PEDESTRIAN SAFETY TESTING USING THE EEVC PEDESTRIAN IMPACTORS

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ABSTRACT

An European Experimental Vehicles Committee (EEVC) working group has developed a set of test procedures for evaluating the safety performance of cars when they strike pedestrians. These are being considered for possible legislative use in an European Directive. The Transport Research Laboratory (TRL) has played a major part in this working group, including the study of accidents and injuries, and development of the test procedures. It has developed the upper legform to bonnet leading edge impactor and test procedure, and has made substantial contributions to the development of the legform impactor used to test the bumper area.

TRL has also performed a large number of tests to cars, using the headform impactors to test the bonnet area, as well as using the upper legform and legform impactors. Many of these tests were performed as part of a New Car Assessment Programme. The experience gained in testing with the impactors has led to a number of minor refinements to the test procedures.

This paper reports some results from these tests, and demonstrates the current level of pedestrian protection. Test locations that offer relatively high levels of protection indicate that solutions to the problem of achieving better pedestrian safety are often readily available, low cost, and could be applied over a higher proportion of the car surface.

INTRODUCTION

In European countries unprotected road users account for a significant proportion of road accident casualties. In 1995 there were just less than seven and a half thousand pedestrians killed and approximately eighty thousand seriously injured on the roads of the European Union. Accident data show that approximately sixty percent of pedestrian casualties were struck by the fronts of cars. In a typical frontal accident at moderate speeds, the impact of the bumper and bonnet leading edge causes the pedestrian to wrap over the front of the car with their head striking the bonnet top, windscreen or windscreen frame. They then slide forward onto the road as the car slows under the action of braking. Pedestrian accident studies have shown that the most frequent causes of serious injuries were impacts of the legs with the bumper, the upper legs, pelvis or abdomen with the leading edge of the bonnet and wings, and the head and chest with the top surface of the bonnet and wings, scuttle, windscreen frame and ground. To help reduce this undesirably high pedestrian casualty rate, the UK Department of Transport (now the "Department of the Environment, Transport and the Regions") funded the Transport Research Laboratory to carry out research into the possibility of reducing pedestrian injuries by making cars less aggressive in accidents. This work by TRL has made a major contribution to the development of the EEVC pedestrian protection test procedures (some of the EEVC pedestrian working group research was partially funded by the European Commission). These procedures have now been incorporated in the European Commission's draft proposal for a European Parliament and Council Directive (1). The test procedures comprise three sub-system impact tests to assess a car's performance. Separate impactors are used to represent the pedestrian in each main phase of impact. The three impactor types are: a bumper impactor representing the adult lower limb to indicate lateral knee joint shear displacement, bending angle and tibia acceleration, a bonnet leading edge impactor representing the upper leg to record bending moments and forces, and child and adult head impactors to record head accelerations. 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.

Within the EEVC Working Group, BASt was responsible for developing the head impact procedure and the prototype head impactors, TRL was responsible for developing the upper legform to bonnet leading edge test method and the "research" upper legform impactor, and INRETS was responsible for developing the legform to bumper test procedure and the "research" legform impactor.

The design of the headform impactors was refined by TNO to produce a "production version". TNO are currently considering further minor changes to the headforms to improve the accelerometer mounting and durability.

The design of the upper legform impactor, developed by TRL, has been refined to produce a "production version" suitable for use as a regulatory tool.

TRL have also developed a prototype legform impactor which is a development of the INRETS research legform but modified for use as a regulatory tool.

This paper provides a brief description of the test methods and the work to improve the prototype TRL legform and upper legform impactors. Observations made by TRL and others following experience with using the test methods are reviewed. Finally, the results of testing current cars are summarised and the significance of these test results are discussed.

THE EEVC PEDESTRIAN TEST PROCEDURES

To gain the maximum benefit, all the parts of the vehicle likely to strike pedestrians should be as "pedestrian friendly" as possible. The impact location on a car of a pedestrian's main body regions is dependent on the pedestrian's build and stature, stance and motion, as well as the vehicle's shape and impact speed. Because of this and the wide range of real life accident circumstances, the whole surface of the car front can potentially strike a pedestrian.

Sub-systems test methods, as a regulatory tool, have many benefits over using pedestrian dummies for both the car industry and approval authorities. If pedestrian dummies were used for legislative tests it would be very difficult to predict and control the impact locations of body parts to test selected danger points accurately, particularly the head. Also a range of pedestrian dummies of different stature would be required to test all areas likely to be hit in real life. A test with a single size (eg fiftieth percentile) dummy would not be sufficient for pedestrian protection. It would also be particularly difficult to achieve repeatable results using pedestrian dummies. Separate sub-system tests, using impactors to represent parts of a pedestrian's body, do not suffer from these problems, are much cheaper in terms of hardware, the impact conditions are known and can be designed for, and they can be used in vehicle development to test sub-assemblies of the car. However, for a sub-system test to represent part of a complete pedestrian impact, a detailed knowledge of pedestrian impact conditions is required; this knowledge was available within the EEVC working group. The mandate for the EEVC working group was to develop sub-system tests that:

a) represented a pedestrian accident at 40 km/h and assessed the level of pedestrian protection provided by the car.
b) restricted the test area for the head impact tests to include only the bonnet top, wing tops, scuttle and base of the windscreen.

The speed was chosen because studies had shown that protection effective at this speed was practical and would produce significant reductions in the severity of pedestrian injuries, whilst requiring reasonable levels of energy absorbing and crush depths from the car structure. Its is assumed that protection effective at 40 km/h would also be effective in accidents at speed below 40 km/h and provide some injury reductions in accidents at higher speeds.

The test area was limited to these areas because research had demonstrated that it was practical to provide protection in these areas. However, the windscreen, A pillars and upper frame contribute considerably to the vehicle's overall strength. Although research has shown that it was possible to make some improvements to these parts, the practicality of this had not been proven. Present types of windscreen glass were generally considered to be acceptable for pedestrian head impacts in accidents at speeds up to 40 km/h, apart from the edges which are supported by the surround.

Accident studies (2) (3) have shown that, at speeds of up to 40 km/h, adult pedestrians are more at risk of being seriously injured than child pedestrians from the impact of the bumper and bonnet leading edge (apart from those children so small as to be hit directly on the head by the bonnet leading edge). The legform to bumper impactor and the upper legform to bonnet leading edge impactor have both been designed to represent the contact between the leg of an adult male pedestrian and the front of a car travelling at 40 km/h. For the bonnet top, both child and adult pedestrians are at risk of suffering serious head injuries and therefore the bonnet top test requirement is for a child headform test to the front section of the bonnet and an adult headform test to the rear of the bonnet. The development of these test procedures are reported in more detail in the EEVC WG 10 report (4).

Legform impactor to bumper test

The impactor that has been developed for the bumper sub-systems test was chosen to represent an adult leg being impacted from the side. The design philosophy of this impactor and test method was to reproduce the significant interactions between a pedestrian's leg and the car front whilst taking measurements that could be related to the risk of injury to the knee joint and the fracture of the leg bones. The legform impactor consists of "femur" and "tibia" sections joined by a mechanical knee. The shapes of the sections have been simplified but have physical properties (length, mass, centre of gravity and moment of inertia) equivalent to the leg of a 50th percentile male. The tibia section includes the mass of a foot. The knee joint has stiffnesses in both shear and bending that are similar to a human knee loaded sideways, as specified by EEVC WG10. The impactor has a 25 mm layer of heavy energy absorbing foam flesh covered with a 6 mm thick neoprene skin.

The test method requires the legform impactor to be propelled to strike the car front in free-flight at 40 km/h. The legform, with the deformable knee joint, will respond in a similar way to a human leg (without broken bones) when impacted by something having the shape and stiffness of the car front. The knee instrumentation reports knee bending angle and shear displacement whilst the accelerometer measures the tibia acceleration. The acceptance criteria for the knee joint are intended to prevent serious ligament damage in both bending and shear. Also, the additional criterion on acceleration would require a deforming structure that limits the contact force, and thereby reduces the risk of tibia injuries.

The upper legform to bonnet leading edge test

In pedestrian accidents the first contact is normally with the pedestrian, side on, and is between the lower leg and the bumper. This contact starts to sweep the pedestrian's legs from under him or her. For the adult the next contact is normally between the upper leg and / or pelvis and the bonnet leading edge. However, the first contact between the bumper and lower legs will affect the nature of this second contact with the bonnet leading edge, particularly the upper leg angle and impact velocity. The extent to which the bumper contact affects the bonnet leading edge impact is very dependent on the vehicle geometry.

When the bonnet leading edge strikes a pedestrian, it generates forces in the pedestrian's body. The contact with the upper leg accelerates the impacted part of the leg and this in turn reacts against the mass and inertia of the pedestrian's body above and below the contact point. This action causes bending of the femur and forces in the joints at each end of the femur, particularly at the hip joint and can result in femur fractures or pelvis fractures. The effective mass seen by the car bonnet is a combination of the mass of the struck part plus some of the mass of the pedestrian's body parts above and below the contact and its value is also effected by vehicle geometry.

For the sub-system test it was necessary to establish the relationship between vehicle geometry and upper leg impact angle, velocity and effective mass. This information was obtained both experimentally and mathematically by simulating impacts between a pedestrian dummy and a range of car shapes (5) (6). In these studies the energy absorbing properties of the cars were selected to be of the correct order needed to provide pedestrian protection. These relationships have been incorporated into the test method in the form of parameter look-up graphs.

The design philosophy of this impactor and test method was to reproduce the significant interactions between a pedestrian's upper leg and the bonnet leading edge whilst taking measurements that can be related to the risk of femur and pelvic fractures. The upper legform impactor is propelled into a stationary car so as to represent a pedestrian's accident at an initial car impact speed of 40 km/h. A diagram of the current impactor is shown in Figure 1. The impactor consists of a front member, which

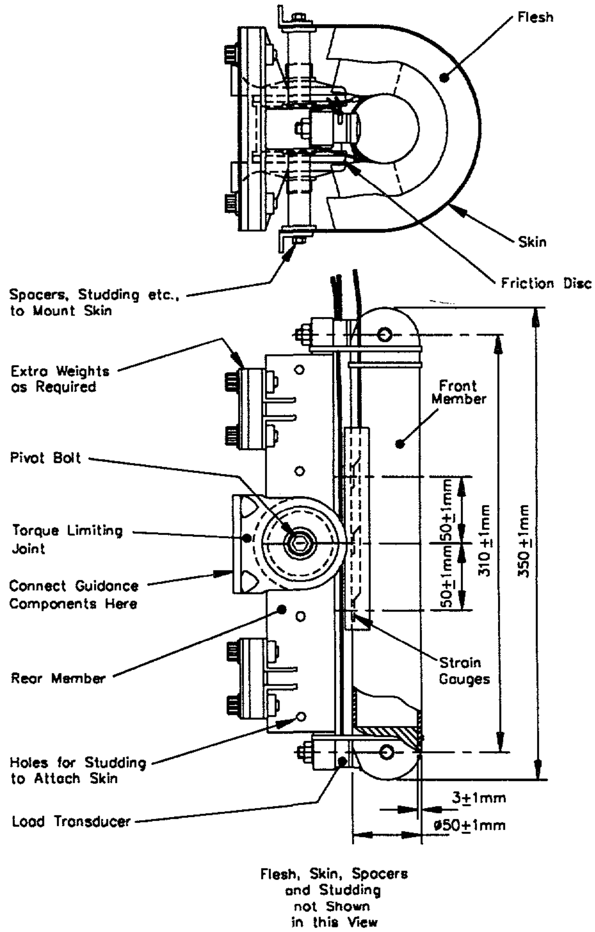

Figure 1. Upper legform impactor

represents an adult femur (though it was intentionally made shorter than an adult femur), supported at top and bottom, via load transducers, to a vertical rear member, which is in turn mounted on the end of the guidance system through a torque limiting joint. The front member is equipped with strain gauges to measure bending and is covered by a 50 mm thick layer of heavy energy absorbing foam to represent the flesh covering a pedestrian's upper leg.

On impact with the bonnet leading edge of a car, the femur tube can react against its top and bottom supports in a similar way to a pedestrian's femur reacting against the pelvis and lower leg. The femur tube is free to bend in the middle, under the influence of the contact forces from the bonnet leading edge, again like the pedestrian's femur.

For each car and each impact location on the car, the car's shape (bonnet leading edge height and bumper lead) will be different, therefore different impact conditions are required for each test. The impactor's angle, mass and velocity values, appropriate for the shape of the car under test, are found from the parameter look-up graphs in the test procedure or, more practically, by a computer program available from TRL. The provision to attach weights to the impactor was to allow the mass to be adjusted to match the effective mass of the pedestrian's upper leg which is appropriate for the shape of the car being tested. The angle and velocity of the propulsion system can also be adjusted to appropriate values for the shape of the car being tested.

Analysis of tests with adult pedestrian dummies showed that, for most car shapes, the angle of the upper leg changed little during the most severe part of the impact with the bonnet leading edge. This is due to the restraining effect of the inertia of the pedestrian's body parts above and below the impact and the short duration of this phase. It was also observed that any rolling of the pedestrian's upper leg that took place during the main bonnet leading edge impact had little effect on the direction of force generated in the car's bonnet leading edge. To reproduce this restraint simply, the upper legform impactor is attached to a linear guide throughout the impact with the car.

The impactor has been used to reproduce well documented pedestrian accidents. These tests confirmed that the impactor and test method faithfully reproduced vehicle damage in accidents with adult pedestrians of average build.

The torque limiting joint was provided to protect the guidance system from damage when testing cars with very poor pedestrian protection. It was not intended to move in tests on cars with acceptable levels of pedestrian protection, and the minimum torque setting specified will not be exceeded in tests with cars that meet the current proposed acceptance criteria.

The acceptance criteria for the upper legform impactor are intended to prevent fractures of the femur and pelvis. However, the current acceptance values are provisional and are almost certain to be significantly raised in the near future making the requirements less demanding while retaining the same targets for protection levels. This is discussed further in the section on the upper legform acceptance criteria.

The headform to bonnet top test

Accident data have shown that the body region most frequently suffering life threatening injuries is the head in both child and adult pedestrian accidents. Adult head impacts points were most frequently towards the rearward part of the top of the bonnet and wings, the windscreen frame and the windscreen. The head impacts of young children were more frequently to the frontal part of the top of the bonnet and wings.

Therefore, two assessments have been included in this sub-systems test. One is based on an impactor representing a child headform to evaluate the forward section of the bonnet and wings and the second based on an adult headform to assess the rear of the bonnet, wings and the scuttle. The child headform is propelled to strike the car in free-flight at 40 km/h at an angle of 50° to the horizontal and the adult headform to strike the car in free-flight at 40 km/h at an angle of 65° to the horizontal.

Both of the headforms that have been developed for these tests are of spherical shape (to give more repeatable results), with a 7.5 mm thick silicone outer flesh. The headforms are equipped with tri-axial accelerometers. The acceptance criterion (Head Injury Criterion of 1000) is intended to prevent serious, life threatening, head injuries.

DEVELOPMENT OF IMPACTORS AND TEST METHODS, AND PROBLEMS IN USE

TRL and others have been using the impactors for several years, and the experience thus obtained has also led to a number of minor refinements of the test procedures, such as improved tolerances and, in some places, a greater clarity of wording. This experience has also led to a number of minor improvements being made to the impactors. The modifications to the legform and upper legform impactors are to improve their reliability, repeatability and ease of use.

Development of the TRL legform impactor

Since the first reporting of the EEVC pedestrian impact test procedures (7), TRL has produced a prototype legform impactor and revised the legform static certification corridors. These revised corridors were included in the EC draft Directive. A total of 13 of these prototype impactors have been manufactured by TRL and are in use in both test houses and car manufacturers' test departments.

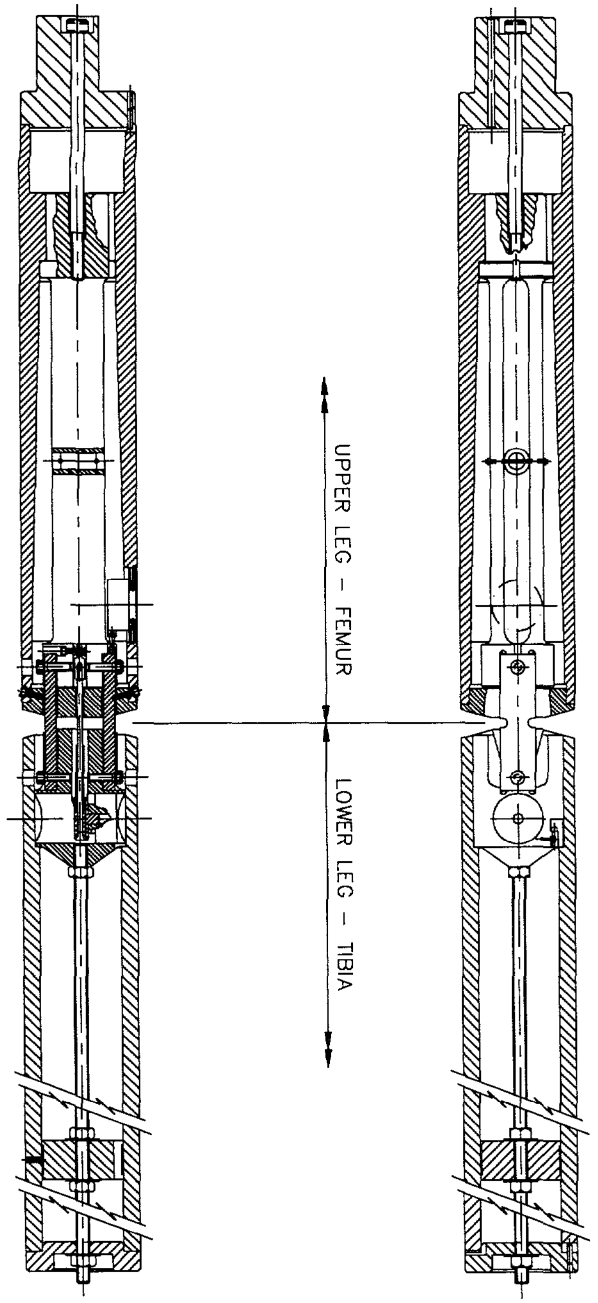

Figure 2. TRL legform impactor

The knee of the TRL prototype impactor contains an elastic spring to produce the shear stiffness together with disposable deformable steel ligaments to provide the bending stiffness. The instrumentation system independently measures the knee shear displacement and bending rotation. The current legform design is shown in Figure 2.

The TRL legform impactor is currently subject to small improvements. In the current prototype there is an undesirable vibration of the knee shear spring leg mass system. The two sections of the legform are connected by the knee shear-spring and the knee shear and acceleration outputs are adversely affected by the natural frequency of vibration of this spring / mass system. The need for a damped shear-spring leg-mass system was considered when the impactor was first developed. However, it was decided to develop and assess firstly an impactor without damping. This assessment has shown that the impactor meets the EEVC requirements and it has proved robust in use but it exhibits this undesirable vibration during dynamic tests. Therefore, a damping system is being added to resolve this outstanding problem, in a further phase of impactor development.

Currently, TRL have made and assessed an experimental damped legform which incorporates a readily available hydraulic damper. This damper met the damping requirement but was not ideal for building into the legform because it was larger than necessary and therefore vulnerable to damage. Testing of this experimental damped legform has shown that the damper has resolved the vibration problem without adversely affecting the knee joint's shear performance. The next phase of development to produce a tailor-made damper unit of minimal size is now in hand, and a damped legform impactor (see Figure 3) will then be made and tested.

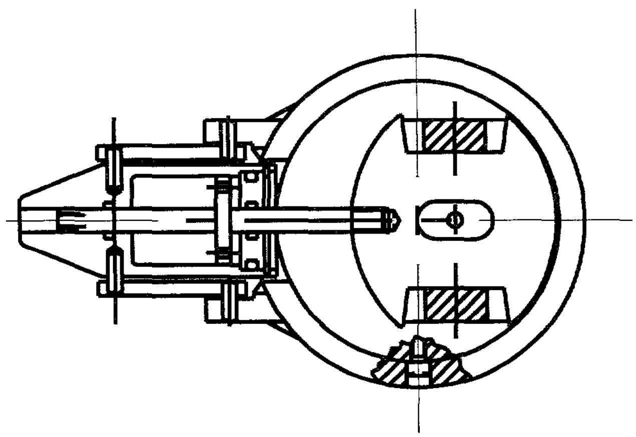

Figure 3. Section through damped legform

Development of an improved dynamic certification test for the legform impactor The current dynamic certification method, developed by TNO, makes use of a pendulum system originally designed to certify the necks of test dummies. This certification method has a number of disadvantages in practice. As the legform is attached to the pendulum its trajectory and impact configuration is not typical of a car impact and the knee shear displacement is too close to the full-scale displacement limit.

To overcome these problems, TRL is proposing a new certification method. The details of this certification method are shown in Figure 4.

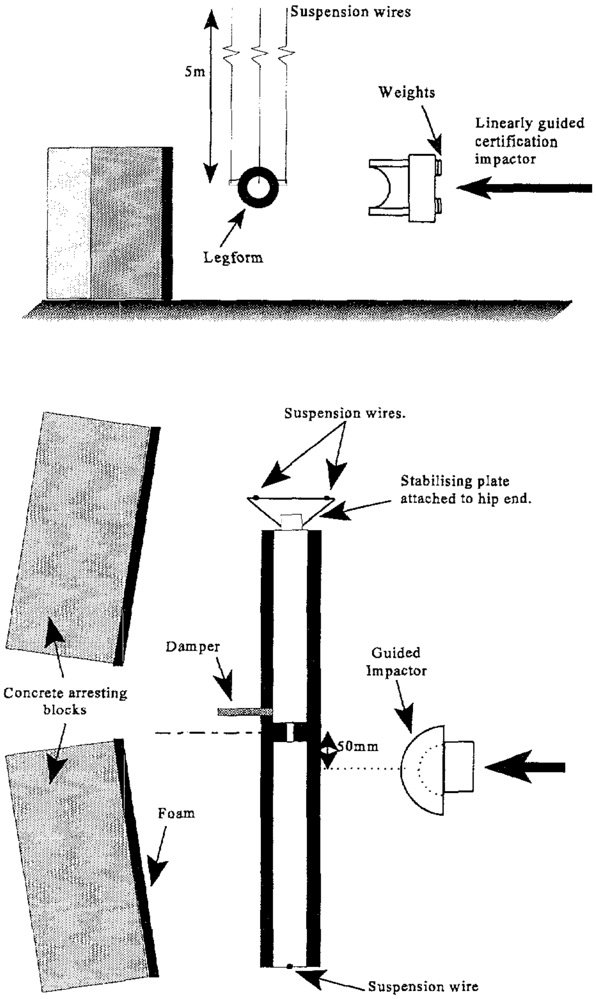

Figure 4. New legform certification method

Testing of the damped experimental legform to this new certification method has shown that it appears to be satisfactory, generating the required levels of knee bending and shear, and giving repeatable results. It is not intended to finalise this certification test method until the final version of the legform impactor with the damped knee shear system is available and the effects of acceptable variations in impactor performance (knee bending stiffness, foam flesh etc) have been further investigated. It should also be noted that the experimental damped legform had no corrections for the added mass of the damper and this will have had a small effect on its performance in the new dynamic certification test.

Problems found in using the legform impactor

Experience with the legform impactor and test method, both at TRL and within industry, have given rise to several observations. These points are reviewed below together with the proposed modifications, if appropriate:

Vibrations Vibrations have been observed in dynamic tests and the legform requires a damper for the knee shear-spring leg-mass system. As described above TRL are developing such a system.

Certification The dynamic certification method is in conflict with the knee shear displacement stops. TRL have developed an improved dynamic certification method which has resolved this problem and is described above.

Bending ligament specification It has been suggested (8) that the effects of the range of knee bending ligament stiffnesses permitted within the corridor, would have a large effect on impactor performance. However, the energy required to bend the knee joint, to the bending acceptance level of 15 degrees, is only about 12% of the total kinetic energy of the legform. Because of this, the distribution of force along the impactor face, rather than knee bending stiffness, should predominate in controlling the knee bending angle. The effect of the bending corridor's width on the ligament bending energy, compared with the impactor's kinetic energy, is less than plus or minus 2% which seems very unlikely to effect test results significantly. In practice, it would be impossible to manufacture a ligament which followed either extreme of the bending stiffness corridor, particularly at the start; this would reduce the effects of the corridor's width still further.

Initial tests using the dynamic certification method to investigate the effect of ligament stiffness have suggested that the corridor would have a maximum effect of about plus or minus 14% on the certification bending angle. This test, with a concentrated load applied close to the knee, is far more likely to be affected by different ligament stiffness than a car test with the distributed load of a car bumper system. Further full scale tests on a car which has passed the legform requirement will be performed, using ligaments at the practical extremes of the bending stiffness corridor, to determine the effects of the permitted range of ligament stiffnesses, within the corridor, on test results.

It is also suggested that there is insufficient testing of bending ligaments to confirm their compliance statistically. The current requirement in the test method is to certify one pair of bending ligaments in the static test and one pair in the dynamic test, and then use the impactor, for a maximum of 20 tests, with ligaments from the same batch of manufacture. However, as well as this it is obviously the responsibility of the ligament manufacturer to establish methods of quality control to ensure compliance. For TRL's own quality control system, large sheets of steel are purchased from which about 1500 pairs of ligaments can be made. Sample ligaments are then made and tested using the static bending certification test to establish an appropriate ligament waist size for the material properties of that sheet of material. Ligaments are then manufactured from that sheet in batches of 50 pairs, with statistical control methods being used to ensure conformity of ligament dimensions. The tolerances of the ligament dimensions have been set at an appropriate level to ensure that their effects on ligament stiffness are small and well within the corridor width. At least one pair from each batch is then tested by TRL in the static bending certification test and the results are monitored to ensure consistency and identify any changes in material properties as the sheet of raw material is consumed.

Methods of further controlling and shaping the ligament bending properties are being investigated since the performance of the steel in plastic bending is different from sheet to sheet of raw material and does not necessarily match the slope of the corridor. However, even if better control of the ligament stiffness is developed no change of the existing static bending certification corridor is anticipated at present.

Shear displacement anomalies Positive or negative peak shear displacements have been observed under nominally identical test conditions. Typical car tests produce shear displacements first in one direction and then in the reverse direction. These positive and negative displacements are often of very similar magnitude, therefore it is not surprising to see this effect. However, the effects of the vibration of the un-damped shear-spring leg-mass system could often contribute to this effect; the damped version should improve the repeatability of shear displacements.

Mechanical shear displacement limits There is concern that the mechanical limits of the shear spring are only about 15% in excess of the acceptance criteria, giving little overload information. The mechanical stops were intended to give a 20% overload capacity and TRL are investigating improvements to give that intended displacement. The shear spring system, and the impactor's dimensions and specification make it difficult, if not impossible, to increase the overload capacity above 20% within the current design. This overload capacity is considered to be sufficient for using the impactor for its primary purpose as a legislative test tool. It should be noted that it is most probable that a bumper system that meets the bending and acceleration requirements will also meet the shear requirements. The current impactor already has a large overload capacity for these two measurements, which will probably provide sufficient feed-back for manufacturers to develop bumper systems to meet the requirement. The value of an overload capacity as a development tool is recognised and the possibility of producing a different version of the impactor (or a kit of parts), with a larger shear overload capacity, for the purpose of developing bumper systems will be investigated if there was sufficient demand for it.

Flesh properties It has been suggested that the neoprene skin and Confor™ foam flesh are not sufficiently well specified nor chosen with biofidelity in mind. The type and dimensions of these materials are specified in the test method and their dynamic performance is controlled and specified by the dynamic certification performance requirements. Like test dummies, the pedestrian impactors have problems with flesh. For durability and practicality reasons the majority of the weight is concentrated in the metal parts or "bones" of the test devices and not in the flesh as in a human. However, the pedestrian legform impactor makes use of Confor™ foam which is more like human flesh than the foam flesh used in test dummies because it is both significantly heavier and more capable of absorbing impact energy. The vehicle crush depth and energy absorption required to meet the legform criteria is much larger than the available flesh crush depth and energy absorption capabilities in both humans and the legform impactor. Consequently the influence of the impactor and human flesh is relatively insignificant to the response. Also the flesh on the leg will have little, if any, influence on the strength of the bone and knee. Therefore, the biofidelity of the flesh is not considered critical.

Development of the TRL upper legform impactor

The original research version of the upper legform impactor, used to develop the test method, was described by Lawrence, et al (9). It has since been refined to produce a "production version", although it has not been changed in principle since its conception.

This production version was most recently modified (in January 1996) to remove an unwanted load path through the foam flesh to the back of the impactor. After this revision of the flesh and skin system a series of impact tests was performed to confirm that the load transducers accurately reported the impactor force. For this the impactor impulse, derived from the measurement of impactor acceleration and mass behind the load transducers, was compared with the impulse derived from the force time histories, and the results are shown in Table 1. These results confirm that the load transducers were accurately reporting the impactor force, with the impulse derived from both methods agreeing to within 1% in all tests. Measurements of impulse rather than force were used for this comparison because instantaneous values of force derived from acceleration and mass are likely to suffer from the inherent noise found in the accelerometer time histories of mechanical systems.

The amended design is now considered to be satisfactory for this aspect.

Acceptance criteria for the upper legform impactor
The current acceptance values for the upper legform to bonnet leading edge test were based on published biomechanical data and the reconstruction of pedestrian accidents with the upper legform impactor (9). The accident reconstructions were carried out as part of the development of the test method using the first research version of the upper legform impactor. These reconstructions demonstrated the large variation in human injury thresholds which are always found in biomechanical studies, making it difficult to select suitable acceptance values. It was concluded that these data were insufficient to select well justified acceptance criteria and the current values have therefore always been regarded as provisional. Improvements to the impactor (improvements to the flesh etc) since these first reconstructions have resulted in the impactor producing larger outputs, making these provisional criteria less appropriate. To provide further data on which to select the acceptance criteria, one additional accident reconstruction programme has been completed and a second one started. Other research institutes are also carrying out accident reconstruction programmes, which will be combined with the TRL results to produce revised acceptance criteria. The initial results from these programmes indicate that the criteria are likely to be increased significantly. The results of this work are expected to be reported before the end of 1998.

Table 1. Results of upper legform impulse tests into a foam covered concrete block (current impactor design with revised flesh system)

Test No	Impact Orientation	Impulse **A** # (Ns)	Impulse **B** ✣ (Ns)	Ratio of **A/B** (%)
1	normal*	111.5	111.3	99.8
2	normal*	112.1	111.4	99.3
3	normal*	112.0	111.8	99.8
4	normal*	165.6	165.7	100.1
5	normal*	163.3	161.8	99.1
6	simulated bonnet leading edge†	134.4	134.5	100.1
7	simulated bonnet leading edge†	136.0	137.2	100.9
8	simulated bonnet leading edge ‡	135.4	135.1	99.8
9	simulated bonnet leading edge‡	135.8	136.0	100.1

* *impactor front member normal to face of test block*
† *centre of impactor front member, to simulated bonnet leading edge*
‡ *impactor front member contact at level of inner skin spacer, to simulated bonnet leading edge*
# *calculated from: Mass behind load transducers x Velocity change (by integration of acceleration)*
✣ *calculated from integration of load transducers outputs*

Test impact energy requirement for the upper legform impactor The current test energy parameter look-up graphs were based on computer simulations, with the results adjusted to reflect the energy required to replicate vehicle damage in accident reconstructions. As a cars become more streamlined, the severity of the bonnet leading edge impact declines and this is reflected in the test energy look-up graph. However, accident reconstructions with newer, more streamlined cars have suggested that the damage caused in the upper legform test may be more severe than that found in accidents at the same speed. This effect may be partially or completely due to the comparatively stiff bumpers of modern cars which reduce the severity of the bonnet leading edge impact at the expense of a more severe impact to the knee and lower leg. Recent accident data have shown an increase in the proportion of knee and lower leg injuries as the proportion of upper leg and pelvis injuries has declined (10). Computer simulations are being performed to examine in more detail the effects of car shape on the upper leg to car bonnet deformation energy and the effects on this energy of modifying the bumper and bonnet leading edge stiffnesses to make them safe for pedestrian impacts.

Problems found in using the upper legform impactor

Experience with the upper legform impactor and test method, both at TRL and within industry, have given rise to several observations. These points are reviewed below together with modifications proposed, where appropriate:

Look-up graphs Manual interpolation of test parameters from the parameter look-up graphs in the regulation can lead to inconsistency in selecting test conditions. A software program to calculate these values has been produced. This program contains an identical data set to that used to draw the parameter look-up graphs and removes the possibility of human error in reading off test conditions. This program has been readily available to all since 1992.

Contact point First contact is not always to the bonnet leading edge reference line. The bonnet leading edge reference line is part of a simplified method of determining a car's shape to set the test conditions. For most vehicle shapes first contact will be very close to the bonnet reference line, however, it was never intended for first contact to coincide precisely with this line.

Impactor durability The impactor body can be damaged in moderate to severe overload conditions. The impactor has been designed to withstand loads in excess of 2.5 times the acceptance criteria. It has been used in tests to steel bull bars and has withstood forces and bending moments in excess of 4 times the acceptance criteria without damage. Only one impactor has been returned to TRL with damage to the body. Although the records of the test house concerned showed that the impactor had not been overloaded, testing at TRL proved that it had in fact been inadvertently subjected to loads in excess of 6 times the acceptance criteria.

Flesh specification The rubber skin and Confor™ foam flesh are not closely specified nor chosen with biofidelity in mind. This observation is similar to that for the legform impactor discussed above. It is considered that the specification in the test method is sufficient. The biofidelity of the flesh is not critical and its performance has been taken into account in determining the acceptance criteria.

Off- road vehicles For some large off-road and multi-purpose vehicles, the test method requires an upper legform test at heights higher that the thigh of pedestrians of normal stature. The upper legform test becomes less appropriate for bonnet leading edge heights in excess of 1000 mm. For these tall fronted vehicles an abdomen impactor or even a chest impactor might be more appropriate. However, these vehicles form a very small proportion of the fleet so it was decided not to develop these impactors. Instead, the vehicles are required to pass an upper legform test because design changes to meet this requirement would result in an improvement from current practice and would reduce injuries, as the upper legform requirements are considered to be roughly similar (but less demanding) to those for protection of the abdomen or chest.

Available crush depth For large vehicles the combination of test energy and current acceptance criteria requires impractically large vehicle crush depths. It must be accepted that these vehicles are particularly likely to cause serious injuries from bonnet leading edge contacts. The acceptance criteria are currently under review and are likely to be increased, which will reduce crush depth requirements pro-rata. However, if this adjustment proves to be insufficient to reduce the crush requirement to more practical levels, it may be necessary to consider capping the energy requirement to limit the required crush depth.

Duplication of testing Both the legform impactor and the upper legform impactor strike the bonnet leading edge, causing duplication. The knee and lower leg injuries occur before the upper leg impact with the bonnet leading edge is complete. However, the position and stiffness of the bonnet leading edge will affect the risk of knee injury. The femur section of the full legform impactor is suitable for reproducing the early stages of the impact with the bonnet leading edge with regard to knee and lower leg injuries. Because the legform has no upper body mass nor instrumentation to record the risk of upper leg injury, it is not suitable for reproducing or assessing the safety of the complete upper leg impact with the bonnet leading edge. Therefore, the two test tools are complementary and are both required.

REPEATABILITY OF THE TEST METHODS

It is clearly important for the test procedures to be repeatable. Four potential causes of a possible lack of repeatability in the tests results can be identified:

a) differences in the test-to-test impact conditions due variations in the propulsion system's performance.

b) differences in the test-to-test performance of the impactors due to variations in the flesh and ligaments etc.

c) real differences in the test-to-test performance of the car, replacement car panels and fitting tolerances.

d) differences, between test houses, with the equipment and data recording systems used.

Repeatability of the legform impactor

The repeatability of the first prototype legform impactor was assessed by TRL by testing a simulated car designed to deform in a repeatable way. The results are shown in Table 2 and show a maximum coefficient of variation of only 4.6%. The repeatability of the experimental damped legform has also been established by carrying out repeated dynamic certification tests using the proposed TRL certification method. Repeatability tests on cars were not carried out with this impactor because the large damper unit used in this experimental model was considered to be too vulnerable to damage from rebound impacts. Table 3 shows the results of these repeatability tests using the new certification test, and these also show low coefficients of variation.

Table 2. Results of first prototype legform repeatability tests into a simulated repeatable car

Test no.	Knee angle (deg.)	Knee shear disp. (mm)	Max. accl. (g)	Impact velocity (ms^{-1})
1	24.32	1.82	140.5	11.31
2	24.91	1.70	143.3	11.29
3	27.52	1.68	146.6	11.29
4	24.47	1.78	147.9	11.27
5	25.53	1.72	151.1	11.33
Coefficient of Variation (%)	4.6	3.0	2.5	0.4

Table 3. Results of repeated dynamic certification tests (new TRL certification method) to the experimental damped legform impactor

Test no.	Knee angle (deg.)	Knee shear disp. (mm)	Max. accl. (g)	Certification impactor velocity (ms^{-1})
1	10.94	6.25	232	7.53
2	10.90	6.18	226	7.58
3	10.54	5.85	210	7.45
4	10.27	5.93	207	7.40
5	10.57	5.88	211	7.42
6	10.79	5.91	214	7.47
7	10.76	5.98	214	7.47
Coefficient of Variation (%)	2.2	2.6	4.3	0.8

Repeatability of the upper legform impactor

The repeatability of the impactor was assessed by a series of impact tests to the certification tube, which represents a car with repeatable characteristics. The results of these tests are shown in Table 4, and show a maximum coefficient of variation of only 1.7%.

Table 4. Results of upper legform repeatability tests into the certification tube *

Test No.	Impact velocity (ms^{-1})	Temperature (°C)	Bending (Nm)			Force (kN)	
			Upper	Centre	Lower	Top	Bottom
1	7.95	18	175	205	183	1.26	1.32
2	7.92	18	173	204	182	1.28	1.31
3	7.97	18	170	202	181	1.24	1.30
4	7.97	18	176	208	184	1.29	1.33
5	8.00	18	171	201	178	1.25	1.26
6	8.00	18	173	204	181	1.29	1.29
Coefficient of Variation (%)			1.2	1.1	1.0	1.5	1.7

** new foam from the same batch used for each test*

Discussion of the repeatability of the test methods

These repeatability tests show that, under tightly controlled conditions, both the legform and the upper legform tests are highly repeatable.

Variations in impact velocity (cause a) above), are likely to affect the results. It may prove necessary to restrict the tolerance to plus or minus 2%.

Variations in impactor performance (cause b) above) will, of course, lead to greater variation when using flesh and ligaments from different batches. The dynamic certification requirements will limit the potential effect of the former, and tight control of the manufacturing process the effect of the latter.

Variations in the car (cause c) above), are real and should not be considered a failing of the test methods. Tight control of the manufacturing process could reduce this source of variation.

Cause d) above covers a number of areas, mainly propulsion systems, impactors, instrumentation and analysis and this aspect is not unique to the pedestrian test procedures. Currently many test houses are using existing propulsion systems which have been adapted for pedestrian testing. Impactors in use at different test houses are expected to behave similarly and the certification requirements will prevent significant differences arising.

TEST RESULTS OF CURRENT CARS

To date, a total of 34 cars have been subjected to pedestrian tests as part of the European New Car Assessment Programme (EuroNCAP). The main difference between the EuroNCAP assessment and the draft EC pedestrian requirement is that, for EuroNCAP, the number of headform tests per car has been reduced from nine to six for both the child and adult headforms.

Tests meeting performance requirements

The results of these EuroNCAP pedestrian tests are summarised in Table 5. As explained above the acceptance levels for the upper legform are subject to review once the accident reconstructions have been completed. For interest, the results have been analysed also for the current best estimate of this revised value, based on the limited accident reconstruction results available to date.

Table 5. Summary of pedestrian test results from the EuroNCAP programme (34 cars) - number of test locations passing the EEVC WG10 test requirements

Impactor type	Number of tests	Number of tests passing	Proportion of tests passing (%)
Child headform	204	72	35
Adult headform	183 #	12	6.6
Upper legform	102	0	0
Upper legform †	102	7	6.9
Legform	101	8	7.9

† using TRL's current best estimate of the revised acceptance criteria for the upper legform test
 # For the 7 small cars the number of adult headform tests was reduced to 3 per car because the adult head test area was small.

The results of the EuroNCAP pedestrian tests have provided considerable data on the performance of current cars. The examination of these data, in Table 5, shows that a number of the test sites are meeting the pedestrian requirements. For each test method the passes are distributed amongst the car models tested, however, some models have a higher rate of passes. Further examination of the EuroNCAP data also shows that, for the bumper, one car met the requirement at all three test points and a further two cars met the requirement at two out of the three test points.

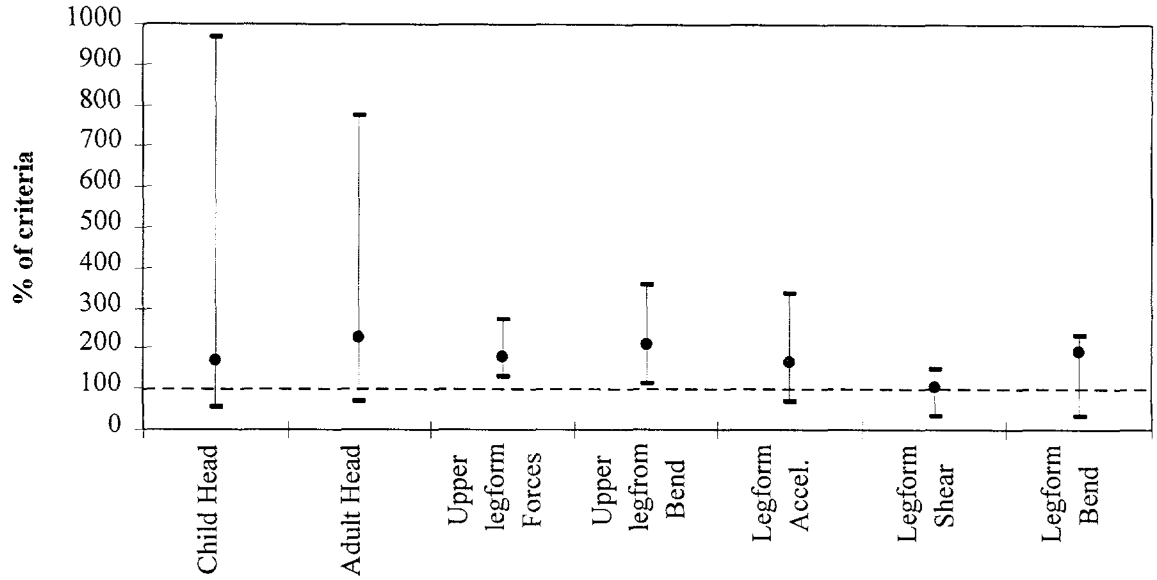

Figure 5. Comparison of spans and means from EuroNCAP pedestrian tests, as per cent of criteria

For the legform knee shear and bending, the built in mechanical limits impose an artificial ceiling on the upper end of the range of measurements.
The upper legform criteria are currently under review.

For the upper legform no cars met the current criteria at any point but, using TRL's current best estimate of the revised acceptance criteria, one car met the requirement at two of the three test points tested and five other cars met the requirement at one of the three points tested. For the child headform test, eight cars met the requirement in four out of the six points tested and a further eight cars met the requirement in three out of the six points tested. For the adult headform, two cars passed the requirement in three out of six tests.

The EuroNCAP pedestrian tests data are presented to show the mean and span for each impactor type in Figure 5 above.

Tests within 25 per cent of the performance requirement

The number of test sites passing or which are close to passing the requirements is also of interest. As current cars have not been designed to meet the requirements, this will provide a more appropriate indication as to how cars might have performed if they had been designed with a moderate attention to pedestrian safety. Table 6 shows the number of tests below a value set at an arbitrary 25% above the acceptance criteria.

Table 6. Summary of pedestrian test results from the EuroNCAP programme (34 cars) - number of test locations passing or within 25% of the EEVC WG10 test requirements

Impactor type	Number of tests	Number of tests passing or within 25%	Proportion of tests passing or within 25% (%)
Child headform	204	103	50
Adult headform	183 #	37	20
Upper legform	102	1	1.0
Upper legform †	102	31	30
Legform	101	16	16

† *using TRL's current best estimate of the revised acceptance criteria for the upper legform test*
\# *For the 7 small cars the number of adult headform tests was reduced because the adult head test area was small.*

The results of the EuroNCAP pedestrian tests in Table 6, show that many test sites met or were close to meeting the pedestrian requirements. Car models with large areas meeting or close to meeting the requirement have been found from the EuroNCAP data. This examination shows that for the legform test three cars were within 25% or better at all three test points and a further two cars had two test points within 25% or better. For the upper legform, using *TRL's best estimate* of the revised acceptance criteria, four cars were within 25% or better at all three test points and a further six cars had two out of three tests that were within 25% or better. For the child headform test eighteen cars had at least four out of the six tests within 25% or better. Of these five cars had five out of the six tests within 25% or better. For the adult headform six cars had three tests within 25% or better and one of these had five out of six tests within 25% or better.

These test results must be seen in the context of the tests being performed on cars which have been designed in the absence of any dynamic pedestrian test requirement, and only the requirement to avoid sharp forward facing edges to meet the exterior projections requirements. The low proportion of passes is then not surprising. The relatively large proportion (about one third) of test locations already passing the child headform test is very encouraging.

The results indicate that significant improvements in pedestrian safety are in some areas achievable, at low cost, by copying current best practice from other cars or other areas of a car. For instance, in many cases hard under-bonnet components could be moved or replaced by softer materials. In some cases it could be as simple as changing the length of a mounting stud. It has to be accepted, however, that, for some areas, compliance will be more difficult and costly.

CONCLUSIONS

1. Experience with using the pedestrian test impactors has shown that the test procedure is both practical and repeatable. Nevertheless, it has led to modifications to the test devices to improve their performance.

2. An improved, prototype legform impactor has been developed which has deformable ligaments solely for knee bending, and an elastic spring for knee shear displacement. The instrumentation now measures these outputs independently. Modified legform bending and shear certification corridors have been introduced in the EC draft Directive.

3. A new and improved legform dynamic certification procedure has been developed.

4. A prototype damped version of the legform has been tested which has demonstrated that this will remove the unwanted resonance of the shear spring.

5. Changes have been made to the upper legform impactor to remove an unwanted load path. Tests have been carried out to verify that the load outputs now read correctly.

6. Further accident reconstructions are being carried out with the upper legform impactor. It is likely that these will lead to a significant increase in the upper legform acceptance levels.

7. Pedestrian test results from the EuroNCAP programme show that a third of child headform tests passed, though less than ten percent of tests passed with the other impactors. However, many more tests were within 25 percent of the pass criteria.

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