

**Department of Transport and Regional Development**  
The Federal Office of Road Safety

# **Pedestrian Friendly Vehicle Front Structures**

## **A Review of the Research Literature**

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**Abstract**

Certain characteristics of vehicle design can have a marked effect on the nature and severity of injuries sustained by a pedestrian when struck by a vehicle. This report reviews the evolution of our understanding of that relationship and discusses the research activities which have led to the development of vehicle test procedures to optimise the protection afforded to a pedestrian in the event of a collision. The relevance of these test procedures to the Australian situation is discussed.

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**Keywords**

Pedestrian Injuries, Vehicle Design, Pedestrian Protection

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**NOTES**

- (i) FORS Research reports are disseminated in the interests of information exchange  
(ii) The views expressed are those of the author(s) and do not necessarily represent those of the Commonwealth Government.

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# **EXECUTIVE SUMMARY**

## **INTRODUCTION**

In 1994 more pedestrians died on Australian roads than did motorcyclists and pedal cyclists combined. Attempts to reduce the number of pedestrian casualties have concentrated on preventing the collision from occurring. This is because it has been assumed, incorrectly, that little could be done to reduce the severity of the injuries sustained by a pedestrian when struck by a car.

## **PEDESTRIAN INJURIES AND VEHICLE DESIGN**

Certain characteristics of vehicle design can have a marked effect on the nature and severity of the injuries sustained by a pedestrian struck by a vehicle. This report reviews the evolution of our understanding of that relationship. The development of vehicle test procedures to optimise the level of protection afforded to the pedestrian in the event of a collision is discussed, with particular reference to the relevance of these test procedures to the Australian situation.

Contrary to popular belief, pedestrians are run under by a striking car, rather than run over. This means that the shape and energy-absorbing properties of the bumper and the upper surface of the front of the car are the direct cause of injury to the legs and head of the pedestrian. In general, injuries resulting from being thrown to the road after being struck by a car are not as severe as the injuries due to the impact with the car itself.

## **DEVELOPMENT OF PEDESTRIAN IMPACT TEST PROCEDURES**

The development of pedestrian impact test procedures has involved the investigation of actual collisions between pedestrians and vehicles to identify those aspects of vehicle design which are related to the injuries sustained by the pedestrian. This work has proceeded in parallel with research into the tolerance of the human body to impact.

The two main groups which have been working on the development of test procedures are the European Experimental Vehicle Committee (EEVC) and the International Standards Organisation (ISO). Because of intractable difficulties in ensuring repeatability in a full scale collisions between a pedestrian crash test dummy and a vehicle, and also concern about the biofidelity of a pedestrian dummy, each group has approached the task by developing component, or sub-system, tests rather than a whole system test. For example, there is a test of the likelihood of a car bumper injuring the knee joint of a pedestrian whose leg is hit from the side at 40 km/h.

## **APPLICATION OF PEDESTRIAN IMPACT TEST PROCEDURES**

The availability of pedestrian impact test procedures has made it practicable to introduce vehicle safety standards for pedestrian protection. The final report of EEVC Working Group 10 contains a draft EC Directive, or Standard, which, if approved, will require that all new models of cars sold in the European Union Countries after October, 1998 will have to pass the sub-system tests and all cars entering service will be required to comply by October, 2001.

The EEVC sub-system test procedures for pedestrian protection are also being used in the New Car Assessment Program (NCAP) crash tests being conducted by the Transport Research Laboratory for the United Kingdom Department of Transport. The first set of these tests has been carried out and the results are expected to be made public in 1996

## **COST-BENEFIT ANALYSES**

Cost-benefit analyses of the probable consequences of the introduction of the draft EC Directive have been carried out by the Transport Research Laboratory (TRL) in the UK. These analyses indicate that the cost-benefit ratio is likely to be about 1:7.5 based on production costs and 1:4.3 based on the after tax cost to the consumer. Research in Germany, at BAST, on the likely benefits of the introduction of the draft Directive yielded data which was consistent with the TRL findings

The European Automobile Manufacturers Association conducted a cost-benefit analysis which concluded that the cost-benefit ratio would be 57:1. However, the estimated cost of compliance with the draft EC Directive was about 20 times greater than the cost arrived at by TRL and BAST and the benefits were restricted to a reduction in pedestrian fatalities alone, excluding the benefits from a reduction in injury severity.

## **PEDESTRIAN PROTECTION AND VEHICLE DESIGN IN AUSTRALIA**

The value of the draft EC Directive in Australia, were it to be adopted as an Australia Design Rule for Motor Vehicle Safety, would be influenced by two additional factors. The first is that the proportion of pedestrians hit by a car, rather than by some other motor vehicle, is higher in Australia than in Europe, which would tend to increase the resulting benefits. The second is that Australia has one of the highest urban area speed limits in the world (60 km/h). The draft EC Directive specifies that the component tests be conducted at a speed of 40 km/h. It is probable that there would still be some benefit at higher impact speeds from requiring compliance with the EC Directive at 40 km/h but the effect of the difference in speed distributions is a matter which has yet to be established.

## **ESTABLISHMENT OF A PEDESTRIAN IMPACT TEST FACILITY**

There are several reasons to support the establishment of a pedestrian impact test facility in Australia. At present, the obvious choice would be a facility which could be used to test for compliance with the draft EC Directive and to investigate the potential benefits of such compliance at impact speeds higher than 40 km/h. Such a facility could also be used to assess the probable effect of a bull bar attached to a car on the risk of injury to a pedestrian struck by that vehicle. In addition to these applications, there would also be considerable value in the availability of a pedestrian impact test facility for research purposes.

A significant limiting factor in the development of more effective test procedures for both pedestrian protection and the protection of vehicle occupants in a crash is the present inadequate level of understanding of human tolerance to impact. The aim of the head injury research program of the NHMRC Road Accident Research Unit (RARU) at the University of Adelaide is to develop a more soundly based criterion for the tolerance of the human brain to impact to the head than is currently provided by the Head Injury Criterion (HIC). This is being attempted by relating the characteristics of the impact to the head to characteristics of the resulting injury to

the brain in fatal pedestrian-car collisions. Because it is the only research program of its type in any country, RARU has been approached by three overseas research groups, in France, Japan and the USA, to collaborate in the validation, or otherwise, of mathematical models of brain injury. The value of these collaborative activities would be greatly enhanced if accurately measured information on head accelerations can be obtained from headform impact tests on cars similar to those involved in the cases investigated by RARU

## **CONCLUSIONS AND RECOMMENDATIONS**

- 1** The level of pedestrian protection provided by current passenger cars can be significantly improved with practicable design changes.
- 2** The draft EC directive based on the EEVC test procedures is the best available means of assessing the level of pedestrian protection of a vehicle.
- 3** It is likely that the benefits in terms of a reduction in pedestrian deaths, injuries and disabilities resulting from the adoption of the draft EC directive as an Australian Design Rule for Motor Vehicle Safety would be cost effective
- 4** Consideration should be given to the establishment of a pedestrian impact test facility in Australia to enable testing of vehicles and vehicle modifications to be conducted according to the EEVC test procedures.
- 5** Consideration should be given to further research into the mechanisms of pedestrian injuries



# **Chapter 1 Pedestrian Deaths and Injuries in Australia**

## **1.1 INTRODUCTION**

Certain characteristics of vehicle design can have a marked effect on the nature and severity of the injuries sustained by a pedestrian struck by that vehicle. This report reviews the evolution of our understanding of that relationship and discusses the research activities which have led to the development of vehicle test procedures to optimise the level of protection afforded to the pedestrian in the event of a collision. The relevance of these test procedures to the Australian situation is discussed.

## **1.2 PEDESTRIAN ACCIDENT PROFILE**

Pedestrian injury ranks second in importance in terms of fatal outcome after vehicle occupant deaths (19% and 68% respectively in Australia in 1994, followed by 10% for motorcyclists and 3% for pedal cyclists) (Road Fatalities Australia - 1994, Statistical Summary).

Pedestrian casualties form a smaller percentage of hospital admissions than they do of fatalities. The relevant percentages were 13, 50, 19 and 18% for pedestrians, vehicle occupants, motorcyclists and pedal cyclists in Australia in 1991 (Dolinis J, O'Connor PJ, Trembath RF, 1995). This is a reflection of the fact that injured pedestrians have a much higher case fatality rate (the number who die expressed as a percentage of all who are injured) than do injured motorcyclists or pedal cyclists. The relevant rates for Australia in 1991 were 8.1, 4.1, and 1.1 per cent respectively, where an injured subject is defined as one admitted to hospital (calculated from Dolinis et al, 1995). The pedal cyclist rate is strongly influenced by the fact that half of the injured cyclists are in the 5 to 14 year age range and they have a case fatality rate of only 0.57 per cent. The case fatality rate for motorcyclists may be lower than that for pedestrians partly because of the use of crash helmets (McLean et al, 1979).

While it may not be altogether surprising that pedestrians have a higher case fatality rate than do motorcyclists and pedal cyclists, it is unexpected to find that they have a slightly lower case fatality rate than do vehicle occupants (8.1 and 8.6 per cent respectively). This is so up to 50 years of age. Beyond that age, injured pedestrians have a higher case fatality rate than do injured vehicle occupants (calculated from Dolinis et al, 1995).

# Chapter 2 Causes of Pedestrian Injuries

## 2.1 INTRODUCTION

For many years it was common to refer to a pedestrian being “run over” by a vehicle. The consequence of this view was that severe injuries, such as a fractured femur or pelvis, were often assumed to have resulted from the static weight of the vehicle as it ran over the pedestrian. In fact, an adult pedestrian is run under, rather than over, by the striking car.

This does not mean that there are never cases in which a pedestrian is run over. Some other vehicle types, such as vans, may project the struck pedestrian forwards onto the roadway where he or she may then be run over by the striking vehicle if the driver has not applied the brakes. A similar sequence of events may occur when a small child is hit by the front of a passenger car. However, in the typical pedestrian collision the pedestrian is run under by the striking car in the manner described in the following section.

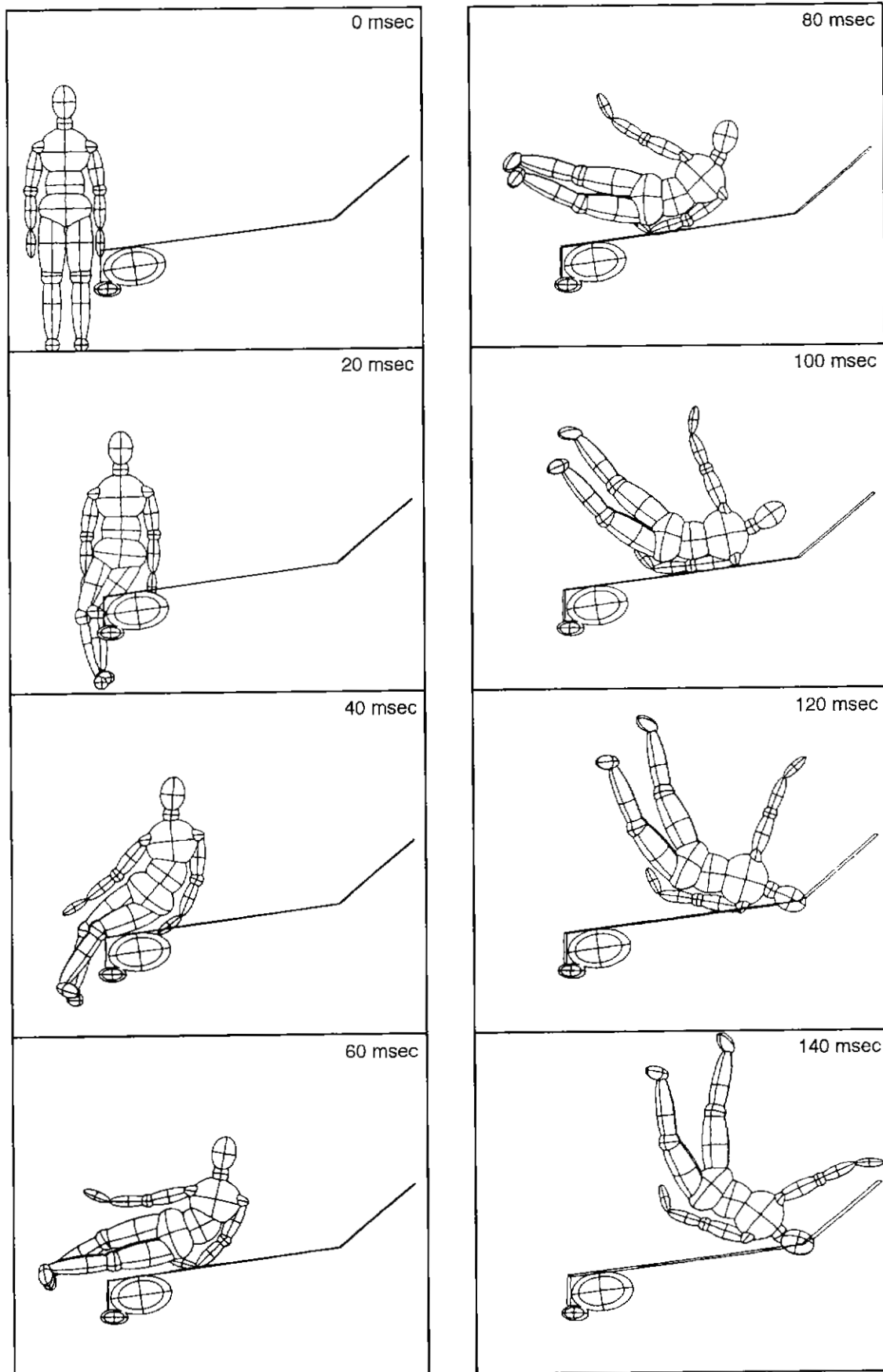
## 2.2 THE MOTION OF A PEDESTRIAN WHEN STRUCK BY A CAR

An Australian in-depth study yielded the first accurate description of the kinematics of the car/pedestrian collision based on the investigation of actual collisions (Robertson et al., 1966). The following extract is from the paper by Ryan and McLean in the proceedings of the Ninth Stapp Car Crash Conference in 1965.

“The sequence of events when a car strikes a pedestrian is as follows, assuming the pedestrian is an adult, standing erect:

The initial impact is from the bumper bar which strikes the lower leg. The effects of this impact for a given vehicle speed depend partly on the amount of body weight this limb is supporting at impact, and partly on the limb’s own inertia. Almost at the same instant, but slightly later, the leading edge of the bonnet (hood) of the car will strike the hip of the pedestrian. If the speed of the car is great enough the pedestrian then rotates about this secondary impact point until his head and chest strike the bonnet, windscreen and/or the windscreen surroundings. The higher the impact speed the further back along the car this third impact point will be.

At still higher speeds the pedestrian now rotates about his head and shoulders, i.e., the third impact point. This can result in either a fourth impact with the car or in the car passing under the pedestrian who then falls to the road. On this fourth impact with the car the pedestrian’s legs strike the rear of the roof of the car. From this point, if the car does not slow down, the pedestrian, who is now travelling almost at the speed of the car, will fall to the road, either behind or on one side of the car.



**Figure 2.1: Motion of a pedestrian struck by a car.  
(Time in thousandths of a second)**

If the driver of the car should suddenly brake, the car will then slow down at a much faster rate than the pedestrian, who tends to continue forwards with undiminished speed, sliding over the roof and bonnet and then falling to the road in front of the car. He finally comes to rest after sliding and rolling along the road " (Ryan and McLean, 1965)

In the same paper it was also noted that:

"With a larger amount of data it will be possible to describe the frontal shape of a car that will inflict minimal injuries when it strikes a pedestrian."

The above description of the motion of a pedestrian when struck by a car is illustrated in Figure 1.1, which is derived from a reconstruction of the collision sequence conducted at the NHMRC Road Accident Research Unit using the MADYMO computer package.

The recognition that the adult pedestrian is struck not only by the front but also the upper frontal surface of the striking car was accompanied by the identification of the components of the vehicle which injure specific body regions. The bumper strikes the leg of the adult pedestrian in the vicinity of the knee joint. This impact can result in fracture of the long bones of the leg and/or dislocation of the knee joint, with or without fracture (the location of a fracture, in terms of height above the ground allowing for the type of footwear, can indicate in most cases whether or not the striking car was braking on impact because the front of the car dips down under braking). The subsequent contact points are determined by the overall shape of the front of the car, notably the height of the leading edge of the bonnet (if there is a definable leading edge) and the horizontal distance between the face of the bumper and that leading edge

Following impact by a car, a pedestrian's legs are accelerated in the direction of the impact. Because the centre of gravity of the human body is at about the level of the navel, this initiates a whole-body rotation of the pedestrian which takes place primarily about the leading edge of the bonnet. This second impact can result in fracture of the femur and/or pelvis. The pedestrian's head then strikes the upper surface of the front of the car. The location on the car of this impact depends mainly on the height of the pedestrian, the height of the leading edge of the bonnet and its horizontal distance behind the face of the bumper, and the speed of the car on impact. The velocity of the head relative to the contact point on the surface of the car and the impact characteristics of that part of the vehicle largely determine the consequences of this head impact.

As indicated in the earlier description of the kinematics of the car/pedestrian collision, at a sufficiently high speed of the striking vehicle the whole body rotation of the pedestrian may continue following the head impact. This can result in further contacts between the pedestrian and the roof or upper surface of the rear half of the car. These contacts rarely result in significant injuries, partly because they usually involve the lower limbs and the roof panel is a relatively soft structure.

Almost every collision between a car and a pedestrian results in the pedestrian falling, or being thrown, from the bonnet of the car to the roadway. This stage of the collision sequence can result in serious injury, particularly to the head, but most cases of severe head injury can be attributed to the earlier head contact with the vehicle. Finally, the pedestrian may sustain further injuries, notably abrasions, from sliding or tumbling along the road before coming to rest.

These characteristics of the car/pedestrian collision have been confirmed and refined in further investigations conducted in several countries from the mid-1960s , including a second in-depth study in Adelaide in the mid 1970s (McLean et al., 1979). For a comprehensive review of these studies see Ashton (1982).

# **Chapter 3 Pedestrian Injuries and Vehicle Design**

## **3.1 INTRODUCTION**

It is now generally accepted that the nature and severity of the injuries sustained by the occupant of a vehicle in a crash are influenced strongly by the level of crashworthiness of that vehicle. This recognition of the importance of vehicle design in injury control is not so common in the case of a collision between a vehicle and a pedestrian. This may be partly a consequence of a belief that the impact forces acting on the pedestrian are so great that there is little opportunity to reduce them to any meaningful degree by changing the design of the vehicle. However, as noted in the first section of this report, the case fatality rate for injured pedestrians is slightly less than that for injured vehicle occupants.

## **3.2 THE OVERALL SHAPE OF THE FRONT OF THE CAR**

Ryan and McLean (1965) postulated that the overall shape of the front of the car influences the severity of the injuries sustained by a pedestrian. This concept was investigated further by McLean in a comparison of pedestrians struck by two makes of car which had very different frontal shapes (McLean, 1972a). The vehicles chosen for the comparison were the original Volkswagen and the Cadillac of the late 1960s, the latter having a rectangular frontal shape when viewed from the side and a very long bonnet. The study was based on 349 pedestrian accidents which occurred in New York State in 1969-70 and for which information was available from mail questionnaires on the estimated impact speed and the point of impact on the car, as well as greater detail on the pedestrian's injuries. The conclusion from this study was that a pedestrian struck by a Volkswagen was less likely to be severely injured or killed than a pedestrian struck by a Cadillac.

During the past two decades there has been a marked change in the overall frontal shapes of passenger cars, prompted at least partly by attempts to reduce the aerodynamic drag factor and thereby to decrease fuel consumption. The replacement of the rectangular frontal shape which has a pronounced bonnet leading edge by a more sloping frontal shape has had a marked influence on the characteristics of the injuries sustained by pedestrians. In an unpublished comparison of pedestrian injury patterns in fatal collisions in South Australia in 1960-63 and 1981-84 it was found that there was a significant reduction in the number and severity of pelvic injuries in the latter group. The average height of the leading edge of the bonnet decreased from 901 mm to 749 mm from the former to the latter group of cars. Today the near elimination of a definable leading edge could be expected to be accompanied by an even greater difference in pattern of injury than was observed in the above two groups of vehicles.

## **3.3 SPECIFIC ASPECTS OF VEHICLE DESIGN**

Detailed studies of specific vehicle factors involved in pedestrian injury causation commenced in Europe and the USA in the mid-1970s. Several of these studies attempted to reproduce either in

the laboratory or mathematically the sequence of events observed in actual car/pedestrian collisions.

### **3.3.1 Full scale collision reconstruction**

In France, two groups were engaged on pedestrian crash reconstruction work. Peugeot-Renault, under the direction of Tarriere, conducted full-scale experiments using anthropometric dummies (Stcherbatcheff et al., 1975) and later cadavers (Brun-Cassan et al, 1983). A consortium headed by Cesari at the Laboratoire des Chocs et de Biomécanique (LCB) of INRETS, the French national transport safety research organisation, conducted a series of car/pedestrian collision reconstruction experiments using cadavers (Cesari et al, 1980).

Experimental reconstructions were also underway at this time in other countries including, for example, Germany (Appel et al., 1978) and the United Kingdom (Harris, 1977). In the United States, Pritz, at Battelle, Columbus Laboratories (later with the National Highway Traffic Safety Administration) conducted cadaver tests aimed at the minimisation of pedestrian injury through vehicle design (Pritz, 1977). This work led on to attempts to improve the dynamic response of anthropometric dummies for use as pedestrian surrogates in such experiments (Pritz, 1978). Similar fundamental biomechanical studies were also being conducted by some of the research groups in Europe mentioned above, and at Chalmers University in Sweden (Aldman et al, 1979).

Attempts to develop mathematical models of the car/pedestrian collision commenced with the work of Segal at Cornell Aeronautical Laboratory in the United States in the late 1960s (Segal, 1969, Cornell Aeronautical Laboratory, 1971). His work indicated that the height of the leading edge of the bonnet might influence the risk of a significant head impact with the road surface as well as the location of the pedestrian's head impact point on the vehicle.

### **3.3.2 Reconstruction of impacts with vehicle components**

In the 1970s, the Vehicle Research Test Center (VRTC) of the United States National Highway Traffic Safety Administration (NHTSA) embarked on a program aimed at the development of practicable ways to modify vehicle design to reduce the risk of pedestrian injury. Based on the findings from a detailed study of pedestrian/vehicle collisions, this work was initially focused on reducing the severity of injuries sustained by the lower body of a pedestrian (Pritz et al, 1975). Ashton, from the University of Birmingham in the UK, was actively involved in this program in its early stages, together with Pritz and others (Ashton et al, 1982). This study concentrated on the level of protection afforded to the head of a pedestrian when striking the central area of the bonnet of a passenger car. Some work was also carried out on assessing the risk of thoracic injury to a child pedestrian as a result of an impact by the leading edge of the bonnet of a car (Elias and Monk, 1989).

In Europe, the EEC established a program to develop standard pedestrian impact test procedures which could be used for both research purposes and vehicle compliance testing (Cesari et al, 1981). The program is described in detail later in this report.

A major study of the kinematics and dynamics of the car/pedestrian collision was conducted at the Technical University (ETH) in Zurich in the early 1980s. It involved full scale testing with anthropometric test devices, cadavers and mathematical simulation, and reported on the

usefulness and reliability of these methods of investigation (Niederer et al., 1983) The main conclusions from this study were:

“Knowledge about pedestrian accidents has reached an extent which allows the definition of the requirements of pedestrian safety on car design in an appropriate form for design and performance evaluation

The design can be undertaken systematically, accompanied by dynamic material and component tests.

Better automobile design for pedestrian safety means, first of all, mitigation of head impact.

A car front designed with regard to collision with pedestrians will show larger deformations under impact than a current car. Nearly constant stiffness properties over the width of the surface of the car front should be realised. The amount of deformability depends on the defined pedestrian tolerances and the assumed collision velocity.

Collision safety for adults is compatible with collision safety for children as far as the stiffness of the impacted parts of the car front is concerned.” (Kaesler and Gaegauf, 1986)



# Chapter 4 Tolerance to Impact in Pedestrian-Vehicle Collisions

## 4.1 INTRODUCTION

The investigation of actual collisions between pedestrians and vehicles identified those aspects of vehicle design which appeared to be related to the injuries sustained by the pedestrian. These investigations provided very detailed injury information but only estimates of the forces involved. In order to be able to investigate the likelihood of, say, a bumper impact at a specified speed producing a certain type of leg injury it became apparent that information was needed on the tolerance of the leg to impacts.

## 4.2 MEASUREMENT OF THE RISK OF INJURY TO THE LOWER LIMBS

Studies of the mechanisms involved in serious leg injuries sustained by pedestrians struck by cars have been carried out in the United States by Pritz, then at the Columbus Laboratories of Battelle (Pritz et al., 1975), and by King (King et al., 1976a,b,c) at Wayne State University in Detroit. Because the pedestrian is struck on the side in most pedestrian/vehicle collisions, these studies have concentrated on the tolerance of the leg to lateral impact. They identified two mechanisms of injury:

- (1) long bone fracture and/or lateral displacement of the knee joint due to shear forces, and
- (2) long bone fracture and/or rupture of the ligaments of the knee and ankle joints.

In a report to Congress on pedestrian injury reduction research NHTSA noted that "The research completed has not allowed a full understanding of the factors that cause lower leg injuries" and that "In addition, more work needs to be done to develop lower leg injury criteria" (NHTSA, 1993). These comments are at variance with the conclusions of groups conducting research in this area in Europe.

Studies of the leg injury mechanisms in pedestrian collisions have been carried out in Europe by the then Laboratoire des Chocs et de Biomecanique (LCB) of INRETS in conjunction with the Medical University of Marseille (Cesari et al., 1989) and also at Chalmers University in Sweden (Aldman et al., 1979). These groups have continued with further collaborative research in this area (see, for example, Kajzer et al., 1990) and the results have been used in the development of dummy legs and component test procedures for leg protection by both the European Experimental Vehicles Committee (EEVC) and the International Standards Organisation Working Group on Pedestrian Impact Test Devices.

The leading edge of the bonnet of the car was at one time a cause of serious pelvic injuries to pedestrians. As car design fashions changed, the height of the leading edge decreased. Consequently the component test procedure for the leading edge of the bonnet, where applicable, assesses the risk of fracturing the femur rather than the pelvis. With the trend towards sloping bonnets on passenger cars, often to the extent that there is no longer any clearly defined leading

edge, the risk of the upper leg being injured by a direct impact from the car has greatly diminished. Therefore provision is made in both the EEVC and the ISO proposed test procedures to delete the requirement for the bonnet leading edge test on such vehicles.

Despite the concern expressed by NHTSA about the need for further research, the report to Congress (NHTSA, 1993) included the following "best estimates" of the maximum tolerance of the leg to lateral impact:

- 4 kN for the femur,
- 1.5 to 4 kN for the tibia,
- 212 to 320 Nm for tibia and femur bending, and
- 200 Nm for lateral bending of the knee, which corresponds to about 6 degrees of angular deflection

The maximum tolerance specifications contained in the EEVC proposed test methods (EEVC, 1994) are:

- 4 kN for the femur,
- a bending moment of 220 Nm for the femur,
- an acceleration of 150 g measured at the upper end of the tibia,
- a knee bending angle of 15 degrees, and
- a dynamic knee shearing displacement of 6 mm.

There is still debate within EEVC Working Group 10 on the appropriate maximum tolerance level for the lateral bending moment of the knee joint. The proposed levels range from 120 to 500 Nm. It is likely that the upper end of the range will be accepted, partly because Zellmer, then of BASt (the German Federal Highway Research Institute) loaded his own knee statically to a lateral bending moment of 200 Nm without injury (Lawrence, personal communication). It is thought that the lower tolerance levels observed in cadaver tests may be attributable to two factors. The first is that most tests have been conducted on cadavers of individuals who were elderly at the time of death, and the second is that active muscle tension is likely to be an important protective factor (Cesari, personal communication).

#### **4.3 MEASUREMENT OF THE RISK OF HEAD INJURY**

Whereas the nature of the impact loading of the pedestrian's leg is unique to the pedestrian/vehicle collision, the characteristics of the impact to the head of a pedestrian do not differ markedly from those of the impact to the head of a vehicle occupant. The objects struck do, of course, differ and there is reason to believe that the distribution of impact points on the head also differ, with the pedestrian's head being more likely to be struck on the side or at the rear compared to predominately frontal, with some lateral, impacts to the head of the vehicle occupant (Unpublished data, NHMRC Road Accident Research Unit).

Both NHTSA and the EEVC Working Group have accepted the Head Injury Criterion (HIC) as the measure of the tolerance of the head to impact (although the European group choose to refer to HIC as the Head Performance Criterion).

The expression for HIC is:

$$HIC = (t_2 - t_1) \left[ \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t) dt \right]^{2.5}$$

where an algorithm selects  $t_1$  and  $t_2$  to yield the maximum value HIC should not exceed 1,000, where “a” is the acceleration of the head, expressed in multiples of “g”, and “t” is time in seconds

#### **4.4 MEASUREMENT OF THE RISK OF THORACIC INJURY**

Greater attention has been paid in the United States than in Europe to assessing the risk of thoracic injury to a pedestrian struck by a car. In fact the EEVC Working Group did not recommend a procedure to test for the likelihood of thoracic injury to a pedestrian.

As is the case with head injuries to pedestrians, the mechanism by which the thorax is thought to be injured is not unique to pedestrians. Consequently the Thoracic Trauma Index (TTI), which was developed for use in side impacts on passenger cars, was adopted by researchers at VRTC in their investigations of pedestrian thoracic injury (NHTSA, 1993). The TTI is an averaged value of the peak measured acceleration of the rib and spine masses. The thoracic impact tolerance level was taken to be 85 to 90 g for an adult pedestrian and 60 g for a child.

# Chapter 5 Development of Pedestrian Impact Test Procedures

## 5.1 INTRODUCTION

Three groups have been working on the development of test procedures to be used in assessing the degree of pedestrian protection afforded by a given vehicle. They are the United States National Highway Traffic Safety Administration (NHTSA), the European Experimental Vehicle Committee (EEVC), and the International Standards Organisation (ISO). Each group has approached the task by developing component, or sub-system, tests rather than a whole system test. This is largely because of intractable difficulties in ensuring repeatability in a full scale collisions between a pedestrian dummy and a vehicle, and also concern about the biofidelity of a pedestrian dummy.

A vehicle occupant crash test dummy, such as the Hybrid III, is required to move only a very short distance before either being restrained by a seat belt or air bag or by striking the interior of the vehicle. By comparison, the pedestrian crash test dummy is subjected to violent whole body rotation about a series of points on the vehicle and each stage of the collision sequence is influenced by the outcome of the preceding stage. For example, fracture of a long bone in the lower limb due to the bumper impact can significantly affect the kinematics of subsequent stages of the collision.

## 5.2 UNITED STATES: NHTSA TEST PROCEDURES

NHTSA commenced work on the development of pedestrian impact test procedures in 1973 (Daniel et al., 1979). Because full scale testing using anthropomorphic child and adult dummies and unembalmed cadavers indicated that the adult head impacts with the car were below normally accepted tolerance levels (Pritz et al., 1978), attention was focused on the development of test procedures for the adult lower leg and the child upper torso (Pritz et al., 1975, Pritz, 1984). This resulted in the publication in 1981 of a notice of proposed rule making (NPRM) for pedestrian leg protection at a vehicle impact speed of 20 mph (Federal Register, 1981).

Subsequent pedestrian-car collision reconstruction research at the Vehicle Research Test Center (VRTC) of NHTSA demonstrated that adult head impacts with the striking car were in fact likely to result in severe or fatal head injury (Pritz, 1983 and 1984) and that there were marked differences in the head injury potential depending on the location of the head impact on the car and, for a given impact location, between some makes and models of car. This work led on to further detailed experimentation involving impacting head forms onto vehicle bonnets.

A particularly interesting finding from the NHTSA research was that some otherwise identical vehicles had different bonnet stiffener designs which resulted in marked differences in the degree of protection provided in the event of a pedestrian head impact (Kessler, 1987). This work has also shown that plastic bonnets, as have been fitted to some American vehicles, such as the now

out of production Pontiac Fiero, were very much stiffer than conventional sheet metal bonnets and hence potentially far more hazardous in the event of a pedestrian head impact.

NHTSA developed a pedestrian head impact test procedure (Hoyt et al., 1990), based on the extensive series of experiments conducted through the 1980s (MacLaughlin et al, 1988). It is noteworthy that the area of the vehicle frontal surface covered by this procedure is limited to the bonnet of the car, excluding the outer boundary (defined as being up to 6 inches from the edges of the bonnet). This test area was selected on the basis of detailed studies of actual pedestrian/car collisions but it may reflect the size of the US car fleet at the time the studies were carried out (during the 1970s). Other studies in Australia, France, Japan and the UK have shown that, for the adult pedestrian, the head impact is not often within the zone selected by NHTSA, although that zone is relevant to head impacts involving child pedestrians. However, an attraction of specifying head impact test requirements for the central part of the bonnet was that significant improvements in pedestrian head protection could be expected, on average across the range of makes and models of car in production, without any change to the external appearance of the bonnet of a car. A notice of proposed rule making for pedestrian head protection based on this test procedure was issued by NHTSA but it was withdrawn in 1990.

The NHTSA research programme also included the investigation of ways to reduce the severity of thoracic injury to child pedestrians (Elias et al, 1989).

A summary of the status, in 1993, of NHTSA's pedestrian injury reduction research was given in a report to Congress (NHTSA, 1993). In that report it was noted that "The research program directed toward exploring the feasibility of reducing the consequences of pedestrian-vehicle impacts was suspended during the summer of 1992 pending agency review of the direction of the program and its priority among other agency programs." Since then, most of the staff who had been working on research in this area have left NHTSA.

## **5.3 EUROPE: EEVC TEST PROCEDURES**

### **5.3.1 Background**

In 1980 the European Experimental Vehicles Committee (EEVC) of the European Community (EC) set up Working Group 7 "to examine how car design could take into consideration pedestrian accidents in European countries". The Working Group reported that "the only improvements to the car that the Group can at this moment encourage, concern the following.

- 1) the use of energy-absorbing materials in the front structures of cars,
- 2) the elimination or masking/concealing of car features that are aggressive by their rigidity or their shape (windscreen frame and scuttle, A-pillars..)"

(EEVC, 1981)

Working Group 7 also recommended that further research be conducted before establishing a regulatory test procedure for pedestrian safety. Importantly, in terms of its effect on the development of current test procedures, the Group recommended that because the "safety benefits to be expected from improvements in vehicle design seem to be most important for the speed range up to 40 km/h, and research should be focused in that speed range". Two aspects of

vehicle design were considered to be important: the overall shape of the car, and the local dynamic stiffnesses of sections of cars that are impacted by pedestrians.

In 1987 ERGA-S, the ad hoc passive safety advisory group of the European Commission, having considered the report of Working Group 7, asked the EEVC to conduct a co-operative research program to develop sub-system tests to evaluate the level of protection afforded to pedestrians by the fronts of cars. NHTSA was invited to participate in the deliberations of the ad-hoc group but the Administration was unable to be represented at the group meetings (EEVC, 1985). It was intended that these sub-system tests would be included as an amendment to EC Directive 74/483/EEC ("external projections") which regulates aspects of the external design of vehicles to minimise the risk of injury to pedestrians and other unprotected road users.

The EEVC formed another working group (Working Group 10) which included, among others representatives of five organisations: the (then) Transport and Road Research Laboratory in the United Kingdom, which was the lead organisation; BAST, the German Federal Highway Research Institute, the Laboratoire des Chocs et de Biomécanique of INRETS, the French National Transport and Safety Research Institute; TNO Crash Safety Research Centre in The Netherlands. and, to provide an industry perspective, the Laboratoire de Physiologie et de Biomécanique of APR (Association Peugeot Renault). These research organisations (sometimes referred to as the EC contractors' sub-group of Working Group 10) covered 60 per cent of the cost of the work with the European Commission providing funds to support the remaining 40 per cent.

Three sub-system tests, of the bumper, the leading edge of the bonnet, and the upper surface of the bonnet and front wings extending back to the lower edge of the windscreen frame, were specified in the mandate given to Working Group 10. The windscreen and A-pillars were not part of the mandated work program. The tests were to be conducted at a car to pedestrian impact speed of 40 km/h.

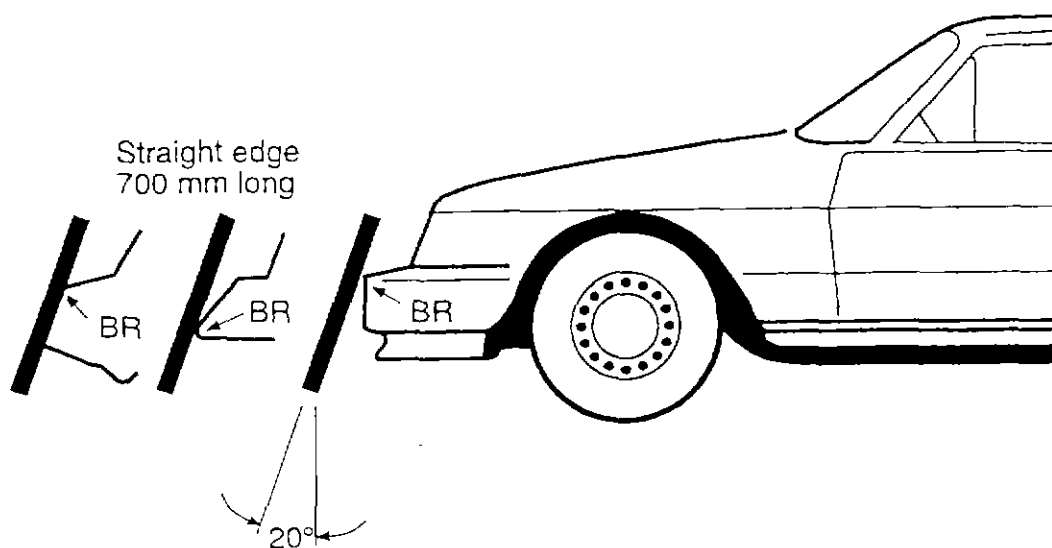
By 1991 the contractors' sub-group had produced reports which contained a description of the method proposed for each sub-system test, and details of the prototype impactors. The head impact test procedure was developed by BAST (Glaeser, 1991), the test for pedestrian lower leg and knee protection by INRETS (Cesari et al., 1991), and that for upper leg protection by TRL (Lawrence et al. 1991). Each of these three sub-system tests was carried out using an impactor developed to represent the relevant body region of the pedestrian. TNO conducted computer simulations and an evaluation of the sub-systems test method. A general description of the work of the contractors' sub-group was presented by the Chairman of the Working Group at the Thirteenth ESV Conference (Harris, 1991). The research data used in the development of each sub-system test had been reviewed previously (EEVC, 1989).

Following the publication of the above reports in 1991, the EEVC Main Committee extended the mandate of Working Group 10 "to consider what work would be necessary to support the results obtained from the EC study and to finalise the work programme" (EEVC, 1994). The chairmanship passed from Harris of TRRL, who had retired, to Janssen, of TNO. In addition to Peugeot/Renault the membership included representatives from Rover, Mercedes-Benz, Fiat and Volvo. The 1994 report of the Working Group contained a review of the work program, a description and evaluation of the sub-system test methods together with a proposed EC Directive, which has the purpose of "reducing injuries to pedestrians and other vulnerable road users who are hit by the frontal surfaces" of specified vehicles (EEVC, 1994).

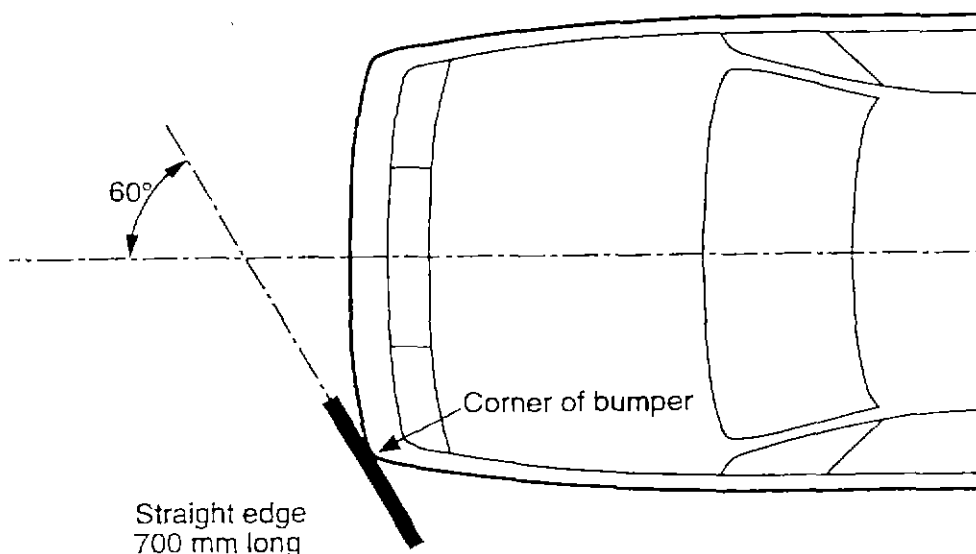
### 5.3.2 Definitions

The definitions relevant to the proposed EC Directive deal mainly with the areas of the vehicle which are to be tested, as shown in Figures 5.1-5.6 (EEVC,1994). Some of the terms defined in the report are not illustrated in these figures. For example, "bumper lead" is the horizontal distance between the bumper reference line and the bonnet leading edge reference line. The "bonnet top" refers to the area bounded by the bonnet side reference lines and the geometric trace of the 1000 mm wrap around distance at the front and the 2100 mm wrap around distance at the rear of the bonnet (see Figures 5.4 and 5.5). If the 2100 mm wrap around distance includes the windscreen, then the lower frame of the windscreen is the rear boundary.

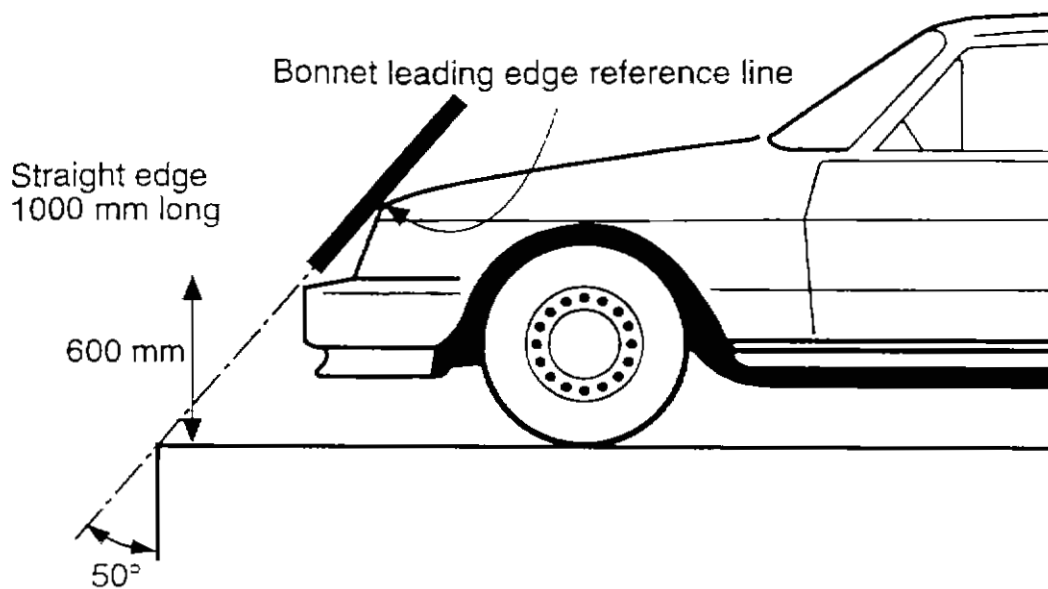
One other definition is that of the "Head Performance Criteria" which, as noted previously in this report, refers to the Head Injury Criterion (HIC).



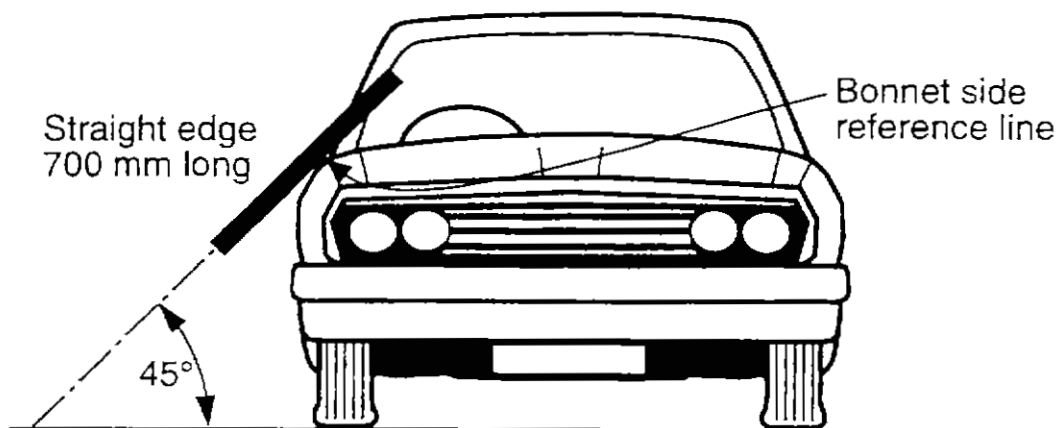
**Figure 5.1: Determination of the Bumper Reference Line**



**Figure 5.2: Determination of the Corner of the Bumper**

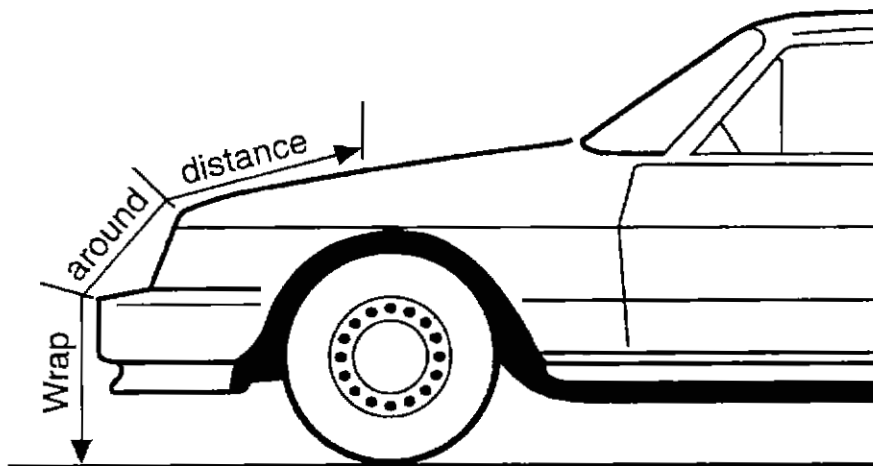


**Figure 5.3: Determination of the Bonnet Leading Edge**

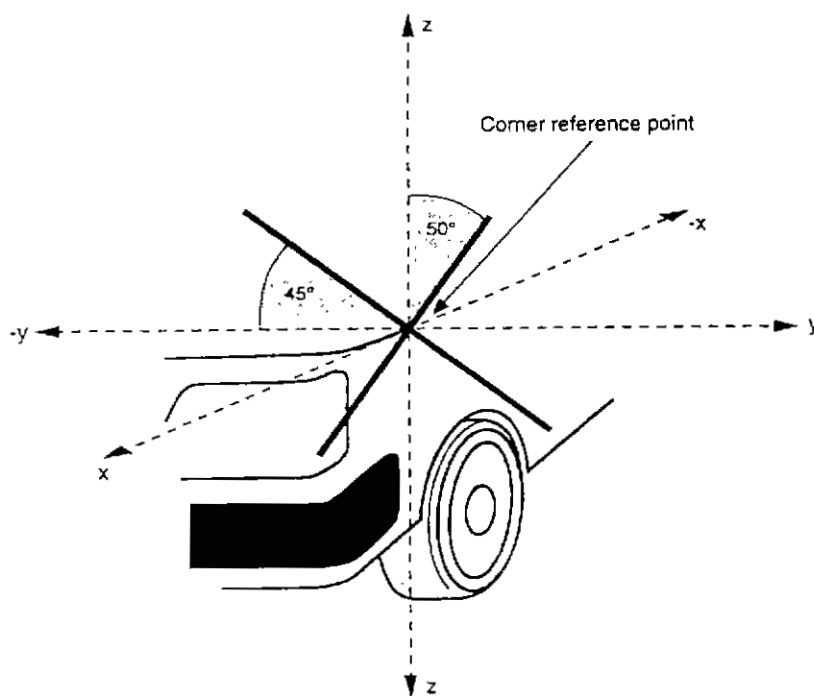


**Figure 5.4: Determination of Bonnet Side Reference Lines**

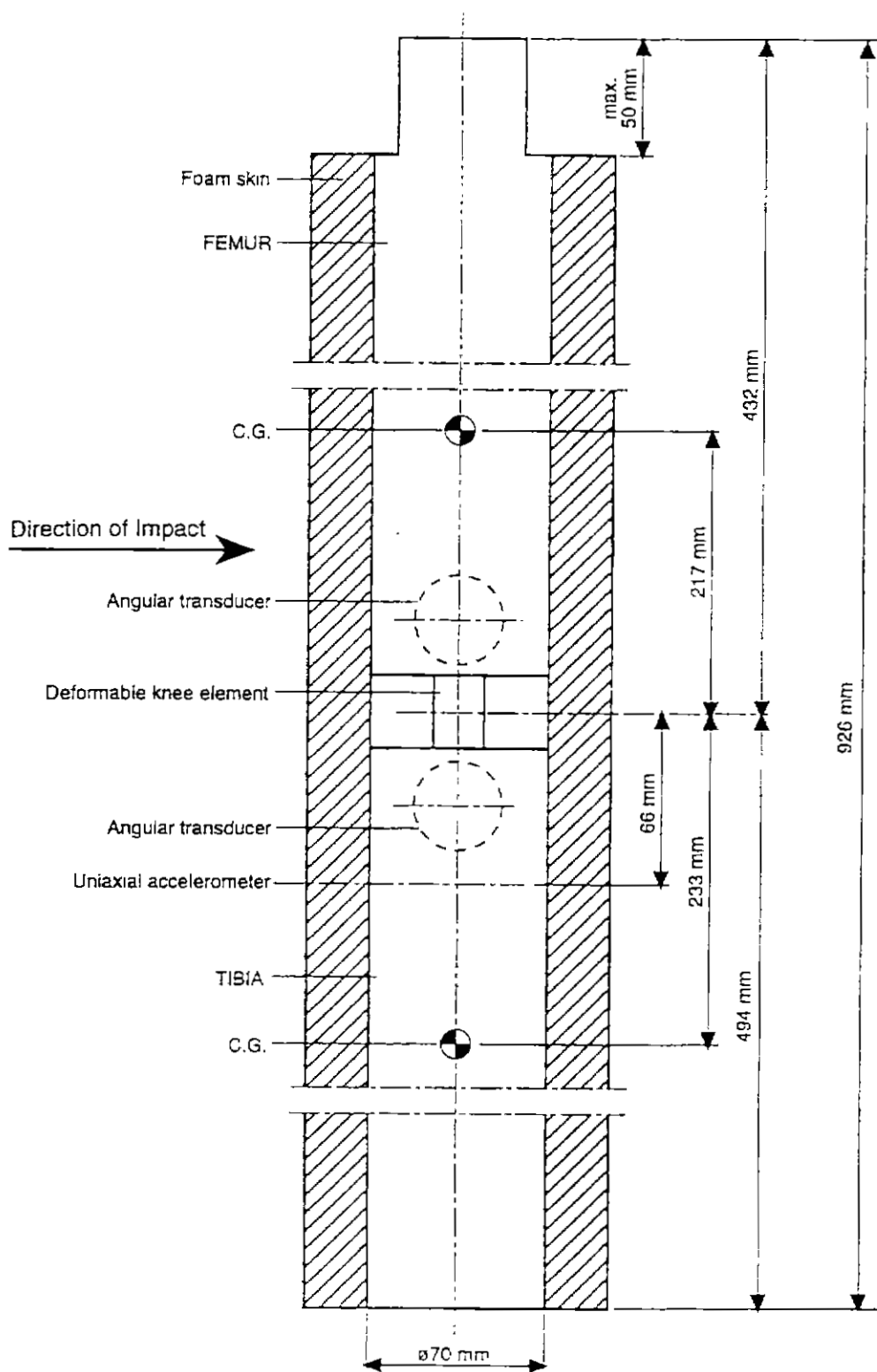




**Figure 5.5: Determination of Wrap Around Distance**



**Figure 5.6: Determination of Corner Reference Point**



**Figure 5.7: Legform Impactor**

### 5.3.3 Legform to bumper tests

In this test a legform impactor represents the upper and lower leg of the pedestrian, including a deformable simulated knee joint (see Figure 5.7). The impactor is fired at the front of the vehicle as shown in Figure 5.8 (EEVC, 1994). On impact, it is in free flight at a velocity of 40 km/h. The instrumentation in the impactor measures the lateral dynamic knee bending angle (not to exceed 15 degrees), the lateral displacement of the lower leg relative to the upper leg at the simulated knee joint (not to exceed 6 mm) and the acceleration measured at the upper end of the simulated tibia (lower leg; not to exceed 150 g).

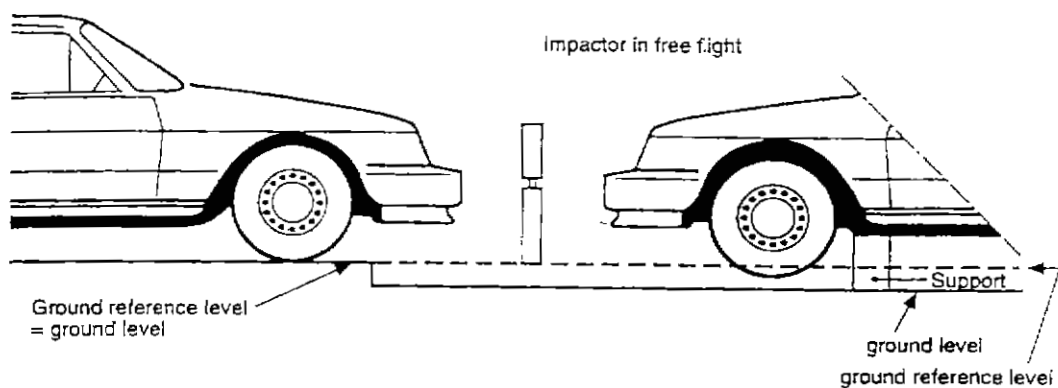
The development of a satisfactory legform impactor presented many difficulties. The task was assigned to INRETS in the contract with the EC but an evaluation of the INRETS impactor by Lawrence and Hardy (1993) identified several areas in need of improvement, particularly in the measurement of lateral displacement of the knee joint. TRL have since modified the design of the impactor and have contracted for it to be produced by Ogle Design Limited (Lawrence and Hardy, 1994). Although development of the method of measuring lateral shear (displacement) in the knee joint is continuing, TRL has been conducting tests with this impactor, which is now commercially available at a cost of about \$15,000. Full details of the test procedure are contained in the 1994 report of the EEVC Working Group 10.

### 5.3.4 Upper legform to bonnet leading edge test

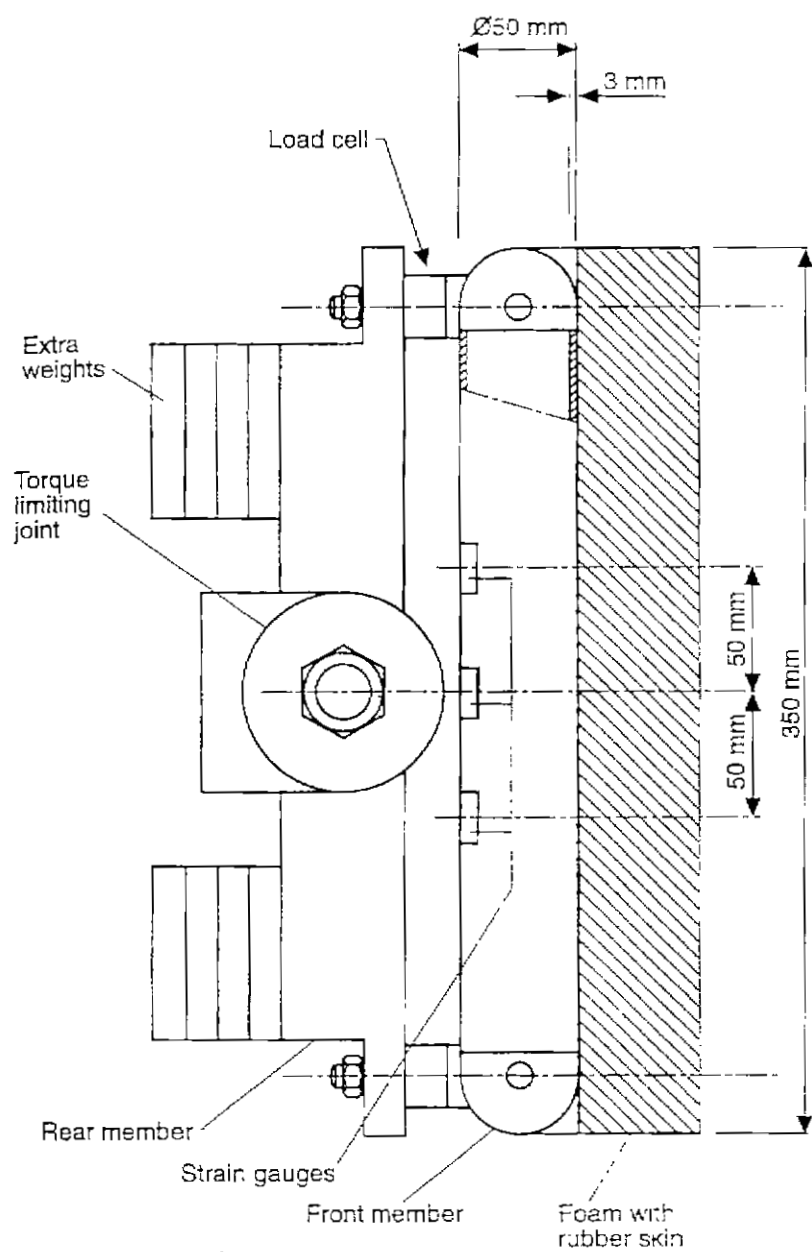
An upper legform impactor, representing a segment of an adult femur, has been developed by TRL (Figure 5.9). The impactor, which is mounted to a propulsion system by means of a torque limiting joint, is guided throughout the impact sequence. A typical alignment relative to the vehicle being tested is shown in Figure 5.10.

The test procedure is based on kinetic energy to limit the variations of impact severity that could result from independent selections of mass and velocity. It also depends on the shape of the front of the vehicle because the bonnet leading edge and the bumper reference heights, and the bumper lead, have a marked influence on the bonnet leading edge test procedure (EEVC, 1994). A computer program which automates the selection of the relevant input parameters for a given car shape is available (Lawrence and Hardy, 1994). It is possible for the requirement for this test to be waived for a car with a bonnet which slopes down to the bumper. When, as will be the case with most cars, a bonnet leading edge test is required, the specified criteria are that the total instantaneous force should not exceed 4 kN and the bending moment should not exceed 220 Nm.

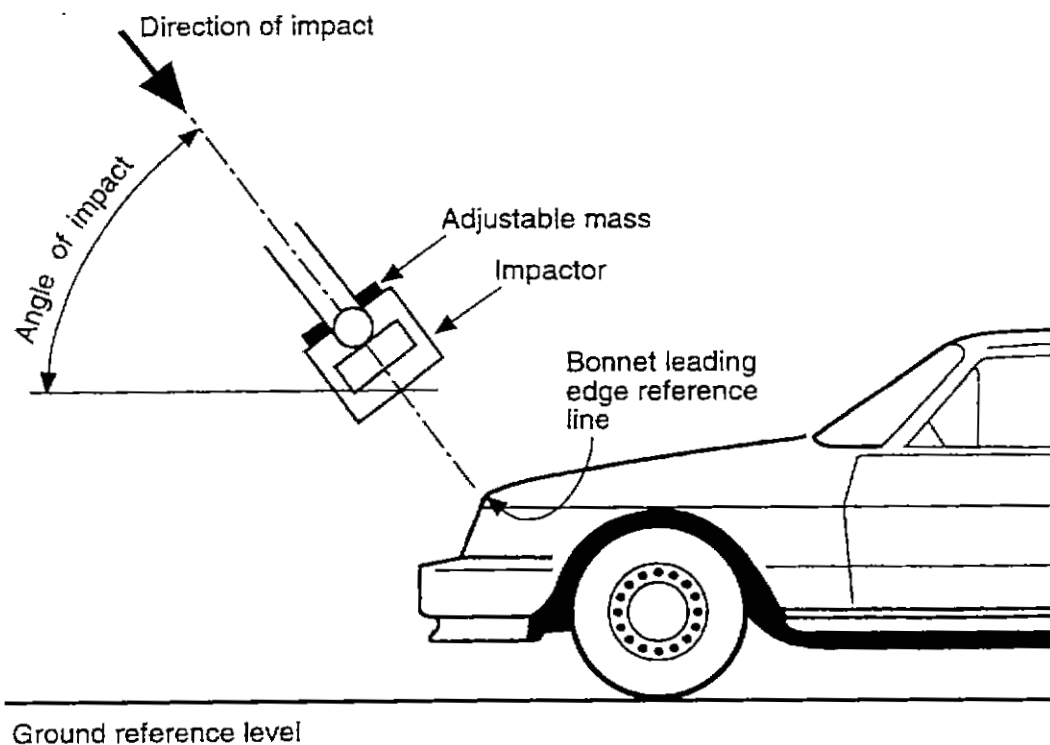
Apart from a need for some relatively minor modifications, no significant difficulties have been identified with either the upper legform impactor or the test procedure (Lawrence and Hardy, 1994). The impactor is now commercially available.



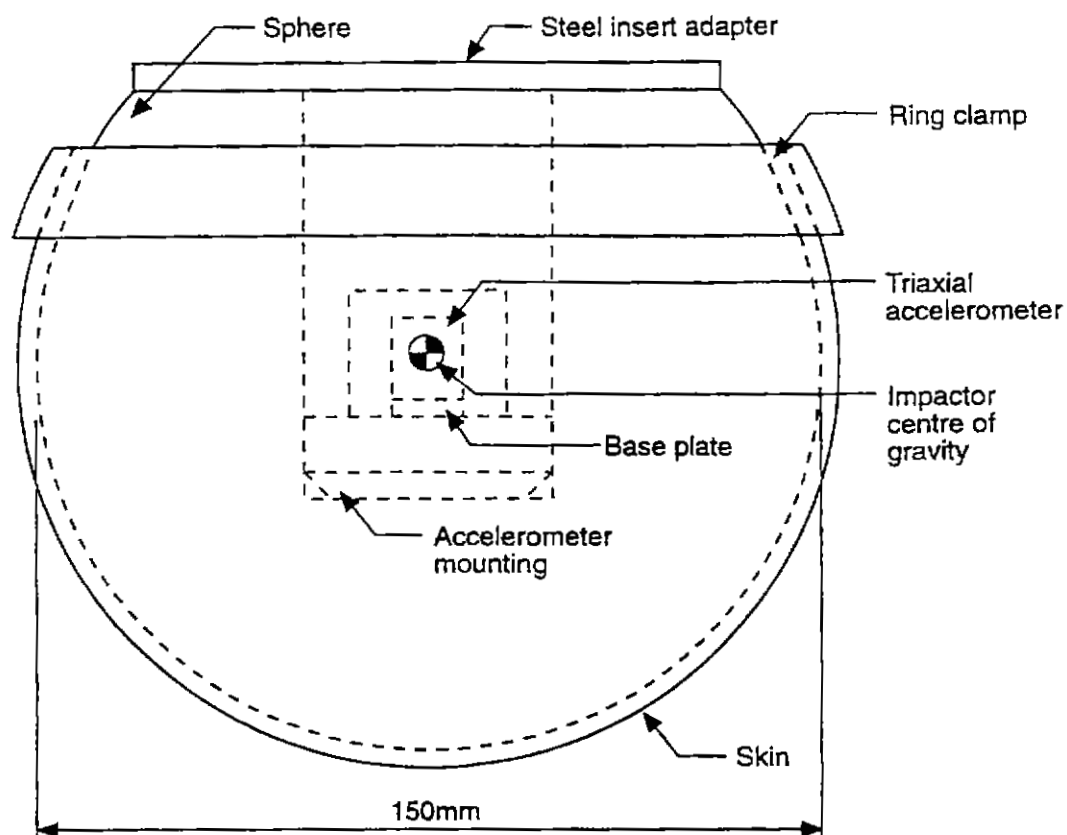
**Figure 5.8: Bumper Test Procedure**



**Fig 5.9 Upper Legform Impactor**



**Fig 5.10: Bonnet Leading Edge Test**



**Figure 5.11: Adult Headform Impactor**

### 5.3.5 Headform to bonnet top test

Two headform impactors are specified for the headform to bonnet test, one to simulate an impact by the head of a child pedestrian and the other that of an adult. The general dimensions of each spherical headform are indicated in Figure 5.11. The child headform is naturally smaller and lighter (115 compared with 150 mm diameter and 2.5 compared with 4.8 kg) (EEVC, 1994).

A 7.5 mm thick rubber “skin” covers the impact surface of each impactor. The function of the skin is to protect the impactor from damage and to enable the use of undamped accelerometers. Tests conducted by the Japan Automobile Research Institute comparing the impact response of cadaver heads with that of rigid and “skin” covered headforms when striking a car bonnet indicated that the skin had no meaningful effect on the response (Sakurai et al., 1993). Headforms which meet the EEVC specifications are commercially available from TNO.

The test procedure was developed by BAST under contract with the EC (Glaeser, 1991, Zellmer and Glaeser, 1994). It has been further developed by BAST and by TRL, with changes primarily relating to the location of the triaxial accelerometers in the headforms and to the properties and fixing of the rubber skin (Lawrence and Hardy, 1994).

The test involves propelling the headform in free flight at a velocity of 40 km/h at an angle of 65 degrees to the horizontal (50 degrees for the child headform test) in a rearward direction parallel to the longitudinal centreline of the car. The child headform tests are performed on the forward section of the bonnet and wings, bounded by wrap-around distances of 1,000 mm and 1,500 mm. The adult tests assess the impact response of the rearward section, with the fore and aft boundaries being defined by wrap-around distances of 1,500 and 2,100 mm, or the lower edge of the windscreen, whichever is closer to the front of the vehicle. In the event of a test being conducted adjacent to the lower edge of the windscreen, the headform should not contact the windscreen glass before striking the vehicle structure. The level of head protection afforded by the vehicle is assessed by the Head Injury Criterion, as noted previously.

### 5.3.6 Impactor propulsion systems

The performance levels required of impactor propulsion systems for the EEVC tests are defined in the test procedures themselves (EEVC, 1994). However it has become apparent that there are many practical difficulties which have to be overcome before a propulsion system can be relied upon to meet these performance levels with sufficient degrees of accuracy and reliability.

Frazer-Nash Defence Systems Division of Aircrow Howden have designed a Pedestrian Impactor Propulsion System which can be used in all three of the sub-system tests. For the two “free-flight” tests the acceleration of the impactor ceases before the impactor reaches the end of the guidance system, by which time it has attained a steady velocity, which is desirable. At present there is no other commercially available propulsion system which can be used in all three tests. However, it has been specifically designed to meet the requirements of EC Regulation No 74/483/EEC (the EEVC recommended test procedures) at impact speeds of 40 km/h. Although the estimated maximum velocity with which it can propel an adult headform is 58 km/h (personal communication from C.A. Field, Frazer-Nash, 1995) this is not high enough to enable it to reproduce the head impact velocity in many of the fatal pedestrian collisions which occur in Australia, as discussed later in this report.

The Frazer-Nash Pedestrian Impact Propulsion System is commercially available at a cost of £70,000.

#### 5.4 INTERNATIONAL: ISO TEST PROCEDURES

In 1983 the International Standards Organisation's (ISO) Technical Committee on Road Vehicles (TC 22) Subcommittee on Impact Test Procedures (SC 10) recommended that a Working Group be formed on the topic of 'Road Vehicle Front Structure - Pedestrian Safety Impact Test'. The scope of the Working Group's activities was to 'Develop a method for discrimination between passenger car front ends as to their relative friendliness when impacting a pedestrian' (ISO/TC22/SC10, Document N173, 1983).

The Working Group (WG2) met for the first time in 1988 under the chairmanship of Wada of Nissan Motor Company. The secretariat is based at the Japan Society of Automotive Engineers. The membership of the group has included representatives from TRL, INRETS, JARI, BAST, and industry groups and companies such as the APR Laboratoire de Physiologie et de Biomécanique, Volvo and Mercedes. The author of this report was invited to become a member at the meeting held in London in May 1990. At the end of that year the name of the Group was changed to 'Pedestrian Impact Test Procedures'. In July 1991 Wada's three year term as chairman ended and he was replaced by Mizuno of the Japan Ministry of Trade and Industry.

It is apparent from the list of organisations represented on ISO Working Group 2 that there was substantial common membership with EEVC Working Group 10. Consequently it is not surprising that the work program of ISO WG2 has followed very closely the corresponding parts of that of EEVC WG10. However, whereas the EEVC group submitted its final report on three sub-system test procedures in 1994, the work of the ISO group has been concentrated on the development of a legform test procedure with some attention being given to a headform test procedure.

At the 16th meeting held in Sweden in September, 1995 the Chairman noted that ISO had advised that WG2 was to complete its work no later than the end of 1996. As no consideration has been given to the development of a bonnet leading edge test, the final report from WG2 will address only the protective properties of the bumper and the upper surface of the bonnet and wings.

In March, 1993 the Chairman of WG2 (Mizuno) wrote to the Chairman of EEVC (Friedel) asking that the drafting of any EC regulation for pedestrian protection make full use of the (then) yet to be drafted ISO test procedures. This is consistent with the stated prime objective of ISO, which is the harmonisation of standards (ISO/TC22/SC10/WG2, doc. N407). The Chairman of WG2 also noted that the following issues were among those that remained to be resolved:

- (1) Clarification of injury mechanisms and human tolerance for the leg area.
- (2) Comparability of test procedures for the head, hip and leg.
- (3) Compatibility of test procedures with existing bumper testing regulations.
- (4) Effect of different countries' licence plate requirements on bumper redesign.
- (5) HIC (HPC in EEVC proposal) of 1,000 yet to be accepted as a valid head injury indicator for children.

It is probable that the final ISO legform to bumper sub-system test will differ little if at all from that in the proposed EC Directive. The compatibility of test procedures for the head, hip and leg, item (2) above, does not appear to be a significant issue.

In 1990, WG2 agreed that ‘bumper geometry on current model vehicles does not have a significant effect on head impact’ (ISO/TC22/SC10/WG2, Resolution No. 18).

Concern about the validity of use of a HIC of 1,000 for child head impacts is understandable but, given the tenuous basis of HIC in the first place (McLean, 1995), it would appear to be preferable to have a head protection test for children using HIC than to have no test at all. Apart from the absence of a test for children, the sub-system test for head protection in the final WG2 recommendation is also likely to be very similar to that in the proposed EC Directive.

The major difference between the Directive and the WG2 recommendation is therefore likely to be the absence of an upper leg sub-system test in the latter.





# Chapter 6 Application of Pedestrian Impact Test Procedures

## 6.1 STATUS OF RULEMAKING

### 6.1.1 United States of America

A Notice of Proposed Rule Making (NPRM) on pedestrian leg protection was issued by NHTSA in 1981 (Federal Register, 1981). It would have required the softening of bumpers and other front end structures of cars. This NPRM was terminated in 1991 (Federal Register, 1991) following studies with more modern vehicles having lower front profiles which did not demonstrate the same reduction in the risk of leg injury (NHTSA, 1993).

The procedures leading to the issue of a notice of proposed rule making for pedestrian head protection were commenced by NHTSA in 1989 and terminated in 1992. The intended notice of proposed rule making (Hoyt et al., 1990) dealt with the central area of the bonnet, excluding the outer 4 inches, measured from the front, rear and side edges. This area was prescribed for three reasons:

- (1) The results of the investigation of pedestrian collisions in the PICS studies showed that, for both child and adult pedestrians, head impacts often occurred in that area.
- (2) The results of physical testing at VRTC had shown that marked differences existed in the level of head protection afforded by the bonnets of current production cars. This suggested that considerable benefits would accrue from simply requiring all manufacturers to match the then current best practice (MacLaughlin et al., 1988).
- (3) Improvements could be made in most cases without any changes to the external dimensions or appearance of the car.

The notice of proposed rule making for pedestrian head protection was withdrawn by the Administrator of NHTSA at about the same time that the car industry agreed to accept the proposed rule on side impact protection for passenger cars. The NPRM appeared to address adequately the head injury potential of the bonnets of existing vehicles but the test procedure was defined in relation to the edges of the bonnet rather than to the wrap around distance as in the EEVC requirements. This left open the possibility that a manufacturer might choose to address the test requirements by, for example, reducing the size of the bonnet on a car or even by eliminating it altogether (the E-type Jaguar had no opening bonnet in the conventional sense, the entire front of the body work of the car pivoted forwards to allow access to the engine). The research group at VRTC which developed the proposed pedestrian head protection rule has been disbanded and there is currently no experimental research activity at NHTSA relating to pedestrian protection and vehicle design, although there is a special pedestrian injury study currently underway as part of the National Accident Sampling System (NASS).

### **6.1.2 Europe**

The final report of EEVC Working Group 10 contains a draft EC Directive, or Standard, for pedestrian protection (EEVC, 1994). As noted earlier in this report, this draft Directive was to have been an amendment to EC Directive 74/483/EEC ("external projections") which regulates aspects of the external design of vehicles to minimise the risk of injury to pedestrians and other unprotected road users. Following objections from some vehicle manufacturers this approach has been abandoned and the draft Directive is now in the process of being considered for adoption as a separate Directive rather than as an amendment. If the draft Directive is approved, by October 1998 all new models of cars will have to pass the sub-system tests, and by October 2001 all cars entering service will be required to comply.

### **6.1.3 Japan**

There is no current proposal for the introduction of a vehicle safety standard for pedestrian protection in Japan as far as passenger cars are concerned. The Chairman of the ISO Working Group on Pedestrian Impact Test Procedures (Mizuno) stated that Japan will not take the lead in rule making but may take up the issue whenever the EC or the USA adopt a regulation (ISO/TC22/SC10/WG2.Document N476, 1995).

## **6.2 VEHICLE SAFETY ASSESSMENT OF NEW AND MODIFIED CARS**

Conducting tests such as those proposed in the final report of EEVC WG10 and publishing the results by make and model of car can play a complementary role to the adoption of mandatory safety standards to improve the crashworthiness of motor vehicles.

### **6.2.1 United Kingdom**

Four cars were tested by TRL using the EEVC pedestrian head impact test procedure in 1994 (Lawrence and Hardy, 1994a). None of the cars complied with the test requirements, but in some cases only relatively minor design modifications would be necessary to obtain a satisfactory test result.

The United Kingdom Department of Transport has initiated a New Car Assessment Program (NCAP) of crash tests to assess aspects of the crashworthiness of passenger cars. The UK program is more comprehensive than the original NCAP program conducted by NHTSA in the United States and is similar to the programs being conducted in Australia, in the United States by the Insurance Institute for Highway Safety, and in Europe at BAST under the sponsorship of ADAC, the German Automobile Club. The UK program is unique in that it includes an assessment of the level of pedestrian protection afforded by each car tested, using the EEVC sub-system test procedures. The first set of these tests has been carried out and the results are expected to be made public in 1996.

Lawrence and Hardy at TRL also investigated the pedestrian injury potential of crash bars fitted to a Range Rover using the EEVC bonnet leading edge test procedure involving the upper legform impactor (Lawrence and Hardy, 1992). They concluded that, although tests on the vehicle with and without a crash bar fitted both resulted in an unacceptably high risk of injury to a pedestrian, it would be feasible to modify the vehicle so as to bring this risk within the acceptable range.

### **6.2.2 Germany**

A research worker at BAST investigated the effect of an impact between crash bars and the head of a child using the EEVC WG10 child headform (Zellmer, 1993). Tests were conducted on crash bars mounted to four 4wd vehicles: Suzuki Vitara, Opel Frontera, Mitsubishi Pajero and the Nissan Patrol. At an impact speed of only 20 km/h, nine of the 14 tests resulted in a HIC value of more than 1,000, indicating an unacceptable risk of serious head injury. Not surprisingly, the tubing was not permanently deformed when struck by the child headform.

Zellmer and Friedel extended this work to include a test using the EEVC legform and upper legform impactors (Zellmer, and Friedel, 1994). The results of the upper legform tests indicated that the crash bars increased the risk of injury to a pedestrian whereas the legform test results were consistent with a slight reduction in the risk of injury to the ligaments of the knee.

## **6.3 COST BENEFIT ANALYSES**

### **6.3.1 European Automobile Manufacturers Association (ACEA)**

The European Automobile Manufacturers Association (ACEA: Association des Constructeurs Europeens d'Automobiles) published a review of pedestrian accidents in Europe which contained a cost-benefit analysis of the draft EC Directive based on the EEVC sub-system tests (ACEA, 1992). The estimated cost-benefit ratio was 57:1, assuming a cost of DM 500 per new car to ensure compliance with the draft Directive and the sole benefit being the prevention of pedestrian fatalities, ignoring any saving from a reduction in injury severity and resulting disability among survivors. The general conclusion of this report was that "the number of pedestrian accidents will continue to decrease as has been observed for 20 years and even faster than in the past, thanks to the avoidance of the accident itself".

### **6.3.2 German Federal Highway Research Institute (BAST)**

A more comprehensive assessment of the likely effect of the introduction of the draft EC Directive was conducted at BAST, the Federal Highway Research Institute in Germany. Allowance was made in this evaluation for the benefits arising from a reduction in injury severity, and the elimination of significant injuries, as well as from the prevention of fatalities (Bamberg and Zellmer, 1994). The authors of this work concluded that the potential cost savings per passenger car would be between DM 46 and DM 63. In other words, the introduction of the EC Directive would be cost effective if the average cost per new car of complying with it was no greater than the range stated. They emphasised that their estimate was based on data for Germany and that the cost-benefit ratio would be less (more favourable) in countries where typical urban travel speeds were lower and, conversely, less effective in countries where urban travel speeds were higher. This is because the EEVC test procedure is conducted at a speed of 40 km/h.

### **6.3.3 Transport Research Laboratory**

The costs and benefits of the EEVC pedestrian impact requirements were estimated in a TRL report by Lawrence et al in 1993. Their assessment included the effect of the requirements on casualty, as well as fatality, reduction, as was done with the BAST evaluation. The estimated average cost of compliance per new car in the first year of the Directive was within the range of £9.60 to £15.43, decreasing somewhat in the next two years before stabilising in year 4 and subsequent years at £9.01 to £12.98. The estimated cost-benefit ratio was 1:7.5 based on production costs and 1:4.3 based on the after tax cost to the consumer. The net savings for vehicles produced in the year 2000 for the countries of the European Community were estimated to be 1,569 million ECU (£1,121M) based on production costs or 1,389 million ECU (£992M) based on consumer costs. These savings were calculated only on those pedestrians killed and seriously injured by contact with the areas subject to the proposed test requirements in the speed range up to 40 km/h. As such, the estimated savings would be expected to be conservative because it is reasonable to assume that the changes to the cars would still be beneficial, albeit at diminishing levels of effectiveness, at higher speeds.

# Chapter 7 Pedestrian Protection and Vehicle Design in Australia

## 7.1 CHARACTERISTICS OF PEDESTRIAN COLLISIONS IN AUSTRALIA

There are at least two characteristics of pedestrian/vehicle collisions in Australia which are relevant to an assessment of the likely value of the draft EC Directive. The first is that the percentage of fatally injured pedestrians hit by cars is higher in Australia than in some of the European countries, as shown in Table 7.1. This difference appears to be even greater in non-fatal cases (88 per cent involved cars in Australia, but only about 60 per cent in the U.K., according to Lawrence et al, 1993). This means that changes to car design to comply with the EEVC test requirements would, other things being equal, be expected to be of greater benefit in Australia than in the other countries listed because the striking vehicle is more likely to be a car.

**Table 7.1 Percentage of Fatally Injured Pedestrians Hit by Cars: Australia and Some European Countries**

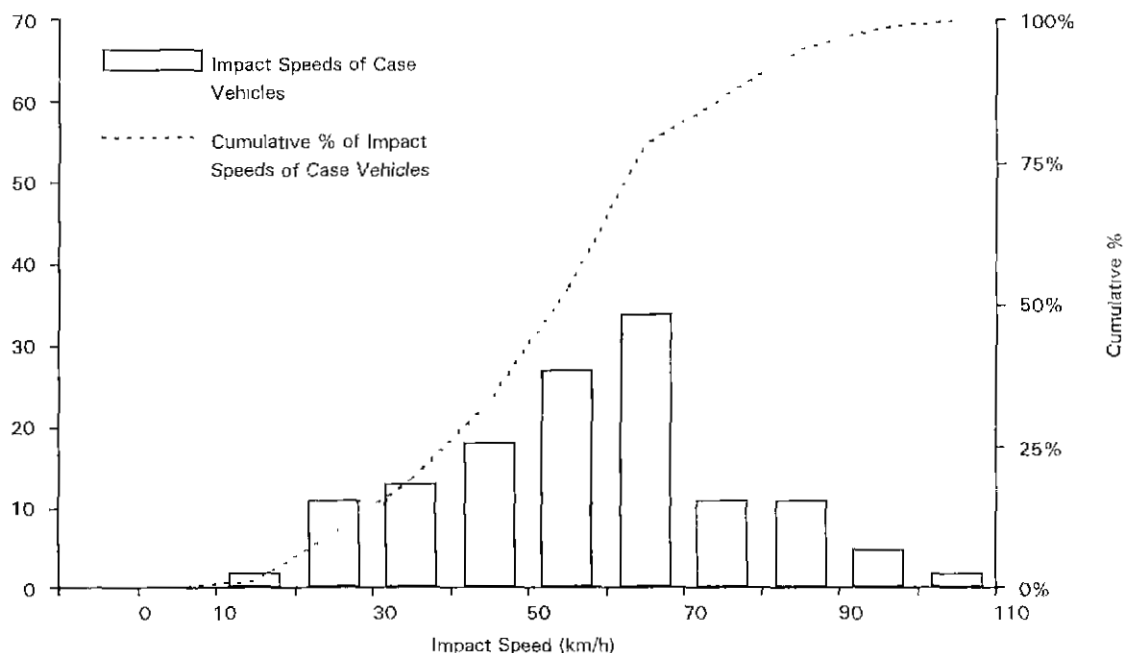
Australia	80 % <sup>1</sup>
Italy	69 %
France	58 %
Germany	63 %
United Kingdom	62 %

Note: <sup>1</sup> Based on South Australian data for 1993 and 1994 (McColl, S.A. Police, personal communication, 1995)

Data for other countries for 1990 as listed in ACEA, 1992

However, other things may not be equal. Australia has one of the highest urban area speed limits in the world. The four other countries in Table 7.1 all have an urban area speed limit of 50 km/h. Assuming that travelling speed distributions are roughly in proportion to the speed limits, and that differences in pedestrian impact speeds are proportionally greater than differences in travelling speeds (see McLean et al, 1994), one would expect compliance with the EEVC requirements to be somewhat less effective in reducing pedestrian fatalities in Australia than in the European countries listed in Table 7.1.

Figure 7.1 shows the distribution of impact speeds in fatal pedestrian collisions which occurred in the vicinity of Adelaide, South Australia. Eighty per cent of the fatalities occurred at impact speeds above 40 km/h (McLean et al, 1994). In a study conducted in Hannover, in Germany, the corresponding percentage was 84 per cent (Otte, personal communication, 1992; and Lawrence et al, 1993). While this may suggest a similar speed distribution between Australia and Germany, and therefore an expected similar benefit from adopting the EEVC requirements, it is still possible that the collisions that occur at speeds above 40 km/h in Germany do so at lower speeds, possibly much lower, than in Australia. This would need to be established through further research.



**Figure 7.1: Distribution of Impact Speeds in Fatal Pedestrian Collisions in Adelaide, Australia (Collisions in 60 km/h speed limit zones only)**

## 7.2 VEHICLE SAFETY STANDARDS

As discussed in the preceding paragraphs, the higher percentage of cars among the vehicles involved in pedestrian collisions in Australia compared to Germany and the United Kingdom may balance out the higher speeds at which pedestrian collisions occur in Australia with respect to the probable benefit that would be derived from introducing the EEVC pedestrian impact requirements as an Australian Design Rule in the form of the draft EC Directive.

# **Chapter 8 Opportunities for Further Research in Australia**

## **8.1 ESTABLISHMENT OF A PEDESTRIAN IMPACT TEST FACILITY**

There are several reasons to support the establishment of a pedestrian impact test facility in Australia. At present, the obvious choice would be a facility which could be used to test for compliance with the draft EC Directive. The only commercially available propulsion device is the one manufactured by Frazer Nash for TRL. The legform test device developed by TRL appears to be more likely to be generally acceptable much sooner than the INRETS legform, particularly because there has been no development work carried out for some time on the INRETS device. There are no production difficulties with the upper legform and the child and adult headforms are commercially available from TNO.

## **8.2 BIOMECHANICS RESEARCH RELATED TO CRASH INJURY PROTECTION**

The aim of the head injury research program of the NHMRC Road Accident Research Unit (RARU) at the University of Adelaide is to develop a more soundly based criterion for the tolerance of the human brain to impact to the head than is provided by HIC. This is being attempted by relating the characteristics of the impact to the head to characteristics of the resulting injury to the brain of the living (at the moment of impact) human.

The head injury research program has been based largely on the study of fatal pedestrian collisions involving passenger cars. In cases in which there was only one impact on the head and the impact speed of the car could reliably be estimated, extremely detailed information, at the microscopic level, has been obtained on the characteristics of the lesions in the brain tissue. For a given speed of the car on impact, the velocity with which the head hits the car depends on the height of the pedestrian relative to the front of the car. The stiffness (hardness) of the head impact point on the vehicle is the remaining determinant of the impact force and the resulting linear and angular accelerations of the head.

The structure of the car at points hit by the head of a pedestrian is often far from simple. For example, the bonnet of a car appears to be a simple sheet metal panel when viewed from above. Underneath, however, it is reinforced by stiffening members. This means that the stiffness of the point struck by the head of a pedestrian can range from very soft, if it is not over a stiffening member, to relatively hard. Furthermore, if the head impact velocity is high enough, the bonnet may deform to the extent that the underside hits the top of the suspension strut or the air cleaner housing or some other under bonnet component. Similarly, while the top of a front wing is relatively soft, the edge of the wing adjacent to the side of the bonnet is often very hard.

For these reasons, attempts have been made by RARU to reconstruct the head impacts observed in actual pedestrian car collisions by dropping an instrumented headform onto the upper front of a car from a height which results in the estimated head impact velocity in the actual collision. This has not been satisfactory because it is not been possible to ensure that the headform strikes the car



close enough to the intended impact point. Hence the need for a powered propulsion system which can be aimed precisely, such as the one developed by Frazer-Nash for TRL, although it is limited in the maximum velocity with which it can propel an adult headform (58 km/h, as noted earlier in this report).

This is the only research program of its type in any country and so RARU is collaborating with two overseas research groups in the validation, or otherwise, of models of brain injury. Willinger, at Université Louis Pasteur, Strasbourg, France, has visited Adelaide on two occasions in connection with the development of both mathematical and physical models of the human head (Willinger et al, 1992), and collaboration commenced in 1995 with King et al., of Wayne State University, Detroit, on the validation of a three dimensional finite element model of the human skull and brain. Ono, of the Japan Automobile Research Institute, has also proposed that a collaborative research program be developed with RARU. The value of these collaborative activities will be greatly increased if accurately measured information on head accelerations can be obtained from headform tests.

### **8.3 EFFECTS OF BULL BARS ON PEDESTRIAN PROTECTION**

The most common single type of modification of the front of a vehicle in Australia is the fitting of bull bars, particularly to four wheel drive (4wd) or off road vehicles. When fitted to a 4wd the upper bars are at about head height for some children and pelvis/upper leg height or higher for an adult pedestrian.

The investigations conducted at TRL and BAST (see 6.2 above) indicated that crash bars, or bull bars, do present an unacceptable risk of injury to pedestrians. However, because of the wide range of bull bars on the market in Australia, there may be some point in conducting a series of demonstration tests of the effect that they have on the level of pedestrian protection of an unmodified vehicle.

Lawrence and Hardy at TRL could see no way of modifying steel crash bars to decrease their risk of injuring a pedestrian because their inertia alone rendered them hazardous. Nor could they suggest any modification to crash bars that would eliminate their high risk of injuring a pedestrian while retaining any useful level of protection for the front of the vehicle in off road use.

Following the child headform tests on conventional crash bars at BAST, Zellmer constructed a different bar for the Mitsubishi Pajero. The 42 mm diameter main (horizontal) steel tube was replaced by a 40 mm diameter tube of "plastic material" having a wall thickness of 2 mm. The front face of the vertical supporting members was covered with 40 mm of expanded polystyrene. At a headform impact velocity of 40 km/h, as required by the EEVC WG10 test procedure, the HIC values were less than 370 for impacts with the tube and 1,114 for an impact with the crash bar supporting member.

These BAST tests showed that it is possible to reduce the head injury potential of bull bars by a radical redesign of the material from which the bar assembly is made and by the provision of energy absorbing padding on the front face of the upright supporting members. However, the testing of the modified bar did not include measuring the impact load to failure of the bar assembly, and so no comment can be made on whether that crash bar would be strong enough to protect the vehicle from immobilising damage in the event of hitting an animal. As noted above, it

is the opinion of the TRL researchers that a pedestrian friendly crash bar would provide little protection for the vehicle.

Further work by BASt has led to the development of a crash bar assembly in which the members that could strike the head of a child pedestrian are encased in self-skinned rigid plastic foam. The resulting assembly has an appearance that is likely to be highly acceptable commercially.



## **Chapter 9    Conclusions and Recommendations**

The review of current literature on research conducted on pedestrian friendly vehicle front structures has led to the following conclusions and recommendations:

- 9.1**    The level of pedestrian protection provided by current passenger cars can be significantly improved with practicable design changes
- 9.2**    The draft EC directive based on the EEVC test procedures is the best available means of assessing the level of pedestrian protection of a vehicle
- 9.3**    It is likely that the benefits in terms of a reduction in pedestrian deaths, injuries and disabilities resulting from the adoption of the draft EC directive as an Australian Design Rule for Motor Vehicle Safety would be cost effective
- 9.4**    Consideration should be given to the establishment of a pedestrian impact test facility in Australia to enable testing of vehicles and vehicle modifications to be conducted according to the EEVC test procedures
- 9.5**    Consideration should be given to further research into the mechanisms of pedestrian injuries.



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## APPENDIX    ACRONYMS

ACEA:	Association des Constructeurs Europeens d'Automobiles (European Automobile Manufacturers Association )
APR:	Association Peugeot Renault
BASf.	Bundesanstalt für Straßenwesen (German Federal Highway Research Institute)
EC	European Community
EEC:	European Economic Community
EEVC:	European Experimental Vehicles Committee
HIC.	Head Injury Criterion
INRETS	Institute National de Recherche sur les Transports et leur Sécurité (French National Transport Safety Research Organisation)
ISO:	International Standards Organisation
JARI:	Japan Automobile Research Institute
NHMRC.	National Health and Medical Research Council (Australia)
NHTSA	National Highway Traffic Safety Administration. USA.
RARU.	NHMRC Road Accident Research Unit, The University of Adelaide. Australia.
SAE:	Society of Automotive Engineers
SC	Subcommittee
TC:	Technical Committee
TTI	Thoracic Trauma Index
VRTC	Vehicle Research Test Center of NHTSA
WG.	Working Group