cars with bumpers that do not meet the injury criteria. Two car shapes were simulated with a pedestrian-unfriendly bumper combined with a pedestrian-friendly bonnet.

When plotted these simulation results produced families of curves suitable for revising the test methods. The energies found were lower for the more streamlined car shapes and higher for the more upright ones. Because of the large number of car shapes simulated, the shape of the energy curves were well described and covered the larger vehicles (off road types) unlike the original WG10 look-up curves, see Figure 2.

In their report on this work Lawrence and Hardy, (Lawrence and Hardy, 1998), compared the TRL simulation results with other recent simulation data. Only the simulation data from JARI covered sufficient car shapes for a detailed comparison (Konosu and Ishikawa, 1998). It could be seen that:
- The TRL data generally followed the same pattern as the JARI data; however, the TRL family of curves followed a more rational pattern.
The TRL energy showed a significant effect for bumper lead as expected from full scale testing. The JARI energy showed little sensitivity for bumper lead and the trends appeared inconsistent, and even reversed in some cases.

Lawrence and Hardy (Lawrence and Hardy, 1998) also noted that the TRL energies, for cars with 550mm and 600mm bonnet leading edge heights and zero and 50mm bumper leads, did not follow the general shape of the family of curves. They concluded that this effect was because, for these few shapes, the legs-astridge stance of the dummy (selected by the WG17 as being typical) results in individual leg contacts to the bonnet leading edge, and only the energy from the first leg contact is reported. For the rest of the car shapes, the second leg was not struck directly by the bonnet leading edge, but it did interacted, to some extent, with the first struck leg causing a higher effective mass and therefore an increase in energy. TRL proposed that the energy should be increased to represent a ‘legs closer together’ position, by either extrapolation or further simulations if it were required to adjust the bottom end of these two curves, so that they match the family.

TRL proposed revised energy curves for the test methods using the TRL simulation results without modifications. They also proposed that an energy cap of 7001 should be considered because the depth of crush required to make vehicles with a high bonnet leading edges safe would be very difficult to achieve. This value was calculated using a method developed by Rover (Green, 1998) and was based on the upper legform acceptance criteria and a maximum vehicle crush depth of 150mm.

The TRL proposals were considered by WG17 and accepted with the following minor changes:

- The energy line for zero bumper lead was removed because in practice very few vehicles have bumper leads of less than 50mm.
- Instead of increasing the energy for the 550mm and 600mm bonnet leading edge and 50mm bumper lead, as proposed by TRL, the energy value for the 650mm bonnet leading edge with a 50mm bumper lead was reduced slightly. This removed the kink in the curve (see Figure 2) making the test requirements more constant for vehicles of these shapes. This change gave the same effect as widening the stance of the legs, which would reduce the interaction between the first and second struck legs.

The Finite Element (FE) pedestrian model used for the work described above was validated against experimental data using a pedestrian dummy with additional features to make it more biofidelic for this use. Therefore the characteristics of FE model used to produce the new WG17 energies may be more representative of a pedestrian dummy than a human being. Ideally it would have been better if it had also been developed and validated against data from pedestrian tests using cadavers. However, in the limited time available before
EEVC Working Group 17 was due to report, it was not possible to carry out this additional work. It is therefore recommended that additional changes and validation be made to develop a more biofidelic pedestrian model. This model can then be used to further refine the upper legform test energy graphs if necessary and provide an insight into the potential differences that might be expected between the response of a pedestrian dummy, a live pedestrian and a cadaver. It can also be used to explore the effect on upper impact energy, of different pedestrian stances and bonnet leading edge shapes.

2.2.3 Euro NCAP upper legform predictions and re-tests
The results from the Euro-NCAP pedestrian tests were of interest when considering legislation to require pedestrian protection. This is because they provided information on the performance of current designs and gave an estimate of the degree of changes required to meet the pedestrian requirements. A paper was written for the Enhanced Safety of Vehicles Conference in 1998, which included an analysis of the performance of the cars subjected to pedestrian tests in the Euro-NCAP test programme (Lawrence and Hardy, 1998b). The analyses of the Euro-NCAP upper legform pass rates showed that no cars and no test sites met the EEVC - WG 10 requirements. At that time the paper was written the revisions to the upper legform acceptance criteria and test energy by EEVC - WG 17 described above were not completed.

Following the WG17 revisions of the upper legform test energies and acceptance criteria TRL produced predictions on the effect of these changes on the upper legform pass rate in the European New Car Assessment Programme. A committee paper describing this work in more detail has recently been supplied to EEVC - WG17 for their consideration (Rodmell, 2000). This work is summarised below:

The new WG17 test requirement for the Upper Legform to bonnet leading edge test differs, in some respects, from the original WG10 test requirement. For most shapes of car the new WG17 upper legform test energies are less demanding than the original WG10 requirements. Also, based on additional biomechanical data, the WG17 increased the acceptance criteria for the upper legform to bonnet leading edge test, making them less demanding than the original WG10 provisional criteria.

These changes are expected to have an effect on the proportion of cars that would pass the upper legform to bonnet leading edge test. The proportion of cars passing the WG10 requirement, as used in the Euro-NCAP programme pedestrian tests, varies according to the type of test, but of 90 upper legform tests examined, none passed. In the first phase of this work Rodmell produced estimates of the number of upper legform to bonnet leading edge tests from 90 Euro-NCAP tests that would have passed using the new WG17 requirements. This was done using accident reconstruction data from tests to non-NCAP cars (see Appendix A of Rodmell, 2000). However, some confirmation of these estimates was required because the data on vehicle sensitivity to test energy used by Rodmell to produce these estimates, showed different sensitivities for each model of car tested and these cars were generally older models than those tested in the Euro-NCAP programme. Re-testing of all the cars previously tested in the Euro-NCAP programme with the upper legform impactor was considered impractical but it was possible to retest five Euro-NCAP vehicles using the new WG17 requirements. The differences in results between the original Euro-NCAP tests (WG10) and the lower energy re-tests (WG17) were then used to make a prediction of how the other Euro-NCAP vehicles would have performed had they been re-tested to WG17. Firstly, the individual trends from old to new results were found for force and bending at each site re-tested on the five vehicles (15 tests sites), using a power equation of the form:

\[
y = a \cdot x^b
\]

Where ‘a’ and ‘b’ were selected to give a best fit through the data points.

Secondly, the average trend (average power) for these test sites was found for force and bending. These average power values were then used, for the vehicles not re-tested, to produce predictions from the WG10 tests results of what the WG17 results would have been. This was done using a power equation of the form:

\[
Output_{predicted} = Output_{original} \times \left( \frac{Energy_{new}}{Energy_{old}} \right)^{Average\ Power}
\]

The re-test results along with the predicted WG17 test results for the remaining 75 EuroNCAP sites were then used to find how many would pass or come close to passing the new WG17 acceptance criteria.

It was concluded that:

1 The reduction in impact energy for the upper legform to bonnet leading edge test significantly reduces the results obtained.
2 There appears to be a direct relationship between the impact energy and the results obtained from the tests.
3 A prediction process can be applied to the impact conditions to give an accurate indication as to the expected results from tests to the new (WG17) energies.
4 Due to the reduction in energy, 23% of tests do not need to be conducted as the energy value drops below the ‘no-test’ energy of 200J.
5 If tested at the new energy level it is predicted that out of the 69 tests to be conducted 24.6% would pass. A further 30.4% would be close (within 25%) to passing the test.
6 From the reduction in energy, 4 vehicles no longer need testing (due to the 200J ‘no-test’ requirement) and from the prediction process 3 cars will pass all the test requirements.

2.3 Legform impactor and test method
The research laboratory responsible for developing the leg to bumper impact procedure was the Institut National de Recherche sur les Transports et leur Securite (INRETS). Subsequent to their contract report (Cesari and Alonzo,
1990) INRETS produced further versions of their impactor and ligaments. Their final work on the impactor was reported in the final meeting of EEVC - WG10 in 1994 and at that stage they had been unable to find a knee ligament design that met both the shear and bending requirements.

2.3.1 Progress with Bumper Impactor and Test Method up to the final report of WG10 in 1994

As the TRL programme included the evaluation of all the proposed impact test devices, it was originally intended to evaluate the original INRETS research (Mk 1) bumper impactor. However, INRETS were unable to make available to TRL the Mk 1 impactor nor detailed drawings of it from which a sample could be made. In mid 1992 INRETS produced drawings of their Mk 2 bumper impactor design. TRL workshops manufactured most of the Mk 2 impactor parts. However details of some parts were not included in the drawing set and INRETS were unable to supply further details.

In mid 1993 INRETS supplied TRL with an example of their Mk 3 bumper impactor and also a copy of their computer program for the analysis of the transducer outputs. TRL examined the leg impactor and compared its physical properties with the INRETS target values and also appropriate values derived from anthropometry data by TRL. TRL also evaluated the analysis program and carried out a limited programme of tests with the impactor to evaluate it and the bumper test proposals. The TRL report (Lawrence and Hardy, 1993b) gave the results of this work and discussed the performance of the impactor and the test method and it is summarised below.

No problem was found in following the test method nor in propelling the impactor into the car at the correct speed and orientation. The impactor instrumentation gave continuous clean outputs throughout impact.

TRL intended to assess the physical properties of the impactor against the target values produced by INRETS. However, TRL concluded that the list of human target values for the impactor masses, centres of gravity and moments of inertia was not sufficiently detailed for a comprehensive evaluation. Therefore TRL produced a list of proposed target values for the impactor using anthropomorphic data. This involved making adjustments to the human values to take account of the impactor’s simplified shape. The TRL assessment of the physical properties of the Mk 3 impactor showed that combining the foot into the lower leg section had resulted in an incorrect mass, centre of gravity and moment of inertia.

The computer algorithm used to calculate the knee shear displacement was found to suffer from a number of problems when the knee was subjected to bending or a combination of bending and shear loading. These problems were partly overcome by a TRL modification to the algorithm. However, shear displacements could not be satisfactorily computed with the Mk 3 knee and ligament design.

Neither ligaments supplied by INRETS nor ones made to their specification met the bending certification requirement in the TRL tests. The design was such that small variations in machining and material heat treatment resulted in a wide variation in performance. Only one of the three shear tests gave values that were close to the ultimate shear requirement although a complete shear performance corridor was not then available. The ligament design was such that the thickness of the metal, which forms the plastic hinges, was difficult and expensive to machine to suitable standards. The design was also such that the shear and bending performance could not be easily and independently adjusted by minor changes in dimensions to achieve the certification requirement for a batch of material. Consequently the ligament design required considerable revision.

Examination of the proposed knee quasi-static certification methods, showed that they produced complex loading. New certification methods were proposed and these were adopted by EEVC - WG10 and included in their final report, see Figures 3 and 4.

TRL drew up a list of proposals and design targets to improve the Mk 3 impactor and to overcome the problems observed.

Following the above work and in an effort to resolve the serious problems found with the bumper impactor TRL agreed to work on the impactor design in co-operation with INRETS. INRETS and the EEVC Working Group accepted the TRL list of target values for impactor masses, centres of gravity and moments of inertia. INRETS also
produced a new design for their impactor (Mk 4) to meet the TRL targets.

In an effort to resolve the problems found with the impactor knee, TRL carried out a theoretical study to devise and optimise knee joint design solutions (Moseley, 1994). The aim of this was to:

- Separate the measurement of the knee shear and bending parameters.
- Produce the correct knee bending and shear stiffness.
- Improve the repeatability of the knee.
- Reduce the cost and complexity of the disposable knee ligaments.

It was hoped that an improved ligament to fit in the existing knee could achieve the above requirements. The INRETS impactor design needed the metal ligament to provide both the specified shear and bending stiffnesses by plastic deformation. The transducer system and analysis algorithms to report shear and bending displacements also required that the positions of the plastic hinges and the distances between them be fixed for all combinations of shear and bending. Unfortunately the TRL study found no design solutions that would meet the requirements and suggested that it was theoretically very difficult, if not impossible, to design satisfactory ligaments that could provide both the defined shear and bending characteristics and the dimensional requirements for the plastic hinges.

However, two new knee design solutions were suggested by the study. The first was intended to be as similar to the INRETS design as possible. The shear mechanism was separated from the bending mechanism, each with an individual measurement of displacement. This method used an elastic spring to produce the shear stiffness and simplified disposable deformable ligaments to provide the bending stiffness. The elastic spring was permanently fitted inside the tibia or femur tube.

The second solution was a simplified system using deformable ligaments to reproduce the bending performance only, and not provide any shear displacement. Instead, load-cell instrumentation taken from existing anthropometric dummy technology would be used to measure shear force and bending moment. This would have the benefit of measuring the forces directly and independently. This would give improved repeatability over the first solution, because in that design, the bending and shear measurements depend on the stiffness of deforming elements that are inherently less repeatable than direct measurements using a load cell.

Ogle Design Limited under sub-contract to TRL designed and manufactured an example of the knee with the ‘elastic shear spring’. TRL tested the knee and found it to be a practical solution, which overcame the problems found with the INRETS impactor. The knee joint bending and shear stiffnesses were found to be of the required order and the bending ligament dimensions and ‘waist’ could be tuned to match the certification requirements. Despite the success of this ‘elastic shear spring’ knee design TRL still had some reservations about the practicality of incorporating it in a complete impactor and meeting the physical requirements of mass centre of gravity and moments of inertia. The knee shear system was considered to be a very complicated way of achieving calibrated shear stiffness at the knee. Given that the deflections involved are so small, it appeared simply to be complex shear-force transducer which allowed a dynamically insignificant amount of deflection.

At that time TRL would have preferred that the second solution were adopted. However, recent tests with the TRL legform impactor have suggested that retaining a shear displacement system provided a more human like response (Matsui, 1999). Nevertheless, the load cell solution would have the advantage of measuring shear and bending force directly. Only relatively minor modifications of the INRETS Mk 4 leg would have been needed to fit the load cell. The computer modelling (Moseley, 1994) indicated that the load cell would give best results if fitted at the centre of the knee joint, between the deformable bending elements. The load cell solution also had the advantage of using readily available instrumentation technology already known to vehicle manufacturers and test houses. Readings would be directly available in known engineering units, with no need for complex data processing.

In the final meeting of EEVC - WG10 in 1994, INRETS reported that they had developed improved ligaments. However, these still did not meet the shear stiffness requirement being far too stiff. When subjected to pure shear or bending these ligaments deformed at predictable locations, as required by the INRETS knee measurement system. However, a similar design was considered and rejected by Moseley (Moseley, 1994) because the deformed shape and stiffness would not be predictable when the ligament was subjected to a combination of bending and shear. There has been no further development of the INRETS legform reported to the EEVC.

The possibility of TRL producing a complete impactor incorporating the TRL knee, and also the need for assessment of it or any other legform impactor meeting the WG 10 requirement, was also discussed in this last meeting. Some WG10 members (TNO and BASt) indicated an interest in undertaking the assessment of prototype impactors. The results of any such assessment were to be sent to the former chairman so that he could consider them and advise the EEVC main committee on this.

2.3.2 Progress with bumper impactor and test method subsequent to the final report of WG10 in 1994

Following the last meeting of WG10, TRL developed a prototype legform impactor in an attempt to assist the implementation of the EEVC test procedure. Lawrence (Lawrence and Thornton, 1996) described the development and assessment of the first and second of versions of this prototype impactor and the report is summarised below.

The EEVC - WG10 specification includes the impactor external shape, mass, centre of gravity and moment of inertia within specified tolerances. First the possibility of achieving these physical targets with an impactor incorporating the TRL knee was examined using a spread sheet model of the mass distribution. Having established that this was possible, the spread sheet model was used to
refine the design solution to best meet the physical targets and the operational requirements. This was achieved by adjusting component shape and materials within the constraints of the specified external shape, the mechanical operation of the knee joint and acceptable impactor robustness. The model was also used to examine the effect of manufacturing tolerances on the above requirements.

When the prototype knee joint had been assessed some mechanical cross talk was observed in the shear spring during the bending certification test. This problem was resolved when the shear spring was adapted to fit into the prototype legform impactor by replacing the rubber block between the spring arms with a steel roller, see Figures 5 and 6.

When the prototype knee joint had been assessed some mechanical cross talk was observed in the shear spring during the bending certification test. This problem was resolved when the shear spring was adapted to fit into the prototype legform impactor by replacing the rubber block between the spring arms with a steel roller, see Figures 5 and 6.

However, this removed the damping that had been produced by the rubber block. Some thought was given to the damping requirements of the spring assembly and it was concluded that the rubber block would have been inadequate. No suitable commercially made system for the provision of suitable damping could be found at this time. At this point it was decided that, within the time constraints, it would be better to proceed with the manufacture and testing of an impactor without damping. If the impactor were found to be satisfactory in all other respects then a damping system could be added in a further phase of impactor development.

A prototype impactor was then made using a combination of new parts and modified components from the original prototype knee joint. The physical properties of dimensions, mass, centre of gravity and moment of inertia of this legform were then measured and were all found to be within the WG10 specification.

The bending stiffness of the prototype knee joint was achieved by the use of disposable pairs of steel ligaments, which deformed plastically at a notched waist, see Figure 7.

Although the ligaments made and tested in the prototype knee joint had demonstrated the potential of this system they had not matched the bending stiffness corridor of WG10; however, it was clear that they could be modified to achieve a better match.

To provide information on the effect of shape and material properties on the ligament’s pre and post yield deformation stiffness, analytical methods and mathematical modelling were used. This study provided an understanding of the factors to control bending stiffness and methods of achieving a ‘best fit’ to the WG10 corridor. Batches of ligaments were then produced and tested in the prototype legform, using the bending certification test, to determine their bending stiffness.

EEVC - WG10 had produced target corridors for the knee bending stiffness based on biomechanical data but with the precise shape drawn around the performance of an early INRETS ligament. The shear stiffness target was also based on biomechanical data of shear displacement and shear force at joint failure. The biomechanical targets provide information on the ideal impactor characteristics. However, once a practical impactor design has been produced, certification corridors are needed to require the impactor to be repeatable and to ensure that it is working as intended. Therefore, as the TRL design had been shown to meet all the other WG10 requirements, it was agreed by the working group, that minor adjustments could be made to the biomechanical target corridors to make them suitable for certification test corridors. Therefore, a shear stiffness corridor was proposed, based on the performance of the shear spring and considerations of the variations in stiffness likely to be found due to acceptable material and manufacturing tolerances. Likewise a new bending certification corridor was proposed, based on the performance of the ligaments that gave the best fit to the original requirement and acceptable variations likely to be found in manufacturing and in material properties.

TRL, BASt and TNO then assessed the performance of the first prototype legform impactor, by test programmes where it was used to test real and simulated cars. In addition TNO adapted a dummy neck certification test procedure to produce a provisional dynamic certification method. Both TNO and BASt noted that the shear spring leg mass system vibrated at its natural frequency in some tests. Following these assessments TRL produced a revised design and manufactured a second prototype impactor with a number of minor improvements, including an improved system for re-assembling the knee during bending.

Figure 7 The bending ligament
ligament replacement and an improved shear spring location. The physical properties of the second prototype impactor were also assessed by TRL and were found to be similar to or close to the nominal values required by WG10 than the first prototype. Again all were within the specified tolerances. However, some dimensions had no tolerances and TRL proposed tolerances for them.

This work was reported to the former Chairman of EEVC - WG10 and the changes proposed were supplied by him to the European Commission and incorporated in the draft pedestrian protection Directive (European Commission, 1996).

It was apparent that there was a demand for the legform impactor from research institutes, test houses and car manufacturers. It was concluded that it would support the development of pedestrian friendly bumper systems and the adoption of the EEVC test methods if the impactor were made available to others. Although not part of this project, TRL started to manufacture and sell prototype legform impactors while work continued on resolving the problem of vibration of the shear spring mass system. The impactor was to be supplied as a ‘prototype impactor’ to acknowledge the need for further development and the first one was supplied in late 1995. To-date a total of 31 have been sold. As with the upper legform, by manufacturing the impactors at TRL, further refinements and improvements to the design were possible in the light of experience gained both in making and in using them at TRL and at customer test laboratories.

Subsequently a programme of work was initiated to find the best methods of providing a damping system for the legform.

2.3.3 Progress with bumper impactor and test method following the forming of EEVC - WG17

The un-damped prototype legform impactor was accepted as the EEVC - WG17 prototype impactor in the first meeting of the working group in October 1997. It was agreed that the addition of a suitable damper would rectify the final problem with the impactor.

Following on from the study to identify the best method of providing the damping of the shear spring system a search was made of suitable commercially available dampers. Only one modified damper was found with the required damping characteristics. This damper was not ideal, being much larger with a longer stroke than required. It was decided to first make and assess an experimental impactor using this large damper. If this were found to be satisfactory, a damper of optimum size could then be obtained and built into the legform. Therefore an experimental large damper legform impactor was designed, made and assessed. In addition an improved dynamic certification test was devised and evaluated. The assessment of this experimental damped legform was reported in more detail by Rodmell (Rodmell and Lawrence, 1998b) and the report is summarised below.

2.3.3.1 Development and testing of an experimental damped legform

A finite element Dyna-3D computer model of the legform was produced and validated against the results of the static shear test and full-scale impact tests. This confirmed that the model accurately reproduced both the test results and the vibration of the shear-spring leg-mass system. The possibility of providing the required damping by friction blocks within the shear spring was examined using this model. It was found that low displacements were obtained and high clamping forces were required, which suggest that this solution was impractical. The damping effect of the flexing plastic hinges in disposable steel dampers was also examined using analytical methods. This analysis indicated that, although theoretically possible, the mechanical requirements are incompatible within the space and displacements of the legform. The computer model was also used to examine the suitability and required characteristics of a hydraulic damper attached to the shear spring. This appeared to be the most promising solution, if a damper could be found of an acceptable size.

Only one company was identified that was able to meet the requirement by modifying one of their standard dampers. This damper body was not ideal, being much larger with a longer stroke than required. Experience has shown that damper manufacturers normally reject requests for tailor-made dampers unless a large numbers are likely to be purchased. Therefore, a two-stage approach was planned. First, the large damper would be purchased and the performance of the impactor with the damper acting between the femur tube and the shear spring would be assessed. If this were found to be satisfactory, a damper of optimum size could then be obtained and built into the legform. This first stage was completed and the damped system assessed and found satisfactory, apart from the vulnerability of the side-mounted damper to damage, which is exacerbated by its large size. Because this experimental legform formed the first stage of the development of a damped legform impactor no effort was made to correct for the effects of the additional components on the mass and mass distribution of the experimental legform.

2.3.3.2 Development of an improved dynamic certification test

The first provisional legform dynamic certification method was developed by TNO. It made use of a pendulum system originally designed to certify the necks of test dummies. Although this certification method had the advantage of providing a comparatively long duration impact, which gave time for the knee to bend it, had a number of disadvantages:

- the pendulum legform assembly was not arrested at its centre of percussion, therefore energy was lost in the hinge and also in bending of the pendulum arm;
- the legform was arrested by an energy absorbing material (deformable honeycomb); the performance of this material may be difficult to control, leading to poor repeatability;
- the legform knee-bending mode was dissimilar to that in a test to a car;
- the method caused excessive loads on the hip end of the impactor;
- the knee shear displacement was too close to the full-scale displacement limit.
To overcome these problems a new certification method was conceived, where the legform, suspended horizontally on wire ropes was struck by a certification impactor. The details of this certification method are shown in Figure 8.

The possibilities of the method were first explored using computer simulations to determine the optimum impact conditions (test velocity, mass and impact location) to generate the best combination of knee bending and knee shear displacement. The sensitivity of this method to reasonable tolerances on the certification impact conditions were also explored with the computer simulations. Following this, full scale certification tests were carried out to establish the actual performance of the experimental damped legform in the certification test. The effects of tolerances on certification impact conditions and temperature, the bending ligament stiffness tolerance and foam flesh from different batches were also explored.

These results showed that the new certification method generated the required levels of knee bending and shear and gave repeatable results. The results also showed that the legform performance was not unduly sensitive to reasonable tolerances on the impact conditions of the certification method. The exploration of the effects on the legform outputs of reasonable tolerances for both the certification test and for the impactor itself (knee bending corridor etc) has provided results that can assist in the selection of certification pass/fail values. However, these may require further adjustments to take account of the performance of the final version of the damped legform impactor with the smaller damper and correct mass and mass distribution.

Following the work reported by Rodmell (Rodmell and Lawrence, 1998b) the first stage of designing a ‘production’ damped legform was completed and two tailor-made dampers obtained by the end of this project in March 1999.

2.3.3.3 Injury risk analysis of leg fracture from bumper contacts
One of the criteria for the legform impactor is a 150g limit on acceleration. In a JARI presentation to the EEVC - WG17 it was suggested that this limit was too low
based on a JARI/JAMA statistical analysis of bumper to cadaver leg test data (Ishikawa, 1998). TRL produced a paper reviewing the statistical methods available for this type of analysis. This demonstrated that the method used by JARI should be used with caution, since they produce a credible curve, regardless of whether there is any meaningful correlation between acceleration and fracture and have other limitations (Rodmell and Lawrence, 1998c). This TRL paper assisted WG17 to confirm the original WG10 criterion taking into account the target of a 20% injury risk and the practical difficulties to produce bumpers to meet this criterion.

3 The cost benefit analysis

Following the report of EEVC - WG10 in late 1991, the EU first considered using the EEVC pedestrian tests methods as an EC Council Directive through ‘adapting to technical progress’. This requires the agreement of the EC Motor Vehicles Working Group. The European Automobile Manufacturers Association produced a Report (ACEA, 1992) just before a meeting of this working group to consider pedestrian protection. This report included a cost benefit study which claimed that the costs of pedestrian protection would exceed the benefits. Although the benefits had been estimated previously, no assessment of costs had been made by the EEVC or TRL.

3.1 The TRL cost benefit study

A preliminary benefit estimate for Great Britain was made by Harris (Harris, 1990) when the test method was first proposed, but a more detailed study was now required to examine the cost benefit issues raised by the ACEA report. TRL undertook this study and this was reported in detail by Lawrence (Lawrence et al., 1993), this report is summarised below.

The costs of implementing the proposed pedestrian impact test procedures are essentially those resulting from the necessary engineering studies and design effort undertaken by the car manufacturers and the extra production costs required for any special feature incorporated into the vehicle to enable the requirements to be met. In order to determine the expected costs, an independent vehicle design consultancy was commissioned to study the proposed test procedures and to estimate the likely costs of design solutions and implementation.

The benefits to be derived from implementation of the test procedures were given in terms of the monetary values placed on the reduction in fatal and serious casualties resulting from vehicle design changes. In order to compare the costs with the benefits, the effect on casualties for all the vehicles produced in one calendar year were estimated over the mean life of those vehicles. For the purposes of these calculations, it was assumed that a Regulation based on the proposed impact test procedures and requirements will have been implemented by the year 2000 and the effect of design changes made to vehicles produced in that year over a life of ten years was calculated. As one proposal is to introduce the proposed test procedure as an EC Directive, the calculations were based on accidents in the European Community (EC) countries.

A number of factors were estimated to enable a calculation of the benefits. The proportional reductions of fatally and seriously injured pedestrians resulting from the implementation of the test procedures were derived from accident studies and test results. These were estimated to be a reduction of 7 percent of all fatally injured pedestrians and 21 percent of all seriously injured pedestrians. The expected numbers of casualties for the years 2000 to 2010 were estimated using past data for the years 1970 - 1990 to extrapolate the trends for pedestrian casualties in the EC countries to the year 2010. The costs associated with a fatal casualty and a ‘seriously injured’ casualty were calculated for the European Community.

From these data, the benefits were estimated for cars entering service in the year 2000 over a standardised average car life of 10 years (2000 – 2010). The value of the savings were reduced by discounting, for the years beyond 2000, to take account of the fact that the extra vehicle production costs are at the start of the vehicle’s life but the savings will be accrued over the vehicle’s life. The costs and benefits were calculated and reported in 1991 ECU but are given below in pounds sterling.

At an average cost of £11.50 per car, the extra costs for cars produced in the year 2000 would be £170 million.

The reduction in fatal and serious pedestrian injuries resulting from vehicle design changes made to comply with the requirements of the proposed test procedure would produce a benefit, discounted to the year 2000, of £1290 million, giving a benefit to cost ratio of 7.5 : 1. The net savings for the vehicles produced in the year 2000 were estimated to be £1120 million for the countries of the European Community.

Following the publication of the TRL report summarised above a number of criticisms were made by ACEA. Only two of these are considered by TRL to have any substance:

1 That the value used in the study for the proportion of fatally injured pedestrians hit at 40 km/h or less was based on an extremely small sample, and was therefore unreliable.

2 That TRL assumed that pedestrians who were saved would become uninjured, rather than assuming that their injuries would be reduced to a lower severity level.

The first point has been assessed by carrying out a study of police accident files (Willey et al., 1995) to establish a more reliable estimate. This study showed that the proportion of fatally injured pedestrians hit at 40 km/h or less was 18 percent, compared with the value previously used in the cost benefit study of 16 percent. If this new value is used in the cost benefit calculation, the proportion of all pedestrian fatalities that would be saved increases from 7 percent to 8 percent.

On the second point, TRL accepts that it is necessary to allow for the residual injury costs. It is reasonable to assume that fatal injuries saved are reduced to serious injuries, and most serious injuries saved are reduced to slight injuries. The serious casualty cost value is an average of a wide range of costs for a range of injury
severities. The benefit of reducing a high severity serious injury to a low severity serious injury is therefore likely to be just as great as that of reducing an average serious injury to a slight injury. Therefore, for calculation purposes, it was be assumed that all fatalities saved are reduced to serious injuries and all serious injuries saved are reduced to slight injuries.

The casualty costs used in the original cost benefit study were: fatal £683,155 and serious £71,100 (at 1991 prices). The slight casualty cost from the same source is £5,800. The net benefit from reducing each fatality to a serious injury is thus £612,055, and £65,300 from reducing each serious injury to a slight injury.

If these two adjustments (the increased proportion of fatalities saved and the revised benefits per casualty saved) are used in the cost benefit calculation the following estimates, given in Table 1, are obtained: (All are for cars produced in the year 2000.)

### 3.1.1 The MIRA cost benefit study

A draft EU pedestrian protection Directive based on the test methods developed by EEVC - WG10 was produced in early 1996. At the subsequent meeting of the EC working group on motor vehicles, Government (UK/TRL, BAST and SWOV) and Industry representatives (ACEA) presented conflicting data on the costs and benefits of such legislation. In an effort to obtain an alternative view, the EC contracted MIRA to review the available cost benefit data.

An exchange of views on legislation to be drafted with regard to pedestrian safety took place at an EC working group on motor vehicles meeting in February 1998. At this meeting the results of the MIRA study were presented (Davies and Clemo, 1997). This study calculated minimum and maximum benefit to cost ratios of 1 to 5.3 and 1 to 32.3 respectively. There were many questions raised about this study. In particular, the flow chart method used to calculate financial benefits was incorrect, resulting in a lower value being calculated (a detailed TRL analysis of the MIRA report was given in the TRL Annual summary report by Lawrence (Lawrence, 1998)). The consensus of these comments, in the EC motor vehicles meeting, was that the costs, calculated by MIRA were too high. Nevertheless, it is interesting to note that the MIRA estimates of the benefits to cost ratios are much closer to those of TRL than those of ACEA. A summary of the EEVC - WG17 activities was also presented to the EC motor vehicles meeting. It was anticipated that the EEVC - WG17 report describing the revision of the test methods would be available, for consideration by the EC, in October 98 (actual produced in December 98 and released to the Commission in March 99). The main conclusions of this EC meeting were:

a) The Commission requested MIRA to reconsider their calculations in the light of the above comments.

b) The Commission would wait for input from EEVC - WG17.

Following the above EC meeting, a detailed set of comments on the MIRA cost benefit calculations was produced and this document along with comments from ETSC and others were available for MIRA to use in reconsidering their cost benefit calculations. Following this MIRA produced more favourable estimates, revising the minimum and maximum benefit to cost ratios to 1 to 1.7 and 1 to 5.7 respectively. (Note: There is no reference for this MIRA revision document because it has not yet been formally released.)

The Commission’s original concerns over cost benefit calculations now appear to have been addressed, and the production of a pedestrian Directive remains a Commission priority.

### 4 Vehicle crash bars (bull bars)

In the early 1990s the fitting of crash bars to off-road type vehicle began to be popular and concerns were raised because it was perceived that they could increase the risk of serious injury to pedestrians in road accidents.

In about 1992 the Vehicle Standards and Engineering division of the Department of Transport set up a working group to develop a code of practice with crash bar manufacturers.

TRL Limited was commissioned to assess the pedestrian safety of one model of off-road vehicle both with and without a crash bar fitted and consider to the potential for a code of practice for crash bars.

The areas of the body of a pedestrian likely to be contacted by a crash bar are dependent on both the pedestrian’s stature and vehicle and crash bar dimensions. For the adult, the top tube of the bar is likely to strike the upper leg, pelvis or abdomen while for the child pedestrian it is likely to strike the chest or head. The lower parts of the crash bars, which protects the vehicle front in the bumper and grill area, also appear likely to increase the

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### Table 1 Revised benefits of introducing EEVC pedestrian protection

<table>
<thead>
<tr>
<th></th>
<th>Revised estimate</th>
<th>Previous estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discounted benefit for fatalities saved</td>
<td>476 M ECU</td>
<td>465 M ECU</td>
</tr>
<tr>
<td>Discounted benefit for serious injuries saved</td>
<td>1234 M ECU</td>
<td>1344 M ECU</td>
</tr>
<tr>
<td>Total discounted benefit</td>
<td>1710 M ECU</td>
<td>1810 M ECU</td>
</tr>
<tr>
<td>Net savings (benefit-cost)</td>
<td>1469 M ECU</td>
<td>1569 M ECU</td>
</tr>
<tr>
<td>Benefit obtained per car produced</td>
<td>114 ECU</td>
<td>121 ECU</td>
</tr>
<tr>
<td>Benefit to cost ratio</td>
<td>7.1 : 1</td>
<td>7.5 : 1</td>
</tr>
</tbody>
</table>

* M ECU = Million ECU

1 Now the Department of the Environment, Transport and the Regions
risk of injury to lower parts of the pedestrians. The EEVC sub-system pedestrian test methods do not include impactors to represent all the pedestrian body parts at risk. However, they were considered the best existing method for this assessment. At this time only the upper legform impactor was available to TRL so only this was used for the assessment.

A Range Rover was used as the base vehicle for this assessment and it, with and without the crash bars fitted, was tested with the adult pedestrian upper legform impactor with the impact conditions set to represent a pedestrian impact at 40 km/h. The vehicle to be tested was fitted with a standard crash bar (Rover approved accessory) or with a prototype crash bar. The prototype crash bar was made with most of the features recommended in the Crash Bar Working Group’s draft code of practice, but the initial recommendation of weight not to exceed 6kg was not met since the bar weighed 15kg.

Impact tests to the vehicle without crash bars and to the vehicle fitted with the standard accessory crash bar gave results significantly in excess of the recommended acceptance levels to limit pedestrian injuries to an acceptable level. The measured levels were all in the range of approximately two to three times the acceptance levels. The standard crash bar results were similar to the results of the vehicle without crash bars. It was thought most likely that the standard crash bar would have given far worse results had its attachment system been of the more rigid type used by some other manufacturers. However, the code of practice crash bar gave the worst test results of all because it absorbed little energy as it hinged back on to the bonnet leading edge and it then spread the load on to the bonnet, preventing local deformation.

From these results it was concluded that a code of practice had certain significant limitations. It could increase the safety potential of a design and in some cases could completely remove a problem feature. Nevertheless the simple approach that has to be adopted for a code of practice can be confounded by the interaction of crash bar and vehicle for a particular design. Although not discussed at length in the report the results made it clear that a regulation or standard, based on impact tests to the crash bar fitted to the vehicle on which it is intended to be used, would be the best method of requiring pedestrian protection.

It was also noted that it may be possible to make a crash bar that improved the pedestrian protection of a vehicle. This would require provision of more crush depth by standing the crash bar away from the bonnet and the use of local compliance and lightweight materials.

5 Development of an ISO standard for pedestrian protection

The International Organization for Standardization created a pedestrian protection working group (ISO - WG2), in 1987. In an effort to harmonise the ISO test procedures with those developed by the EEVC - WG10, TRL has participated in some of these ISO meetings. Progress in this working group has been slow. To date it has copied, with some changes, the EEVC - WG10 adult legform test method and the adult headform test method. ISO has also been developing a child headform test method, similar to the EEVC one, however, for this test method the differences between the ISO and EEVC impactor are more marked with ISO using a larger diameter and mass for the child headform. These three ISO - WG2 procedures are in various stages of being agreed at the working group and ISO/TC22/SC10 levels. The mandate for ISO - WG2 was to produce test methods suitable for reproducing an accident at any car-impact speed up to 40 km/h. This differs from the EEVC - WG10 mandate which was to produce test methods that reproduce an accident at 40 km/h. These different mandates are the reasons for some of the differences between the ISO and EEVC procedures.

The ISO adult headform mass of 4.5 kg differs from the EEVC headform mass of 4.8 kg. Both the EEVC and ISO headform tests make use of a free-flight headforms. The mass of just the head of the average adult male is 4.5kg. The headform impactor mass is intended to match the effective mass of a human head attached to the body, when the head impacts a vehicle, in a pedestrian accident. The difference between the two methods is because the EEVC have concluded that an additional 300g is required to account for the forces acting through the neck, during the head impact, while ISO have concluded that no force acts through the neck. A tolerance of ± 0.4kg is being considered by ISO - WG2 to resolve this harmonisation problem. Similarly, for the child ISO have come to different conclusions regarding effective head mass and are proposing 3.5 kg to represent a 6 year old child, whereas EEVC concluded that the effective mass of the head is less than the actual static mass due to the forces acting through the neck (tension) and use 2.5 kg. In addition ISO are proposing a diameter which matches that of a 6 year old child head, but EEVC decided to scale down the adult impactor diameter to produce the required child mass thus standardising the designs. This results in the EEVC child headform impactor being a smaller diameter than that of the average 6 year old child.

The ISO procedure for the legform to bumper test method has now been accepted as a draft procedure. The main difference between the ISO and EEVC test methods is in the lateral knee joint stiffnesses in bending and shear and the methods of specifying them. However, the latest biomechanical data (Kajzer et al., 1997) appears to indicate that the bending stiffness is too low and that the EEVC requirements are more appropriate. The biomechanical test by Kajzer were to the legs of complete cadavers, restrained via force transducers fixed to the top and bottom of the femur bone, were the leg was impacted laterally by a representation of a bumper. In legform biofidelity tests by Matsui (Matsui, 1999) where the ISO, EEVC and JARI legforms were subjected to a similar test to those of Kajzer, described above, the ISO legform was found to be the least biofidelic.

It is likely that the ISO working group will consider developing procedures for other impact phases of a pedestrian accident. To date their procedures are similar to
those of EEVC - WG17. However, it appears less likely that they will adopt the EEVC upper legform to bonnet leading edge test method. Instead they may opt to develop procedures for child and adult thorax.

None of the modifications that ISO have proposed to the EEVC procedures appears to make significant improvements over the EEVC methods and some are detrimental. This ISO activity should not influence progress of the European legislation.

6 IHRA pedestrian working group

In May 1996, at the initiative of the National Highway Traffic Safety Administration (NHTSA), a meeting of the Enhanced Safety of Vehicles government focal points was held to discuss the need for International Harmonised Research Activities for motor vehicles. Following this meeting, a series of committees was established, each covering a specific topic or themes, one of which was pedestrian protection. The UK government has made a commitment to support this work. The Ministry of Transport of Japan was selected to lead the International Harmonised Research Activities (IHRA) pedestrian working group and TRL has participated to represent Europe on this working group as part of the work of this research project. Several of the members of this new IHRA working group, including the Japanese chairman, are also members of the ISO (WG2) working group.

The mandate of the IHRA pedestrian working group is to develop harmonised pedestrian test methods for passenger cars. The first meeting was held in Tokyo in July 1997 and a further three meetings have been held to-date.

In these four meetings there has been a considerable exchange of information, particularly accident data and information on the available EEVC and ISO test methods. The group has decided to develop sub-system test methods to reflect the world-wide vehicle population and accident situation. As a result, their test methods may cover a larger range of vehicle shapes and sizes, test velocity, test areas, and pedestrian body parts than the EEVC and ISO procedures. The first priorities has been to develop a test method for head injuries caused by impacts with the car bonnet, windscreen and windscreen surround and a test method for leg injuries caused by bumper impacts. However, they have agreed that test methods for other body regions needing protection should be progressed in parallel. The body regions being considered for test procedures are: head, chest, abdomen, pelvis and possibly the neck for both child and adult, and also the adult femur, knee and tibia. To aid this process, standardised information sheets were being developed to record accident data and available test methods and test tools. The intention was to use computer simulation data to determine the impact conditions for this larger range of vehicle sizes, vehicle impact areas and pedestrian body parts.

Limited progress was made towards producing test methods during the period of this project. Initial discussions were devoted to defining a passenger car.

Originally it was intended that this definition, which was used to select both accident data and the vehicles that would require testing, should represent the vehicles most often involved in pedestrian accidents world-wide. Because no accident data was available from developing countries, this discussion centred on whether US type heavy sports utilities and pick up trucks should also be included along with more usual sized cars, car based vans and delivery vans. The current IHRA definition is up to 9 persons and 2,500kg. However, the heaviest sports utilities, pick-ups and vans used in the USA weigh about 3200 kg and 14 out of 37 US models of this type exceed 2500kg. These vehicles form a significant proportion of the US fleet.

The IHRA group decided to:

a) develop test methods based on EEVC and ISO test methods but extended to cover a wider range of vehicle shapes, different possible higher impact speeds and a larger test area (including the windscreen, A pillars and windscreen upper frame);

b) develop impactors, test methods and injury criteria, in addition to the EEVC and ISO ones, to represent other body parts likely to suffer serious or life threatening injuries.

The IHRA working group will report progress at the 2001 ESV conference. The future of the working group will be decided after that.

7 Discussion

The aim of the research project, was to support the development of the EEVC pedestrian test methods and the adoption of these test proposals as an EC Directive. In addition the project also aimed to support the efforts of the working groups developing world-wide pedestrian test procedures.

As can be seen from the summary of research outlined above, this project has succeeded in these aspirations in developing, reviewing and updating the test methods.

The project has achieved its main aim of supporting the adoption of the EEVC pedestrian test methods as an EU Directive through the work of the EEVC Working Groups 10 and 17 who have developed complete and well proven test methods. The development of the legform and upper legform impactors and the contribution to developing and assessing the headform impactors has helped to make these test methods suitable for use in a Directive. However, there are practical difficulties of making a step change from the current low levels of pedestrian protection requirements to full compliance with the EEVC test methods. Phasing in of the test requirement could be considered to resolve this problem. One option for phasing in pedestrian protection could be initially to omit one or more of the tests. However, this option could result in an overall reduction in pedestrian protection. Omission of the upper legform test to the bonnet leading edge for example, is likely to result in it becoming more dangerous even if its design remains unchanged. This is because a more gentle bumper impact, to meet the bumper
test, will increase the severity of the bonnet leading edge contact. Worse, in the absence of a test to the bonnet leading edge, the legform test will encourage manufacturers to increase the strength of the bonnet leading edge in order to help arrest the femur section of the bumper test tool (the legform impactor) and prevent excessive bending of the impactor’s knee. Because of these concerns EEVC – WG17 recommended that the test methods should be adopted as one, complete package (EEVC, 1998). A more suitable method of phasing in pedestrian protection would be to use all the test procedures but phasing in the proportion of each test area that would be required to pass.

Participation in the work of the IHRA and ISO working groups has helped in the development of test methods which are similar in principle to those of the EEVC. However the nature and constitution of these groups has resulted in rather slow progress.

8 Conclusions

1 The research undertaken in this project has made a major contribution to the work of EEVC Working Groups 10 and 17 in developing test methods suitable for use in regulations to require certain standards of pedestrian protection for vehicles.

2 The European Commission has made a commitment to put before European Parliament a proposal for a pedestrian protection Directive based on the recommendations of EEVC Working Group 17. This decision acknowledges the progress made in producing the test methods and tools and indicates that the aim of this project has been achieved.

3 Systematic and detailed reviews of the EEVC test methods have been made and many suggestions produced to improve and revise the wording and figures of the test methods.

4 The designs of the headform impactors have been evaluated and advice provided on design modifications to resolve observed problems.

5 The upper legform impactor and test method has been improved by:

   a developing an improved dynamic certification method;
   b resolving a problem of an unintended load path in the upper legform impactor;
   c developing a production version of the upper legform impactor suitable for use in legislative tests;
   d refining the provisional acceptance criteria values by reconstructing well documented pedestrian accidents and carrying out a statistical analysis of the results;
   e refining the upper legform test energy look-up graph by developing and using a mathematical simulation model;
   f producing estimated of the number of cars tested under the Euro-NCAP programme that would have passed the upper legform test had the new energies and acceptance criteria been used.

6 The INRETS legform impactors and test methods were evaluated and problems observed have been resolved by:

   a using anthropomorphic data to produce new targets for the mass, centre of gravity and moment of inertia for the simplified shapes of the tibia and femur impactor sections;
   b developing and assessing an experimental legform impactor with a damped shear spring system. Initial work on designing a production version of the legform impactor suitable for use in legislative tests was undertaken;
   c developing improved static and dynamic certification methods and certification pass fail requirements;
   d carrying out a statistical analysis of the results of biomechanical tests with different bumpers to determine the risk of tibia fracture due to acceleration forces.

7 A cost benefit analysis for the proposed pedestrian protection test procedures and requirements was undertaken. Further analysis was undertaken following publication of the MIRA study and submitted to the EC.

8 Technical support has been provided to the DETR in discussions with the EC and the car industry.

9 Phasing in of the test requirement could be considered to resolve the practical difficulties of making a step change from the current low levels of pedestrian protection requirements to full compliance with the EEVC test methods.

10 The option of phasing in pedestrian protection by initially omitting one or more of the tests is not recommended because it is likely to result in that area becoming more dangerous. Instead, phasing in of the area required to pass the tests is recommended.

11 An initial study to assess the pedestrian safety of one model of off-road vehicle both with and without bull bars was undertaken and it was concluded that their safety should be assessed by impact tests and that a code of practice for bull bars manufacturers would not be effective.

12 It may be possible to make bull bars that improve the pedestrian protection of a vehicle.

9 References


EEVC (1994). Proposals for methods to evaluate pedestrian protection for cars. EEVC.

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Abstract

Pedestrian casualties form a large proportion of road user casualties in most developed countries. Car design measures to reduce the severity of pedestrian injuries will also benefit many pedal cyclists and a small number of motor cyclists.

Historically, funded by the DETR, TRL undertook a large proportion of the research that has led to the current EEVC pedestrian protection test methods.

The aim of the research project ‘Pedestrian protection test procedures and design’ was to support the development of the EEVC pedestrian test methods and the adoption of these test proposals as an EC Directive. The research project ‘Pedestrian protection test procedures and design’ commenced in April 1992 and was completed in March 1999. The work in this period included the evaluation and improvement of the test procedures; the assessment and development of the test tools; the reconstruction of accidents to obtain biomechanical data for the femur and pelvis contact with the bonnet leading edge acceptance values; a study of the cost and benefits of improved pedestrian protection and an initial study of the value of using a code of practice to improve the pedestrian protection of bull bars and is summarised in this final report.

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